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Jeremy N. Ciporen
Oregon Health & Science University

Brandon Lucke-Wold
West Virginia University

Gustavo Mendez
Rush University

William E. Cameron
Oregon Health & Science University

Shirley McCartney
Oregon Health & Science University

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Endoscopic Management of Cavernous Carotid Surgical Complications: Evaluation of a Simulated Perfusion Model

Jeremy N. Ciporen[1], **Brandon Lucke-Wold**[2], **Gustavo Mendez**[3], **William E. Cameron**[4], and **Shirley McCartney**[1]

[1]Departments of Neurological Surgery, Oregon Health & Science University, Portland, Oregon

[2]Department of Neurosurgery, West Virginia University School of Medicine, Morgantown, West Virginia

[3]Department of Neurosurgery, Rush University Medical Center, Chicago, Illinois, USA

[4]Departments of Behavioral Neuroscience, Oregon Health & Science University, Portland, Oregon

Abstract

Objective—Endoscopic surgical treatment of pituitary tumors, lateral invading tumors, or aneurysms requires surgeons to operate adjacent to the cavernous sinus. During these endoscopic endonasal procedures, the carotid artery is vulnerable to surgical injury at its genu. The objective of this simulation model was to evaluate trainees regarding management of a potentially life-threatening vascular injury.

Methods—Cadaveric heads were prepared in accordance with the Oregon Health & Science University body donation program. An endoscopic endonasal approach was used, and a perfusion pump with a catheter was placed in the ipsilateral common carotid artery at its origin in the neck. Learners used a muscle graft to establish vascular control and were evaluated over 3 training sessions. Simulation assessment, blood loss during sessions, and performance metric data were collected for learners.

Results—Vascular control was obtained at a mean arterial pressure of 65 mm Hg using a muscle graft correctly positioned at the arteriotomy site. Learners improved over the course of training, with senior residents ($n = 4$) performing better across all simulation categories (situation awareness, decision making, communications and teamwork, and leadership); the largest mean difference was in communication and teamwork. Additionally, learner performance concerning blood loss improved between sessions ($t = 3.667$, $P < 0.01$).

Conclusions—In this pilot endoscopic endonasal simulation study, we successfully demonstrate a vascular complication perfusion model. Learners were able to gain direct applicable expertise in endoscopic endonasal techniques, instrumentation use, and teamwork required to optimize the technique. Learners gained skills of vascular complication management that transcend this model.

To whom correspondence should be addressed: Jeremy N. Ciporen, M.D. [ciporen@ohsu.edu].

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Keywords

Cadaver; Carotid vascular complication; Cost-effectiveness; Endoscopic endonasal approach; Reproducibility; Simulated training

Introduction

Endoscopic training is emerging as an effective opportunity for improving surgical skill sets for residents, fellows, and faculty, in a cost-effective manner.[1] Simulation training can increase proficiency and allow learners to reach milestones set forth by accrediting agencies.[2] Furthermore, simulation allows for appreciation of relevant neuropathology and anatomy that may be pertinent intraoperatively.[3] In particular, endoscopic skull base approaches, which have a steep learning curve, can be practiced in a controlled and replicable environment.[4]

Multiple publications have addressed the topic and incidence of cavernous carotid injury during pituitary and skull base surgery.[5-18] Ciric et al[19] reported that 52% of surgeons who performed >500 endonasal pituitary surgeries reported an internal carotid artery (ICA) injury. Other studies have reported a 4%–9% incidence of ICA injury in patients who underwent expanded endonasal skull base surgery.[20] Valentine and Wormald[21] have established an endoscopic sheep model of ICA in which a muscle graft is used to control vascular injury. Although the model combines pressure and hemostatic dynamics to replicate a clinically relevant scenario of ICA injury, the model is limited due to the differences in sheep versus human anatomy.[21]

A preponderance of current simulation models focus on tumor resection.[22,23] The use of 3-dimensional models has improved training feasibility; however, these models lack the intricacies of complex human anatomy, especially in relation to vascular injury.[24] Anesthesia models have been developed to control hypotension during simulated training experiences,[25] but until recently, simulated vascular complication models for surgical training have not been readily available. The live sheep model is the most comprehensive model addressing vascular injury repair, but it is difficult to replicate at most training programs and is limited in that human anatomy cannot be fully appreciated.[21]

Cadaveric heads offer advantage in simulated training experiences.[26] Cadaveric heads are readily stored in containers with formalin allowing cost-effectiveness, replicability, and continued use over extended time periods. A cadaveric head model highlights the importance of proper exposure to the sphenoid sinus, sellar, parasellar, and clival structures via adequate removal of the face of the sphenoid. The anatomy directly correlates with what a surgeon will face during a surgical procedure, and instruments and endoscopes are the same as those used in the operating room.

We present the findings from a pilot simulation study of a cadaveric head perfusion model, which can be used innumerable times to train residents, fellows, and faculty. Additionally, the model can be used in the context of continuing medical education courses on appropriate endoscopic management of vascular complications.

Methods

Preparation

Five adult cadaveric heads were used for this pilot study. The heads were acquired as part of the Oregon Health & Science University Body Donation Program. Heads were frozen and thawed once before use. A 1:100 solution of anticoagulant citrate dextrose (John B. Pierce Laboratory, New Haven, Connecticut, USA) mixed with warm water was prepared. The great vessels in the neck (jugular veins, carotid arteries, and vertebral arteries) were washed out for 15 minutes, and the head was allowed to sit overnight in a cold room at 5°C. The heads were embalmed and stored in formalin fixative solution (10%).

Dissection

Heads were placed in a slightly flexed position with good visibility of the nasal passages. Zero- and 30-degree endoscopes of 4-mm diameter and 18-cm length were used (Karl Storz, Tuttlingen, Germany). The endoscope was connected to a fiberoptic camera and light source. Exposure of the sphenoid sinus was performed, as previously described.[27] Briefly, the middle turbinates were lateralized and a bilateral sphenoidotomy was performed. The incision was made at the articulation of the rostrum and vomer. A cottle elevator was used to clear the mucoperiosteum, and the rostral bone was removed bilaterally with a Kerrison rongeur and drilled flush to the floor of the sphenoid sinus and laterally just medial to the plane of the medial orbital walls bilaterally. Visualization of the sella, tuberculum, clivus, opticocarotid recesses, and cavernous carotid arteries was achieved. The bone overlying the sella and cavernous carotid artery was removed using a Kerrison rongeur. An 11-blade knife was used to make a 3-mm laceration in the right internal carotid artery at the level of the genu.

Perfusion and Training

To measure model feasibility, a small group of neurosurgical residents ($n = 3$) was used for testing and cavernous carotid perfusion model simulation assessment. Subsequently, testing and assessment were undertaken in a second learner group ($n = 7$) of additional neurosurgical residents using a similar yet more rigorous model setup.

In all scenarios, a cannula was inserted into the common carotid artery and secured with a clamp. Once the cannula was in place, it was connected to a perfusion pump that delivers the flow of simulated blood. The artificial blood (composed of red food coloring, water, and store-bought “vampire blood”; Forum Novelties, Inc., Melville, New York, USA) was mixed with these contents to achieve color and consistency that made it the most realistic. The artificial blood was recycled from one simulation to the next to maintain cost-effectiveness and consistency. An embalming perfusion pump (embalming machine JW-50 Noayr, Emmetsburg, Iowa, USA) was used to deliver the simulated blood for the first group. In the second learner group ($n = 7$), a rapid infusion Belmont pump was used (Belmont Fluid Management System 2000, Billerica, Massachusetts, USA). This pump provides the rate of infusion in mL/minute.

Additionally, an arterial line was set up with this infusion pump via the cannulated carotid artery. Mean arterial pressure (MAP) was transduced to accurately control MAP experienced by the learner as the cavernous carotid bled, to ensure that realistic MAPs, those experienced in the operating room, were presented. Learners experience a range of MAPs (65–110 mm Hg). In the first learner group ($n = 3$), an embalming pump was used and a conversion from psi to mm Hg was made to approximate the pressure experienced by the learner as the cavernous carotid artery bled.

An endoscopic approach was standardized for each of the 10 learners who completed the simulation during 2 simulation sessions. Each learner was faced with the same bony exposure and location and size of the cavernous carotid injury. A supervising instructor facilitated the training experience and provided relevant guidance for important anatomic landmarks when appropriate. A 4-handed approach was used similarly to that outlined by Wormald et al.[28] The instructor held and directed the endoscope as an intrinsic control between trials. This allowed learners to familiarize themselves with instrumentation. The learner was instructed as to the order and method to obtain vascular control of the cavernous carotid injury. The learner was instructed that once bleeding occurred to virtually give instructions to decrease the blood pressure, ask for proximal vascular control, use the suction to guide the bleeding away from the endoscope, use a pituitary instrument to initially place a half cottonoid patty over the bleeding site, and apply pressure. The cottonoid was then exchanged with the free muscle graft harvested from the temporalis muscle with a new cottonoid placed over muscle graft to apply enough pressure to control the bleeding. Learners faced a task of obtaining vascular control with normal, then elevated, and then normalized perfusion pump pressure, in the first assessment ($n = 3$) and normalized MAPs in the second assessment ($n = 7$) as per the A-line pressure.

Three sessions were employed for each learner. In the first learner group, embalming perfusion pump unit measurements were psi; 1 psi converts to 51.7 mm Hg and a conversion of psi to mm Hg was made. Learners were presented with a range of mm Hg; 155.14 mm Hg, then 206.8 mm Hg, followed by 103.4 mm Hg, at which time learners were expected to have obtained vascular control. In the second learner group, there were 3 sessions; the first 2 sessions were 7 minutes in duration with a final 4-minute session. Learners were presented with a MAP range of 65–110 mm Hg, and it was determined that a pressure of 65 mm Hg was ideal for obtaining vascular control. Blood loss by learners was measured for each session. An independent evaluator blinded to training level scored learner performance during the simulation experience on a scale of 1–4 (1 = poor, 2 = marginal, 3 = acceptable, and 4 = good). If the evaluator deemed a learner as performing between 2 levels, a midway score was assigned (i.e., 2.5 if the evaluator viewed the learner's performance between marginal and acceptable). Scoring categories were situation awareness, decision making, communications and teamwork, and leadership.

Statistical Analysis

Statistical analysis was performed using GraphPad Prism software, version 6 (GraphPad Software, San Diego, California, USA). Data are shown as mean ± standard error of mean, unless otherwise specified. Paired Student's *t*-tests were used to compare differences between data collected at different time points. Statistical significance was considered at $P < 0.05$.

Results

Simulation Model

The perfusion model produced clinically relevant pressurized bleeding as appreciated by pooling of simulated blood (Figure 1A). This is an important component due to the high-pressure and high-flow dynamics of carotid artery injuries.[28] Adequate working space was obtained with this approach for placement of the endoscope, as well as surgical instrumentation through the bilateral nasal passages (Figure 1B). Learners ($n = 10$; 1 learner per 1 instructor in each simulation time) were able to perform the stepwise approach to obtain vascular control and ultimately place the muscle graft over the carotid injury and apply counterpressure for vascular control (Figure 1C and D).

The model is highly replicable and useful for continued training practice. The cadaveric heads have been used >50 times for over 10 months with maintained tissue quality in the process of model testing and simulation training. Setup (Figure 2) is simple and cost-effective (see costs later). This cadaveric simulation controlled for the endoscopic instruments used in the operating room (e.g., Skull Base Tray, Karl Storz), the bone exposure, the site of carotid injury, as well as the techniques by which the carotid artery injury is controlled (Video 1). Repetitive training allows participants to familiarize themselves with endoscopic instrumentation and the anatomy.

Learner Assessment—All learners ($n = 10$) “would participate in simulated training in the future if given the choice” and strongly agreed that they “would like to see simulation integrated into the curriculum” (Tables 1 and 2). The pilot learner group viewed the course as valuable and very valuable (see Table 1). In the second learner group, all learners ($n = 7$) strongly agreed that the simulation “surgical exposure was realistically represented” and strongly agreed ($n = 4$) or agreed ($n = 3$) that they had “learned an algorithm to manage vascular injury” (see Table 2).

Some example comments from learners were: “great job, very important to training,” “this was a fantastic learning experience,” and “I was extremely impressed, and I feel I learned a great deal in a relatively short amount of time.” One learner stated that the experience was “humbling” due to the intricacies associated with endoscopic skull base approaches. The participants have requested further simulated training experiences in the future as part of their ongoing training.

Learner Performance—In the second learner group ($n = 7$), performance was evaluated on a series of metrics. Average performance scores for each metric were tabulated by postgraduate training year (PGY) of learners for questions within categories of situation awareness, decision making, communications and teamwork, and leadership (Table 3). On the basis of these values, the average score for each category between junior (≤PGY 4; $n = 3$) and senior residents (≥PGY 5; $n = 4$) is reported (Table 4). Mean differences between senior versus junior residents for situation awareness, decision making, communication and teamwork, and leadership were 0.625 ($t = 2.892$, $P < 0.01$), 0.441 ($t = 2.816$, $P < 0.05$), 1.056 ($t = 2.893$, $P < 0.001$), and 0.57 ($t = 2.893$, $P < 0.01$), respectively. Senior residents performed better across all categories of the simulation with the largest mean difference in communication and teamwork. The simulation highlights areas requiring further instruction and training for junior residents.

In the second learner group ($n = 6$; one assessment was not completed from the 7 learners), measurements of blood loss over 3 sessions were compared (Table 5). Mean blood loss for session 1 versus 2 was 1129 mL versus 865.8 mL ($t = 3.903$, $P < 0.01$). Learners significantly improved blood loss between sessions 1 and 2 and by the third session were able to control the vascular injury within the allotted 4-minute time frame with an average blood loss of 333 ± 20.8 mL.

Costs

The cost of a fresh cadaveric head is \$500–\$700, whereas a full cadaver costs ~\$2500 per body. Most programs with a body donation program have an embalming machine, and this can be used to provide the pressurized simulated blood through the carotid and vertebral arteries. Alternatively, we have used an Arthrex pump (Arthrex, Munich, Germany) and Belmont rapid infusion pump (Belmont Instrument Corporation, Massachusetts, USA) to deliver pressurized flow throughout the cannulated vessels. This reflects the reproducibility of the model. Institutional overhead costs have not been included.

Discussion

Endoscopic endonasal transsphenoidal and extended trans-sphenoidal approaches have been steadily increasing as the standard of care for sella, suprasellar, parasellar, and clival pathology. There are a number of challenges a surgeon faces when a catastrophic vascular injury occurs. First is the emotional stress of the occurrence and knowledge that what may have been an elective procedure on benign pathology, such as a pituitary macroadenoma, has turned into a life and death situation. Second, visualization is obscured, making it difficult to see the adjacent critical structures and site of bleeding. Impaired visualization can lead to technical errors that lead to injury of critical adjacent structures and can worsen and extend the site of vascular injury. Inadvertently enlarging or using the wrong strategy to obtain vascular control can lead to higher morbidity and mortality. While no 2 cavernous carotid injuries are the same, a treatment strategy/algorithm based on lessons learned from endoscopic training has been shown to improve outcome.[29]

Surgical simulation has gained significant momentum in the arena of resident and fellow training. In the setting of resident duty hour restrictions and limited hands-on experience in the most technically challenging of cases, graduating residents may lack experience for managing a vascular complication and might not obtain this experience until they are in practice. In practice, a vascular injury is rare but occurs and is likely underreported. Padye et al[29] collected follow-up data from 110 participants who had taken their sheep-based vascular injury workshop. The participants were surveyed by an e-mail questionnaire regarding the instance of major arterial bleeding and the management undertaken. Nine cases were reported in total: 1 basilar artery and 8 ICA injuries. Each case was managed endoscopically with the muscle patch application they learned in training. There were no deaths, 1 case of pseudoaneurysm with successful endovascular treatment, 2 cases of impaired carotid flow, and 1 carotid dissection managed conservatively. These articles and those in Table 6 further demonstrate the importance of a reproducible cost-effective endoscopic endonasal cavernous carotid injury simulation.[5-18]

The Accreditation Council for Graduate Medical Education has requirements for general surgery and obstetrics and gynecology surgical simulation as part of educational milestones. While neurologic surgery and otolaryngology do not have these requirements at this time, the value of surgical simulation is evident.[29-31] As duty hours and patient safety concerns limit resident autonomy, cadaveric anatomic and simulation-based learning provide the opportunity for learners to gain the technical endoscopic skill set required. The complexity of these approaches warrants continued training opportunities. By using clinically relevant models that represent realistic pathology and potentially life-threatening occurrences such as vascular injury, learners can develop an appreciation of relevant anatomy and develop the technical skills for utilization of instrumentation before entering the operative arena. Learners also gain the experience of using these instruments in a cooperative manner, in a stressful scenario and visually compromised field secondary to simulated pressurized bleeding. Bly et al[32] have shown that cadaveric simulation models offer an advantage in learning new endoscopic approaches.

In this pilot simulation study of a cadaveric head vascular perfusion model, we show the model was replicable and cost-effective. It was effective when used to train learners how to manage vascular complications endoscopically. The model is more cost-effective than whole body cadavers and has the potential to be used with SimMan technology to replicate clinically relevant changes in vital signs.[33] The simulation model we describe is highly realistic and provides an excellent opportunity for teaching complex surgical skills. As with any pilot study, there are some study limitations. Study limitations include small learner sample size, single-institution training site, lack of biofeedback data, and lack of multidisciplinary training. In the future it will be valuable to consider a larger sample size, inclusion of operative colleagues (e.g., anesthesiology and otolaryngology), obtaining biofeedback data, and perhaps multi-institutional collaboration to provide further learner performance improvement data.

Using the simulation model, we describe how learners were able to familiarize themselves with instrumentation and appropriate intraoperative visualization. Successful management of a carotid injury with a muscle graft was demonstrated. Applicable to the study is an understanding of the anatomic segments of the cavernous carotid. The Cincinnati system describes segments of the ICA as a progression from C1 to C7. This advancement goes beyond the traditional rostral to caudal numbering system originally proposed by Fischer.[34] Pertinent to endonasal endoscopic approaches are the C3 (lacerum), C4 (cavernous), and C5 (clinoid) segments.[35] Variability exists in the tortuosity of the anterior and posterior genus of the cavernous carotid artery. Lin et al[36] recently developed a grading scale for the cavernous carotid artery that can be used to assess intraoperative risk of damage at the genu. Advanced imaging in conjunction with simulated cadaveric training may offer the best approach to establish reliable and realistic training experiences for residents, fellows, and faculty.

Floreani et al[37] have shown that cadaveric models are excellent for teaching relevant vascular anatomic sites that have increased potential for intraoperative complications. Furthermore, simulated training offers the ability to set benchmark standards for resident performance during training. Residents early in their training can be assessed prospectively over time. Direct feedback can be provided to ensure that they are reaching surgical performance goals in a timely manner.

Conclusion

Simulated training offers a unique opportunity to improve surgical skill sets in a safe and controlled manner. The benefits of the cerebral perfusion and endoscopic carotid artery injury model described transcend this specific simulation. This simulation teaches and more importantly reinforces a treatment algorithm, as well as the technical skills necessary to safely manage and perform effectively in a highly stressful scenario. Maintaining the MAP around 65 mm Hg was ideal for obtaining vascular control. This simulation model is effective in providing relevant instruction about anatomic vasculature, proper use of instrumentation, and evaluation of intraoperative communication. Learners reported the training valuable and would like to have more opportunities in the future. Most importantly, the model is replicable, cost-effective, and can be used for repetitive simulation training experiences. Widespread value and portability of this model as a simulation training technique to ensure educational value warrants further exploration.

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Abbreviations and Acronyms

ICA	Internal carotid artery
MAP	Mean arterial pressure

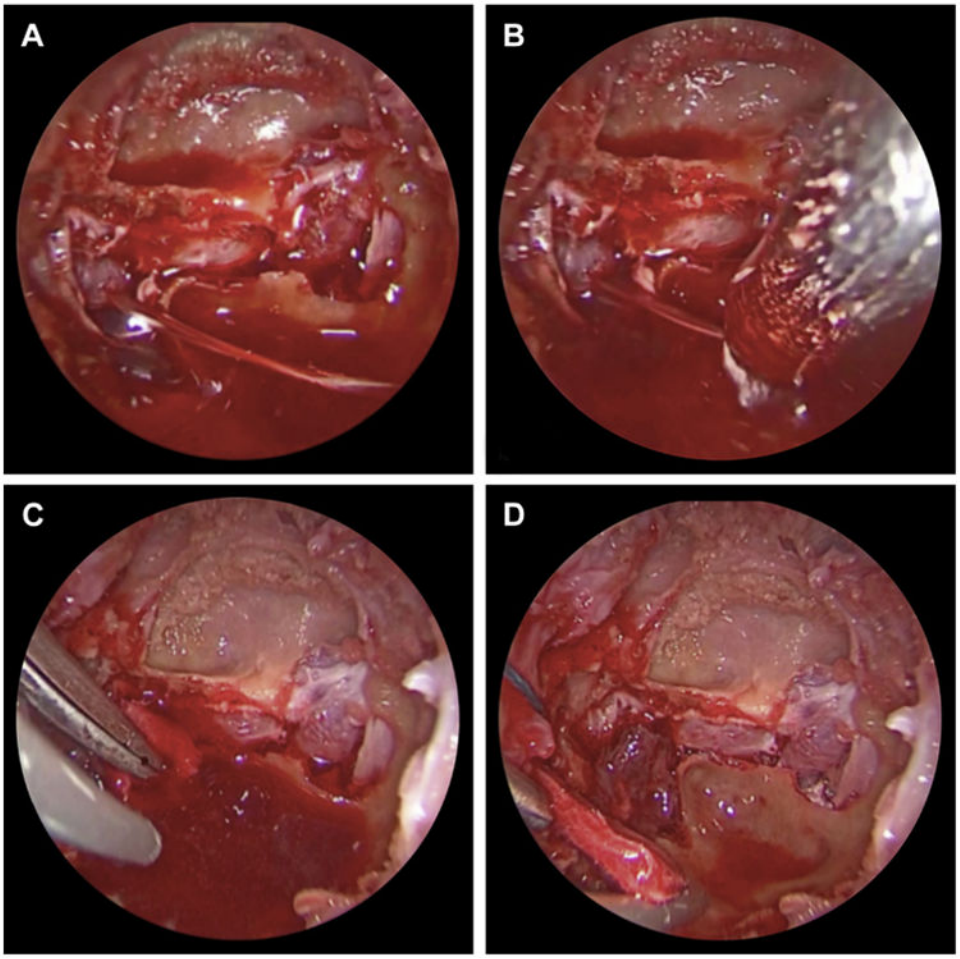

Figure 1.

(**A**) Right cavernous carotid injury simulation, (**B**) suction placed to divert the flow of blood away from the endoscope, (**C**) placement of a half by half cottonoid patty and manual pressure to control the bleeding as the muscle patch is prepared, and (**D**) muscle patch placement over the site of injury for control of bleeding (occlusion of the internal carotid artery) with the pressure brought to 2 psi (=103.4 mm Hg).

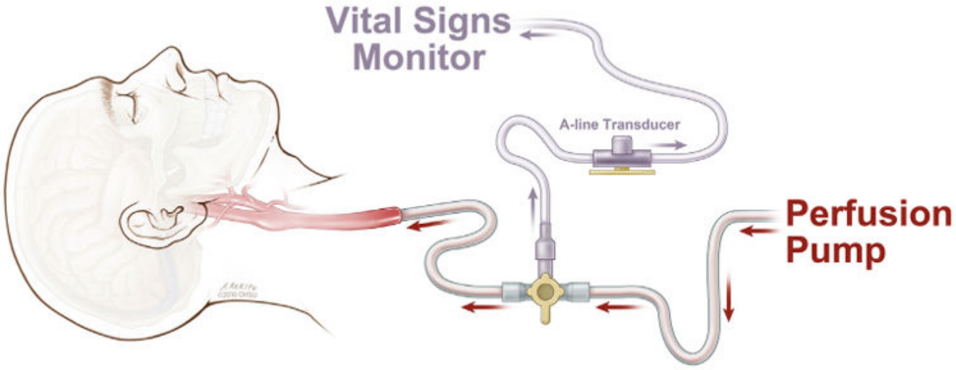

Figure 2.
An artist's illustration of the simulated perfusion model setup.

Table 1

Learner Feedback on Neurosurgical Model Simulation (*n* = 3)

	Question:				**Valuable**	**Very Valuable**
1	Was this course valuable in your training?				1	2
		Strongly Disagree (n)	**Disagree (n)**	**Neutral (n)**	**Agree (n)**	**Strongly Agree (n)**
2	Simulation training improved my surgical skills				1	2
3	Skills learned in the simulated environment transfer to the operating room				1	2
4	Simulated experiences should be incorporated into neurosurgical training prior to entering the operating room					3
5	Simulation training is a good complement for operating experience					3
6	Simulation improved/reinforced my understanding of the relevant anatomy				1	2
7	Simulation improved my understanding and use of the instrumentation?				1	2
8	Would you like to see simulation integrated into the curriculum?					3
			No			Yes
9	Will you participate in simulated training in the future if given the choice?					3

Table 2

Learner Feedback on Neurosurgical Model Simulation (*n* = 7)

	Question:	**Strongly Disagree (n)**	**Disagree (n)**	**Neutral (n)**	**Agree (n)**	**Strongly Agree (n)**
1	Overall, the simulator is a useful tool in training neurosurgical residents				1	6
2	Surgical exposure realistically represented					7
3	The carotid artery component realistically approximated bleeding from the carotid artery				2	5
4	The vessel repair technique was realistic		1		2	4
5	The vital signs component realistically approximated vital signs in the OR				2	5
6	I learned an algorithm to manage vascular injury				3	4
7	The preparation of the field was ideal for managing this surgical complication				2	5
8	Use of operative instruments was comparable to OR				2	5
9	I was able to focus on the task at hand				1	6
10	I felt a sense of urgency when the simulator began to bleed				2	5
11	I felt a sense of urgency when the simulated patient had hemodynamic instability		1		3	3
12	Ultimately I was satisfied with the level of immersion that the simulator provided				2	5
13	Would you like to see simulation integrated into the curriculum?				2	5
			No			**Yes**
14	Would you participate in simulated training in the future if given the choice?					7

Table 3

Average Performance Scores Organized by Postgraduate Year of Training (*n* = 7)

Category	Element	Postgraduate Year	Average Score
Situation awareness	Gathering information	1	2.5
		4	3
		5	4
		6	3.5
		7	3
	Understanding information	1	2.75
		4	4
		5	4
		6	4
		7	4
	Projecting and anticipating future state	1	3.25
		4	3
		5	3.5
		6	3.5
		7	3
Decision making	Considering options	1	3
		4	3
		5	3.5
		6	3
		7	3
	Selecting and communicating options	1	2.5
		4	3.5
		5	3.5
		6	4
		7	3.5
	Implementing and reviewing decisions	1	3
		4	3
		5	3.5
		6	3
		7	3.5
Communications and teamwork	Exchanging information	1	2.25
		4	3
		5	4
		6	4
		7	3
	Establishing a shared understanding	1	2.75
		4	3.5

Category	Element	Postgraduate Year	Average Score
		5	4
		6	4
		7	4
	Coordinating team activities	1	2.25
		4	2.5
		5	4
		6	3
		7	3
Leadership	Setting and maintaining standards	1	2.75
		4	3
		5	4
		6	3.5
		7	4
	Supporting others	1	3
		4	3
		5	4
		6	3.5
		7	3.5
	Coping with pressure	1	3.75
		4	4
		5	4
		6	4
		7	4

Scoring scale:
1 Poor Performance endangered or potentially endangered patient safety, serious remediation is required.
2 Marginal Performance indicated cause for concern, considerable improvement is needed.
3 Acceptable Performance was of satisfactory standard but could be improved.
4 Good Performance was of a consistently high standard, enhancing patient safety; it could be used as a positive example for others.

N/A Not applicable.

Table 4

Junior Versus Senior Resident Performance Comparison ($n = 7$)

Category	Junior Resident[*] ($n = 3$)	Senior Resident ($n = 4$)	Student's t-test, P Value
Situation awareness	3 ± 0.166	3.625 ± 0.139	$t = 2.892$, $P < 0.01$
Decision making	2.944 ± 0.1	3.375 ± 0.109	$t = 2.816$, $P < 0.05$
Communication and teamwork	2.611 ± 0.162	3.667 ± 0.142	$t = 4.889$, $P < 0.001$
Leadership	3.222 ± 0.169	3.792 ±0.115	$t = 2.893$, $P < 0.01$

[*] Junior (≤postgraduate year [PGY] 4; $n = 3$) versus senior (≥PGY 5; $n = 4$).

Table 5

Learner Blood Loss During Sessions ($n = 6$)

Learner	Session 1; 7 minutes (mL)	Session 2; 7 minutes (mL)	Session 3; 4 minutes (mL)
1	1150	900	286
2	1282	796	290
3	911	960	356
4	1267	845	423
5	1071	828	317
6	1094	134 (pump malfunction)[*]	326
Mean ± SEM	1129.17 ± 56.28	865.8 ± 28.96	333 ± 20.8
Student's *t*-test Trial 1 versus 2	$t = 3.903$, df = 9	$P < 0.01$	

SEM, standard error of mean.

[*] Not included in analysis ($n = 5$); df = degrees of freedom.

Table 6
Summary of Carotid Injuries Following Endoscopic Endonasal Approaches

Report	Surgery Type	Patient Age	Complication	Outcome
Hudgins et al., 1992[9]	Endoscopic paranasal sinus surgery	Varied	1 patient with subarachnoid hemorrhage and 1 patient with aneurysm of the anterior cerebral artery	Emergent balloon embolization with massive hemorrhage
Cappabianca et al., 2001[5]	Endoscopic transsphenoidal surgery	Varied	Pseudoaneurysm of intracavernous carotid	Successful endovascular repair
Liang et al., 2004[13]	Endonasal endoscopic surgery	Varied	Internal carotid artery rupture from carotid cavernous fistula	Muscle flap plug with maintained vascular control
Koitschev et al., 2006[12]	Endonasal sinus surgery for sinusitis	Varied	Laceration of the cavernous carotid artery	Balloon or coil occlusion of lacerated vessel
Pepper et al., 2007[15]	Endoscopic sinus surgery	Varied	Cavernous carotid hemorrhage	Balloon embolization with successful vascular control
Karaman et al., 2009[11]	Endoscopic sinus surgery	40-year-old female	Carotid-cavernous fistula	Endovascular transarterial embolization with excellent recovery
Zhou et al., 2009[17]	$N = 7$ Microsurgical transsphenoidal $N = 3$ Endoscopic transsphenoidal	Varied	8 subarachnoid hemorrhages, 1 cavernous carotid thrombosis, 1 cavernous sinus hemorrhage	Of 400 treated patients, the 10 with vascular injuries died from complications
Pawar et al., 2010[14]	Endoscopic sphenoid mucocele marsupialization	87-year-old male	Cavernous carotid pseudoaneurysm formation	Rupture and death 4 months postoperatively
Zuo et al., 2012[18]	Transnasal endoscopic surgery for tumor resection	Varied	3 cavernous carotid injuries, 1 lacerum segment injury, and 1 clinoid segment injury	4 cases treated successfully with endovascular techniques. 1 mortality due to massive hemorrhage
Felippu et al., 2013[8]	Transnasal approach for lesions of the orbital apex	Varied	100 total cases with 1 case of cavernous carotid artery rupture	Mortality
Kalinin et al., 2013[10]	Endoscopic transsphenoidal approach for pituitary adenoma resection	4 patients, varied ages	1 case cavernous carotid occlusion and 3 cases pseudoaneurysm formation in cavernous carotid artery	1 mortality and 3 endovascular treatments with successful recovery
Dedmon et al., 2014[7]	Endoscopic sinus surgery	44-year-old male	Epistaxis with pseudoaneurysm of the cavernous carotid artery	Repaired with endovascular coiling: coil extrusion through wall of pseudoaneurysm
Rangel-Castilla et al., 2014[16]	$N = 3$ endoscopic $N = 3$ endoscopic transfacial $N = 1$ myringotomy $N = 1$ endoscopic meningioma resection $N = 1$ PCA clipping $N = 1$ ICA coiling	Varied	Iatrogenic cavernous carotid injury	Extracranial-intracranial bypass with modified Rankin scale score of 0 or 1 at 19-month follow-up
Cobb et al., 2015[6]	Endoscopic endonasal approach for osteoblastoma resection	13-year-old female	Iatrogenic cavernous carotid injury	Balloon-assisted microsurgical repair of lacerated vessel

PCA, posterior cerebral artery; ICA, internal carotid artery.