

# “Live Cadaver” Model for Internal Carotid Artery Injury Simulation in Endoscopic Endonasal Skull Base Surgery

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**Background:** Intraoperative injury of the internal carotid artery (ICA) is the most dreaded complication in endoscopic endonasal surgery (EES) of skull base. Training for ICA injury is practically impossible in live operative settings. **Objective:** To evaluate a pulsatile perfusion-based live cadaveric model for ICA injury simulation in a laboratory setting. The major emphasis of the study was to evaluate various means of controlling acute bleeding and evaluating the practical utility of this model for training purposes. **Methods:** Five embalmed, uninjected cadaveric heads were prepared for study by connecting to a pulsatile perfusion pump system filled with artificial blood solution. EES approaches were used to evaluate different types of ICA injuries similar to operative scenarios. Various methods of managing ICA injuries such as packing, clipping, and trapping, were evaluated. The educational advantages of the live cadaver model were assessed using questionnaires given to participants in a hands-on dissection course. **Results:** The trainee was faced with several scenarios similar to those encountered during an actual intraoperative ICA injury. Packing, clipping, and trapping of the ICA injury were successfully achieved in all segments of the ICA. Clip-based reconstruction techniques were successfully developed. All trainees reported gaining new knowledge, learning new techniques. The responses to the questionnaire confirmed the significant educational value of this model. **Conclusion:** The live cadaver model presented here provides real-life experience with major vessel injury during EES in a laboratory setting. This model could significantly improve current training for the management of intraoperative vascular injuries during EES.

**Key words:** Cadaver, Endoscopic endonasal surgery, Internal carotid artery, Skull base, Vascular injury, Surgical simulation

Endoscopic developed many skull endonasal surgery (EES) has into a preferred approach for base pathologies. EES provides a unique set of technical challenges that must be overcome while progressing along the learning curve.<sup>1-3</sup> These challenges include lack of stereoscopic vision with reduced depth perception, operating via minimal access corridors, and the use of long shaft instruments.<sup>1</sup>

Intraoperative injury of the internal carotid artery (ICA) is the most dreaded complication in EES because it can lead to major morbidity and mortality. The reported rate of ICA injury in various EES series ranges from 0.3% to 9%.<sup>4,5</sup> Training for major vessel injury in live operative settings is not technically feasible. Several animal and virtual reality-based models have been used to simulate real-life surgical catastrophes,<sup>6-9</sup> but their utility remains limited due to anatomical inaccuracy and unrealistic quality.<sup>9,10</sup> Although trainees can develop anatomical knowledge and surgical skills with cadaveric models, it is currently difficult to simulate vascular injury in the laboratory setting.<sup>11-13</sup> Aboud et al<sup>14,15</sup> reported a perfusion-based live cadaver model for microneurosurgical

training and neurovascular crisis management. In this study, a similar model was evaluated for EES training with special emphasis on ICA injury management. This live cadaver model combines real human anatomy with pulsatile blood flow to mimic life-like conditions. 16 ICA injuries created during EES by drilling or sharp dissection were evaluated for various available methods to control bleeding.

## METHODS

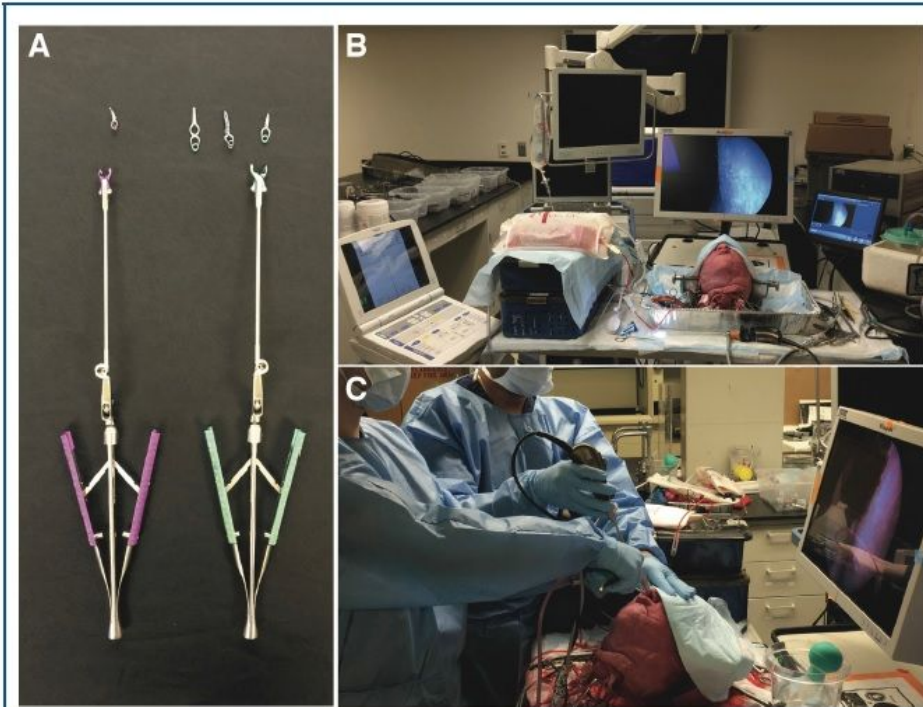
This study was performed in the Surgical Neuroanatomy Laboratory of the Center for Cranial Base Surgery at the University of Pittsburgh School of Medicine and was approved by the Committee for Oversight of Research Involving the Dead at the University of Pittsburgh.

Operating room settings were recreated in the laboratory, which is well equipped with a high-definition endoscopic system (Karl Storz, Inc., Tuttlingen, Germany), a high-speed minimal access drill, neuronavigation system (Stryker Corp., Kalamazoo, Michigan), micro Doppler (Mizuho USA, Union City, California), suction, irrigation, and a wide array of neurosurgical, endoscopic skull base, and other microdissection instruments. A bipolar coagulation system and various aneurysm clips with endo-clip applicator (Mizuho; Figure 1) were made available for this study.

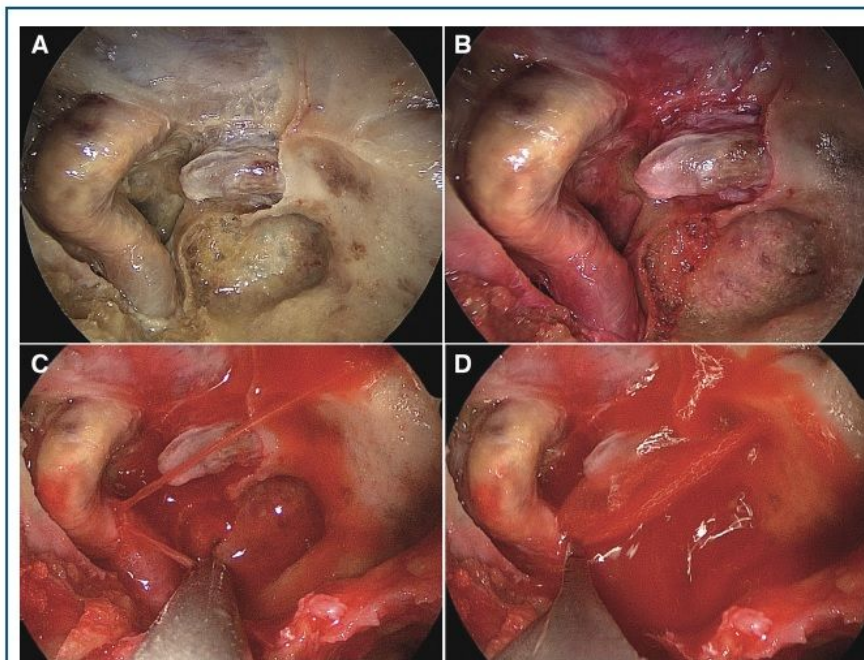
Five consecutive cadaver models were prepared as devised by Aboud et al<sup>14,15</sup> using lightly embalmed, uninjected heads. They were specially preserved with 20% ethylene glycol without use of formalin or any other fixing material. Bilateral common carotid arteries, vertebral arteries and internal jugular veins were exposed in the neck and cannulated. Plastic tubes of appropriate sizes were inserted and tied tightly to all of the vessels. The subarachnoid space in the cervical spinal canal was cannulated with 8 to 10 gauge tubes on both sides and sealed with bone wax. All of the vessels were irrigated individually with saline until the returning fluid was consistently clear. The subarachnoid space was also washed with tubes placed in the spinal canal prior to sealing. Any leak from open vessels was sealed or ligated. The cannulas were then connected to plastic bags containing artificial blood, which was prepared using saline and water-based paints with thickener to better reproduce blood viscosity. These were wrapped with pressure bags to transmit pressure from the mechanical pump (iPulse Circulatory Support System, made by Abiomed, Danvers, Massachusetts). We used an intra-aortic balloon pump to transmit pulsatile pressure to the pressure bags through which the artificial blood is transmitted. A flow rate of 2.8 to 3.4 L/min with a rate between 36 and 45 pulses/min was applied (the machine can provide a rate up to 120 pulses/min). Pressures up to 180 mm Hg can be applied through the arterial blood reservoir (Figure 1).

An endoscopic endonasal approach (EEA) to the sellar and parasellar region was performed. Once the sphenoid stage of the procedure was completed, a 2-surgeon, 4-handed technique was utilized (Figure 1), and the floor of the sella turcica was removed widely using a high-speed drill and Kerrison rongeurs. The bone covering the cavernous sinus was then drilled and removed, and the parasellar ICA was exposed bilaterally from the level of the lateral optic-carotid recess superiorly to the clivus inferiorly (Figures 2 and 3). In this situation, the venous bleeding from the cavernous sinus was managed by controlled cottonoid packing.

Senior surgeons with extensive experience in EES were the first to evaluate the model for its practical application. Based on their experience, 2 broad categories of training models were identified for injury in various segments of the ICA: sharp instrument (scissors or sharp dissectors) causing “potentially repairable” injury (Figures 2-4; Videos, Supplemental Digital Content 1-4) and blunt instruments (high-speed drill or Kerrison rongeur) causing “unrepairable” injury (Figure 5; Video, Supplemental Digital Content 5). Methods for bleeding management were evaluated in both settings. These scenarios were then practiced by residents and fellows under the guidance of senior surgeons (Figures 2- 5; Videos, Supplemental Digital Content 1-5). The educational value of the live cadaver model was assessed using a questionnaire given to the participants of a hands-on dissection course at our institution. The participants were asked to comment on the following items: (1) Have you had prior experience with intraoperative vascular injury during EEA?; (2) Did you feel that the model system was lifelike and simulated a real ICA injury?; (3) Did your confidence in placing a vascular clip increase during the session?; (4) Do you think that this model is a good training exercise for the management of intraoperative vascular injury?; (5) Did you gain new knowledge or skills in the management of bleeding? (6) Do you want to train using this model in the future?



**FIGURE 1.** Specimen perfusion setup: **A**, special tools used for clipping of vessels after injury. **B**, Both common carotid arteries, vertebral arteries, and internal jugular veins were exposed in the neck and cannulated and connected to the perfusion system to circulate saline colored with red dye. This system can be programmed to pump the dye at physiological arterial systolic blood pressures. **C**, Trainees using the cadaveric model with 2-nostril 4-hands technique.

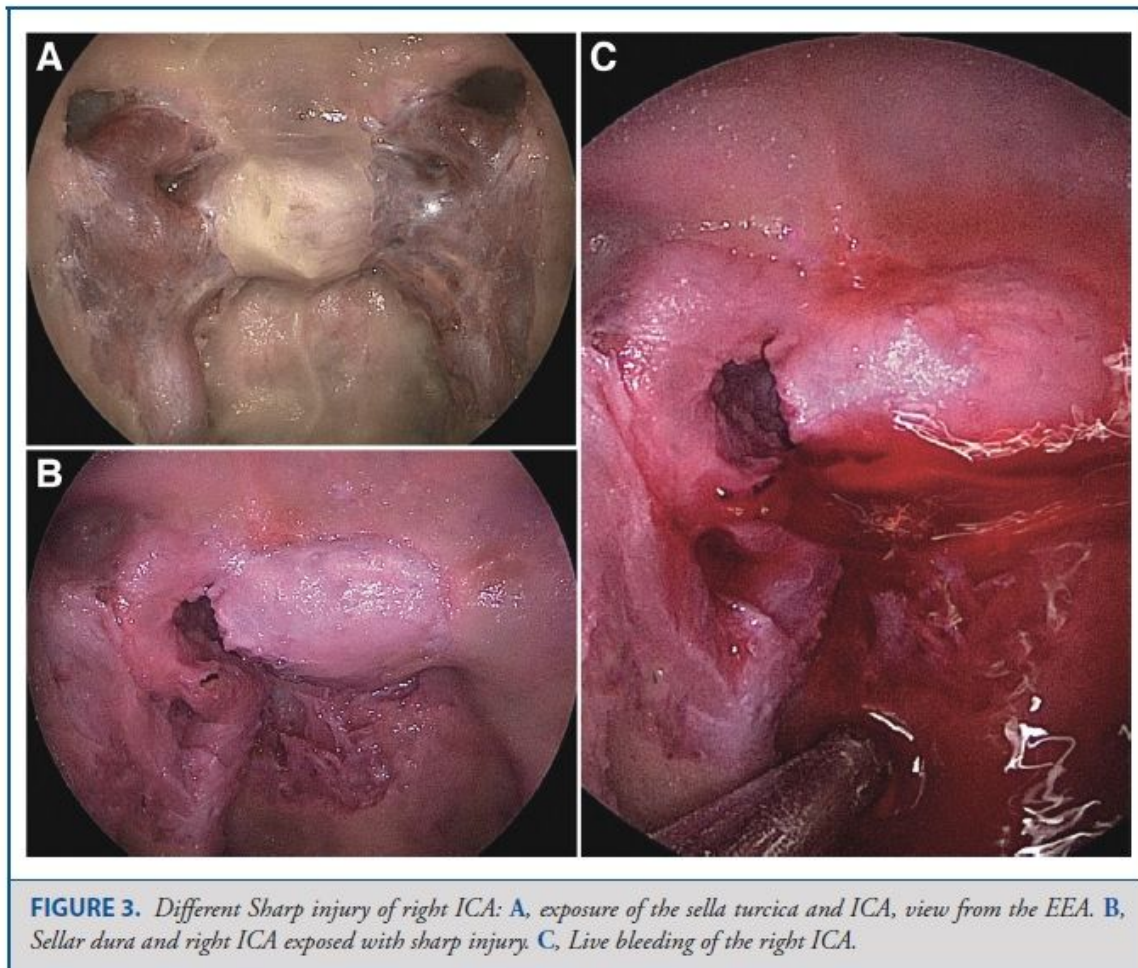


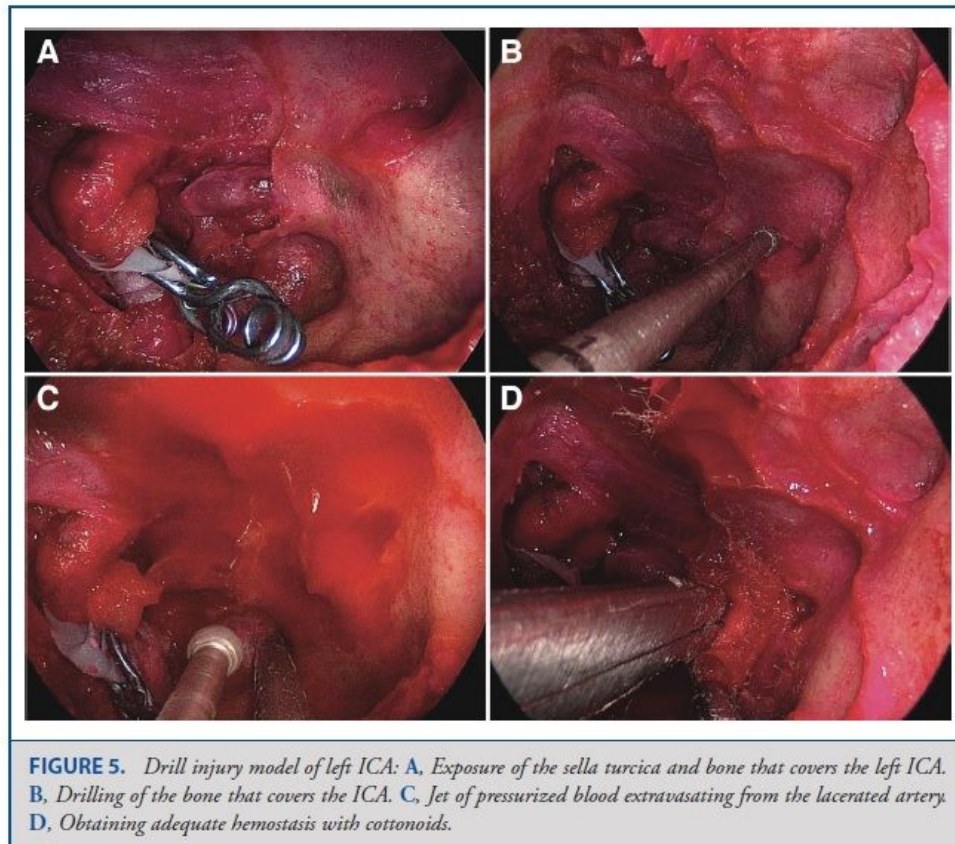
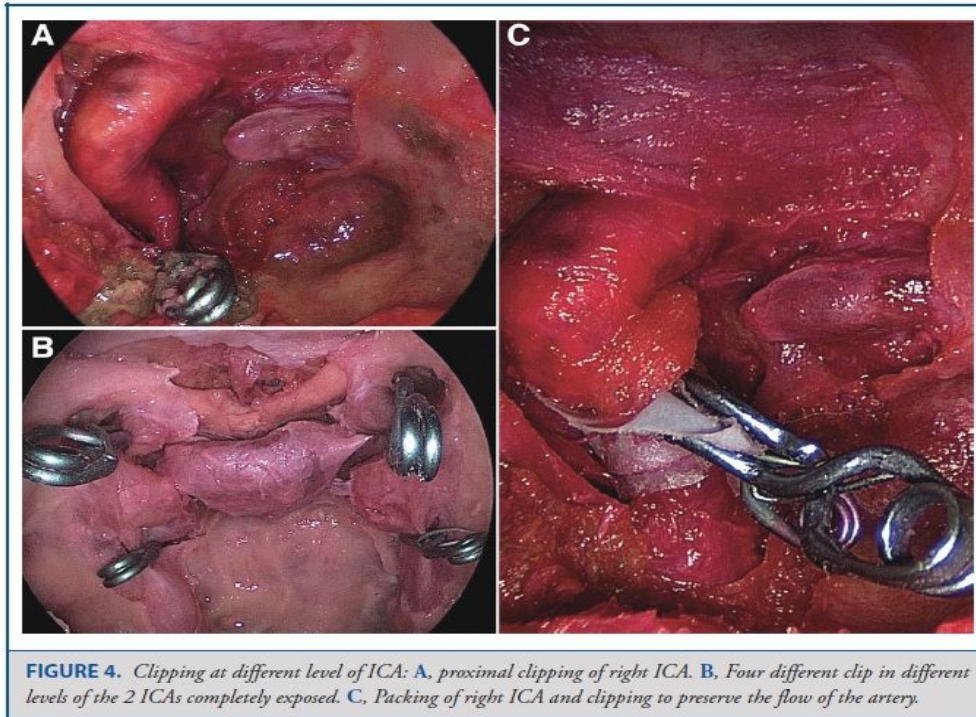
**FIGURE 2.** Sharp injury of right ICA: **A**, exposure of the sella turcica and right ICA. view from the EEA. **B**, Bleeding of the cavernous sinus without injury of ICA. **C** and **D**, Live bleeding of the right ICA.

## RESULTS

### Sharp Injury

This scenario is the result of a well-defined injury to the ICA. Here the senior surgeon was faced with conditions of profuse bleeding and reduced visibility depending on the size of injury. Using a 4-hand technique, they were able to visualize the defect and place a suitable aneurysm clip proximal to the injury site to effectively reduce extravasation of blood. After bleeding was controlled and visualization restored, the site of injury was identified and direct repair with vessel preservation was attempted. Depending on the location, size of injury, and quality of the parent vessel, simple or complex clip reconstruction techniques were attempted. In cases of small injury and no atherosclerosis, direct repair with a single clip was achieved. However, larger injuries and presence of atherosclerosis required clip-wrapping techniques for vessel preservation. Doppler ultrasound was used for assessment of distal flow after vessel repair (Videos, Supplemental Digital Content 2-4). In general, more medial and anteriorly located defects were easier to repair than posterior or laterally located defects. Initially, trainees had difficulty managing defects without sacrificing the parent vessel, but with some practice it was possible to seal the defect and preserve partial patency.





## **Exposure-Related Injury**

This is a common scenario of injury observed in intraoperative settings, where there is no good exposure of the carotid artery. Blunt instruments (high-speed drill or Kerrison rongeur) were used to cause an “unrepairable” injury, and senior surgeons were faced again with similar conditions of profuse bleeding and limited visibility. Profuse bleeding was managed by controlled cottonoid packing. It was only possible to stop bleeding with extensive packing or the sacrifice of the parent artery (trapping; Video, Supplemental Digital Content 5). Similar situations were managed by trainees with difficulty and some assistance by senior surgeons, but again vessel reconstruction was not possible in this scenario.

## **Questionnaire Results**

From a total of 32 participants, 72% did not have any prior clinical experience with intraoperative vascular injury during EES. Ninety-seven per cent of respondents stated that the model system was lifelike and simulated a real ICA injury and 94% stated that confidence in placing a vascular clip increased during the session. Ninety-seven per cent of the respondents agreed that the model is a good training exercise for the management of intraoperative vascular injury and wanted to use this model again; just 1 participant (3%) did not find the model useful enough, without leaving specific comment (Table 1).

## **DISCUSSION**

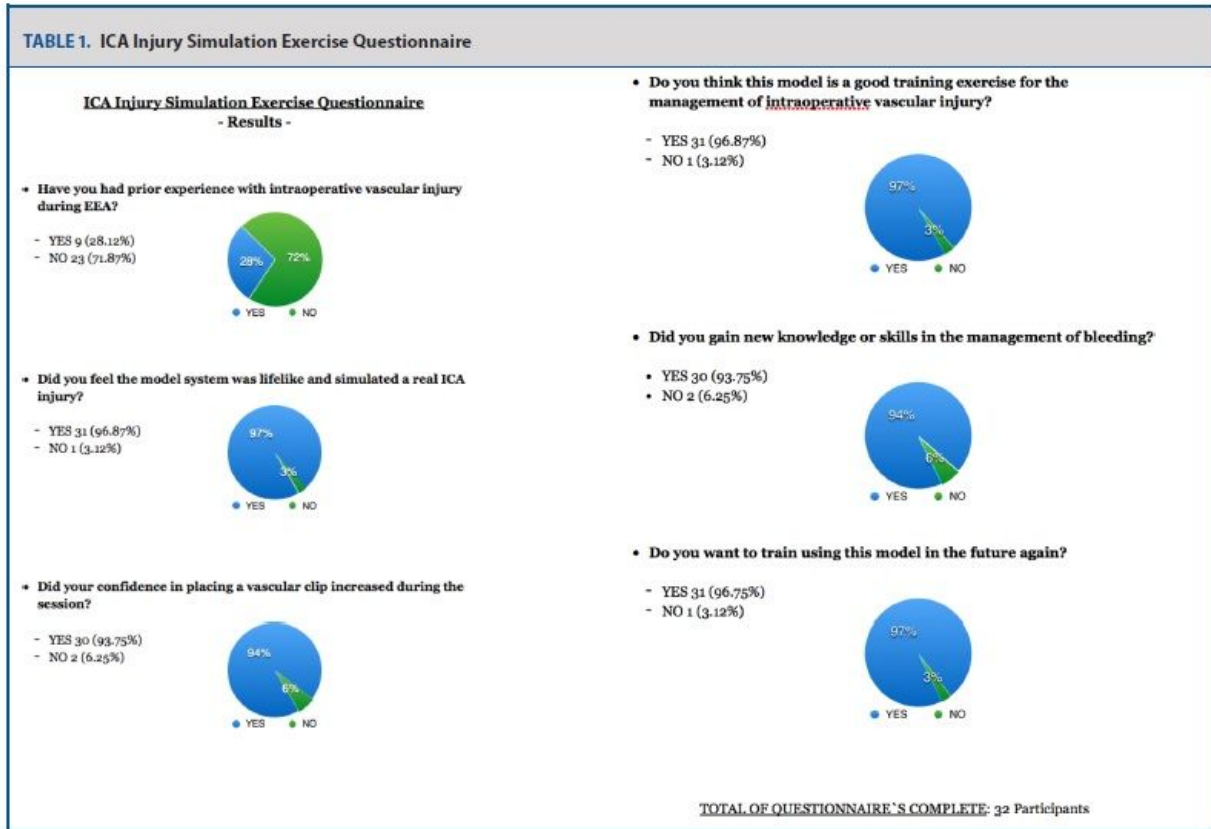
Although ICA injury is a fairly uncommon event, its occurrence in endonasal skull base surgery has been well documented.<sup>4</sup> The severity of this complication during endoscopic skull base approaches highlights the potential challenge presented to an unprepared surgeon.<sup>17,18</sup> Moreover, the lack of vascular suture repair via EES reduces treatment options and increases the risk of morbidity. Typically, the most effective way of dealing with vascular injury is packing with cottonoids to control bleeding, trying to maintain patency of the vessel, and following with endovascular stenting. Another treatment option is sacrifice of the ICA when clinically tolerated, which may carry a risk of major stroke of 20% to 30%.<sup>4</sup> Clip reconstruction techniques are commonly employed in transcranial surgery to repair vascular injuries, and may represent an alternative option for EES that is worthy of further evaluation.<sup>19</sup>

Aside from actual surgical experience, there are very few models for effectively preparing trainees for the rare, yet potentially catastrophic possibility of ICA injury.<sup>14-16</sup> This type of high-pressure injury can lead to profuse and life-threatening blood loss proves very challenging to manage, especially for the novice. Available physical simulators currently used for surgical training fail to combine the physiological and circulatory conditions of the living body with the accurate human anatomy at the same time. Live animal models provide the physiological and circulatory conditions but lack the relevant anatomy.<sup>6-9</sup> On the other hand, human specimens provide the clinically relevant anatomy but lack the circulatory conditions noted in clinical practice.<sup>11-13</sup> The live cadaver model combines the life- like conditions of the living body with the real human anatomy, and is the only training model available that provides such a combination.<sup>14-16</sup> This unique feature allows trainees to practice surgical procedures as if they are performing a real surgery in the operating room, using the same instruments and techniques

(Table 2). The responses to the questionnaire regarding ICA Injury Simulation Exercise showed that this model is an excellent training exercise for the management of intraoperative vascular injury that may help both experienced surgeons and trainees in gaining knowledge to manage this situation in the operating room.

A recent study proposed a perfusion-based model similar to the one presented here, showing that it provides a realistic training environment to prepare residents and trainees for arterial catastrophes during EES.<sup>16</sup> However, they did not explore various injury types and they limited the exercise to vessel packing. Here, we extend the potential clinical applications of this training model for the treatment of massive arterial bleeding by simulating several scenarios and a variety of advanced forms of vascular injury management and repair. We believe that the results of our study may encourage other groups to pursue further training in vascular injury management with the

model presented here, with a potentially positive impact in surgical performance. This simulation has the very real ability to provide training that can lead to the ultimate goal of all simulation: avoidance of morbidity and even mortality in live patients.



**TABLE 2. Comparison of ICA Injury Simulation Models**

Type of model	Anatomic accuracy	Physiological accuracy	Operational cost	Clinical viability	Reproducibility	Limitations
Virtual simulation	+	+	+++	+	++++	+++
Cadaveric model	+++	+	++	++	+++	+++
Animal model	++	++++	+++	++	+	+++
Livecadaver model	++++	+++	++	+++	+++	++

+: Lower level  
 ++++: Highest level

### Limitations and Future Applications

The limitations of the simulation model presented here include the use of a blood substitute without the potential for true thrombosis, possible leakage from multiple open vessels, and the availability and cost of a perfusion pump. In addition, no distal vascular control was needed in this model because the contralateral ICA was not connected to the perfusion system; this limitation can be easily overcome by applying a similar perfusion system to both ICAs and vertebral arteries to better simulate a parent Circle of Willis. Future directions include development of dedicated

tools for vascular clipping and advanced vascular reconstruction techniques, not only for ICA repair but also for potential treatment of intracranial aneurysms via the EEA. In addition, the model itself can be further advanced by adding simulated hemodynamic monitoring and feedback to more realistically replicate all aspects of intraoperative patient management and stress.

## CONCLUSION

The live cadaver model with a pulsatile perfusion system attached to light embalmed cadaveric specimens combines real human anatomy with life-like conditions. It presents a true simulation of the conditions of live surgery during of endoscopic endonasal carotid rupture. This model could significantly improve the current training for management of an intraoperative endoscopic endonasal carotid rupture. A significant proportion of complications may be avoided by using practices that encourage standardized protocols, improved teamwork, and communication. The live cadaver model is an ideal training modality to simulate a surgical crisis and allow the teamwork training required for crisis management.

## Disclosure

The authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article.

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