“Live cadavers” for training in the management of intraoperative aneurysmal rupture

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OBJECT Intraoperative rupture occurs in approximately 9.2% of all cranial aneurysm surgeries. This event is not merely a surgical complication, it is also a real surgical crisis that requires swift and decisive action. Neurosurgical residents may have little exposure to this event, but they may face it in their practice. Laboratory training would be invaluable for developing competency in addressing this crisis. In this study, the authors present the “live cadaver” model, which allows repetitive training under lifelike conditions for residents and other trainees to practice managing this crisis.

METHODS The authors have used the live cadaver model in 13 training courses from 2009 to 2014 to train residents and neurosurgeons in the management of intraoperative aneurysmal rupture. Twenty-three cadaveric head specimens harboring 57 artificial and 2 real aneurysms were used in these courses. Specimens were specially prepared for this technique and connected to a pump that sent artificial blood into the vessels. This setting created a lifelike situation in the cadaver that simulates live surgery in terms of bleeding, pulsation, and softness of tissue.

RESULTS A total of 203 neurosurgical residents and 89 neurosurgeons and faculty members have practiced and experienced the live cadaver model. Clipping of the aneurysm and management of an intraoperative rupture was first demonstrated by an instructor. Then, trainees worked for 20- to 30-minute sessions each, during which they practiced clipping and reconstruction techniques and managed intraoperative ruptures. Ninety-one of the participants (27 faculty members and 64 participants) completed a questionnaire to rate their personal experience with the model. Most either agreed or strongly agreed that the model was a valid simulation of the conditions of live surgery on cerebral aneurysms and represents a realistic simulation of aneurysmal clipping and intraoperative rupture. Actual performance improvement with this model will require detailed measurement for validating its effectiveness. The model lends itself to evaluation using precise performance measurements.

CONCLUSIONS The live cadaver model presents a useful simulation of the conditions of live surgery for clipping cerebral aneurysms and managing intraoperative rupture. This model provides a means of practice and promotes team management of intraoperative cerebrovascular critical events. Precise metric measurement for evaluation of training performance improvement can be applied.

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KEY WORDS live cadaver; perfused cadaver; surgical training; cerebral aneurysm; pulsatile model; neurovascular

THE intraoperative rupture of an intracranial aneurysm can be a critical event that can jeopardize a patient's outcome. The rate of this event ranges from 6% to 20% of all surgical cases.^{5,9,11,14,16} In some reports, the aneurysmal rupture rate is as high as 41.6%.²¹ In

a recent study that reviewed the literature, involving a total of 9488 aneurysm surgeries, Madhugiri and colleagues¹⁷ found that the rate of intraoperative rupture in the entire group was 9.2%.

Factors such as the reduced number of working hours

ABBREVIATION MCA = middle cerebral artery.

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for residents and the trend toward minimal or even noninvasive treatment of surgical pathologies have resulted in residents' decreased exposure to major surgeries. This decreased exposure becomes particularly crucial in vascular surgery when surgeons encounter vascular injuries and intraoperative rupture of cerebral aneurysms; thus, the call for significant training in a laboratory setting.^{4,7}

Although the training models and simulators currently available provide a wide range of opportunities to practice skills and play a unique role in surgical training, they do not successfully replicate all the characteristics of the living human cerebral vasculature, particularly the combination of real human anatomy with lifelike surgical conditions. In this report, we present a practical training strategy with the "live cadaver" model, which uses the human anatomy under functional conditions to practice the management of intraoperative aneurysmal rupture and other neurovascular crises.

Methods

Cadaver Preparation

Twenty-three cadaveric head specimens harboring 57 artificial and 2 real aneurysms were used in 13 courses from 2009 to 2014 in the US and abroad. All specimens were ethically donated according to the individual's legally executed, advance-directive bequest on file at the host site. Sponsoring institutions included the Arkansas Neurosciences Institute (Little Rock, Arkansas), the Practical Anatomy Workshop (St. Louis, Missouri), the Medical Education and Research Institute (Memphis, Tennessee), and National Yang-Ming University (Taipei, Taiwan).

Specimens were specially prepared and preserved with alcohol-based disinfectant and ethylene glycol, without the use of formaldehyde or any other embalming materials. The common carotid arteries, vertebral arteries, and internal jugular veins were exposed in the neck section by dissecting each vessel 1–2 cm to allow cannulation. Plastic tubes selected to fit the caliber of each vessel were inserted and tied to the vessels' walls. Precautions were taken to maintain flow to both the internal and external carotid arteries. In addition, one 8- to 10-gauge tube was inserted intradurally in the subarachnoid space into each side of the spinal canal and advanced to reach the cisterns; after this, the canal was plugged with bone wax (Fig. 1).

Saline was used to irrigate and flush the vessels repeatedly to remove blood remnants and guarantee patency of the vascular tree. Each vessel was irrigated separately until the return fluid was consistently clear. The subarachnoid space was washed using the tubes placed in the spinal canal. Any leaks from arteries and veins on the sectioned surface of the neck were sealed by either ligation or coagulation. The vessels were then connected to "serum bags," called artificial blood reservoirs, which were wrapped with pressure bags to apply pressure to the reservoirs. One of the tubes in the spinal canal was connected to a reservoir of clear liquid to simulate CSF. The other tube was left open to drain excess fluid. The arterial reservoir was further connected through the pressure bag to a pump that provided pulsating pressure (Fig. 1). We used secondhand intraaortic balloon pumps (System 90/97, Datascope Corp., and TCI Heart Mate, Thermo

FIG. 1. Artistic illustration showing the connections and the settings of the model. Copyright A. Tim Irby. Published with permission.

Cardio Systems, Inc.). A rate between 60 and 80 pulses/minute was applied; the machine provided a rate up to 120 pulses/minute. Pressures up to 180 mm Hg can be applied through the arterial blood reservoir. For our purposes, we applied a pressure of 80 mm Hg as a baseline because the pressure fluctuated with each pulse, in the same way as systolic pressure, due to the pulsating pressure provided by the pump. A pressure ranging from 20 to 40 mm Hg was applied to the venous blood reservoir. The reservoirs (both arterial and venous) were placed a few centimeters higher than the specimen to control pressure and prevent air embolisms in the vessels during dissection.

In these settings, there was no real arterial–venous circulation. The actual movement of fluid inside the arteries in our model was back and forth according to the pulse transmitted from the pump, whereas the fluid inside the veins remained static, albeit under pressure. Artificial blood can be prepared with water-based paints, or it can be purchased as a prepared formula for training purposes (all sites in the study used the same fluid). In this setting, the human anatomy is presented in more lifelike circumstances that allow a true simulation of surgical procedures in terms of bleeding, the pulsation of arteries, and the softness of tissue (Video 1).

VIDEO 1. Clip showing the working station of the live cadaver and some of the surgical procedures. Copyright Emad Aboud. Published with permission. [Click here to view with Media Player.](#) [Click here to view with Quicktime.](#)

More details about preparing and operating on this live cadaver model have been published elsewhere.¹

Artificial aneurysms of various sizes and shapes were created in the areas where they usually occur: 16 at the bifurcation of the middle cerebral artery (MCA), 18 in the posterior communicating segment of the internal carotid artery, 12 at the carotid artery bifurcation, and 11 in the paraclinoid region (Fig. 2). For experimental purposes, ad-

ditional aneurysms were created in other locations, such as the anterior communicating artery, the basilar tip, and the pericallosal and posterior-inferior cerebral arteries, but these were not included in the training courses.

Creating the Aneurysms

To create the aneurysms, we harvested a venous graft from the cadaver's neck, mostly from the external or internal jugular veins, while preparing the same specimen or obtained previously from other specimens. During harvesting, we left a thin layer of the loose fatty tissue attached to the vein wall. The graft was cut into the desired length, usually 10–15 mm, and was then turned inside out, so that the inner surface became the outside. One end of the graft was sutured closed with 8-0 or 9-0 sutures, and the graft was then inverted again to its original position so that the sutures were hidden inside the aneurysmal sac, and the loose tissue attached to the wall covered the suture line on the outside so the dome had a rounded shape. The loose tissue attached to the wall helped close the hole in the dome during the rupture simulation.

At this point, the aneurysm was ready to be sutured in place. An arteriotomy that fit the diameter of the aneurysm's base was made on the parent artery, and the aneurysm was sutured to the edges of the arteriotomy with 8-0 sutures (Video 2).

VIDEO 2. Clip showing the creation of artificial aneurysms with some examples. Copyright Emad Aboud. Published with permission. Click here to view with Media Player. Click here to view with Quicktime.

At bifurcations, the base of the aneurysm was shaped to be part of the bifurcating branches on 1 or both sides to allow for reconstruction. Care was taken to keep the contour and configuration of the parent artery as it was and to spare the adjacent branches in cases of ophthalmic and posterior communicating artery aneurysms. In these cases, we sutured the aneurysm in intimate proximity to these vessels to make clip placement and reconstruction more challenging. Once sutured into place, the aneurysm was tested to check the filling of the sac and blood flow in distal and adjacent vessels, and to detect any leakage from the base. If such a leak occurred, additional sutures were placed. After this is completed, the aneurysm model is ready for training exercises (Video 3).

VIDEO 3. Clip showing examples of clipping of different aneurysms. Clinoidal Car A = clinoidal carotid artery; Ophth. A = ophthalmic artery; R. CN II = right cranial nerve II; R. Frontal = right frontal; R. Temporal = right temporal. Copyright Emad Aboud. Published with permission. Click here to view with Media Player. Click here to view with Quicktime.

Training Scenario

One or 2 live cadaver model stations were set up for each of the courses (Fig. 3). The cadaveric head was placed and fixed with head holders. Then, the blood reservoirs were placed so as to be slightly higher than the specimen to prevent air embolisms and control the pressure. The clear liquid reservoir (CSF simulator) was hung on a serum pole with a controlled flow, and the pump was placed to the side of the working station. In general, an instructor first demonstrates clipping of the aneurysm and the man-

FIG. 2. Example of artificial aneurysms (asterisks). **A:** Left superolateral paraclinoid aneurysm. **B:** Right paraclinoid aneurysm, superior type. **C and D:** Right MCA bifurcation aneurysms. L. Car Art = left carotid artery; L. Oph Art = left ophthalmic artery; L.O.N = left optic nerve; M2 = M2 trunk of middle cerebral artery; R. MCA = right middle cerebral artery; R.O.N = right optic nerve.

agement of an intraoperative rupture. Then, trainees work for 20- to 30-minute sessions each, during which they practice clip placement and reconstruction techniques and manage intraoperative ruptures.

Results

Intraoperative Rupture Scenarios

Different scenarios were used for training sessions. In all cases, the instructor first demonstrated clip placement techniques and how to manage a rupture. To demonstrate an intraoperative rupture, a hole was made in the aneurysmal wall, usually at the dome. When the pressure was increased to 150–180 mm Hg, profuse bleeding occurred and was managed by the instructor.

When trainees come to practice, the hole in the dome will not bleed profusely until the pressure is high enough because the loose tissue kept at the wall of the aneurysm covers and closes the hole. If the aneurysm bleeds even under low pressure, the hole is loosely sutured to approximate the edges. At first, the arterial pressure remains at its normal levels just to keep the aneurysm filled with normal flow, and trainees practice clip placement techniques without any bleeding from the aneurysm. A pulsatile oozing from the hole may occur, but it does not obscure the trainee's vision or interrupt the procedure. After several clip placement procedures, and while trainees are still working in the field to apply or remove a clip or while they are exploring around the aneurysm, the instructor or a third person will raise the pressure acutely, causing profuse bleeding that simulates a sudden intraoperative rupture.

FIG. 3. Live cadaver stations in different courses. *Green arrows* = the pumps, *blue arrows* = blood reservoirs, *red arrows* = clear liquid to simulate CSF, *yellow arrows* = the connections to the reservoirs and pump.

This situation allows the trainee to manage the rupture and control bleeding under the supervision of a faculty member (Video 4).

VIDEO 4. Clip showing aneurysmal rupture scenarios and training exercises. Copyright Emad Aboud. Published with permission. [Click here to view with Media Player.](#) [Click here to view with Quicktime.](#)

A second scenario was conducted on 2 different occasions. For this scenario, an angiogram was obtained previously in 2 specimens, 1 with an ophthalmic artery aneurysm and 1 with an aneurysm at the MCA. The subarachnoid spaces at the side of the aneurysms were filled with clots of artificial blood (Luna Innovation, Inc.) to simulate a recent subarachnoid hemorrhage. Trainees studied the angiogram before starting the procedure, during which they followed the anatomical pathways that led to the aneurysm shown on the angiogram. They suctioned blood clots from the cisterns, secured proximal control, and made their way to the aneurysm to place a clip, in the same fashion as in live patients with subarachnoid hemorrhage (Video 5).

VIDEO 5. Clip showing a different training scenario with angiograms and subarachnoid bleeding. M1 Sup Trunk = M1 segment of the middle cerebral artery, superior trunk; R. M1 = right M1 segment of the middle cerebral artery. Copyright Emad Aboud. Published

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A third scenario was conducted in which there were 2 specimens with the live cadaver. The first had a nonruptured aneurysm and the second had a ruptured one. Trainees rotated on both specimens separately, practicing clip placement techniques on 1 specimen and managing the rupture on the other.

In 2 specimens we found real aneurysms, 1 at the bifurcation of the MCA and the other in the anterior communicating artery, so we used this great opportunity to practice the same training procedures (Video 6).

VIDEO 6. Clip showing training exercises on real aneurysms. Copyright Emad Aboud. Published with permission. [Click here to view with Media Player.](#) [Click here to view with Quicktime.](#)

Surprisingly, the artificial aneurysms tolerated all the maneuvers and clip placement attempts by the participants in each course. We rarely needed to repair or resuture the aneurysm after several clipping procedures. On some occasions, we added sutures to the base or repaired a tear in the parent vessel where the aneurysm was attached.

Scrub nurses attended 6 of our courses and scrubbed in with the residents, assisting in procedures and practicing their role in crisis management when an intraoperative

rupture occurred. In all cases, a third person, sometimes the instructor, controlled the pump and pressure.

Model Evaluation

Residents were enthusiastic to work on a cadaver that could bleed, with arteries that pulsated, and they welcomed the opportunity to manage an intraoperative rupture, a procedure that they might not have encountered yet. Most of the participants in all the courses stated that the live cadaver session was the part of the course they liked the most. The live cadaver model enabled trainees to practice aneurysmal clip placement and all maneuvers and techniques to control intraoperative aneurysmal rupture, including tamponade, suction, proximal and distal vascular control, temporary clip placement, coagulation, and hypotension (the pressure in the specimen can be controlled through adjustment of the pressure in the arterial reservoir). Overall, 203 residents and 89 attendants (practicing neurosurgeons and faculty members) have practiced with and tested the live cadaver model. Of these, 91 (27 faculty members and 64 participants) completed a questionnaire to rate their personal opinions of the live cadaver model (Table 1). Most either agreed or strongly agreed that the model was a true simulation of the conditions of live surgery on cerebral aneurysms and represented a realistic simulation for aneurysmal clip placement and intraoperative rupture.

Discussion

A Proficient Model for Aneurysmal Rupture

Although the intraoperative rupture rate of an aneurysm may not be totally influenced by the surgeon's experience, Lawton and Du found that the outcome for patients with intraoperative aneurysmal rupture improves as a neurosurgeon's surgical experience increases, and as the neurosurgeon's experience increases, the number of ruptures during predissection and clip application decreases.¹⁵ Gaining experience requires surgeons to have more exposure and operate on more cases. Changes in training programs and work hours nowadays have decreased residents' and young neurosurgeons' exposure to open aneurysm surgery, which would affect their expertise.^{7,8}

Simulation and laboratory training are the best compensation mechanisms to regain the loss of expertise and skill. This fact was realized by Yaşargil and other pioneers early on with the introduction of microneurosurgery. In his landmark book on microneurosurgery, Yaşargil states: "In delicate organs such as the central nervous system, the surgeon's individual skills play a crucial role in determining patient outcome. Hence, the emphasis has been placed on laboratory training, preparing surgical trainees for the operating room experience."²⁴ To simulate a real surgical procedure, one must imitate and include all elements of live surgery. John Hunter, the noted Scottish surgeon of the 18th century, is believed to have said that "surgery is anatomy plus hemostasis" (Dr. John Jane Sr., personal communication, February 2014).

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. On the other hand, human cadavers provide the clinically relevant anatomy but lack the circulatory conditions noted in clinical practice. The live cadaver model combines the lifelike conditions of the living body with the real human anatomy in 1 model, and is the only training model available that provides such a combination. 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, such as suction, bipolar coagulation, echo Doppler ultrasonography, and even flow measurement, and other devices common to the operating room.

The estimated cost of the materials for this model is modest. An intraaortic balloon pump that is no longer used for patient care can be purchased for less than \$1000. The cost of cannulas, reservoirs, and pressure bags is modest. In addition, the model can be used in a number and variety of procedures on 1 specimen. If the model is intended to be used in university or institutional settings attached to a hospital, most of the materials needed, including the pump, can be obtained free from expired and used materials in the hospital.

TABLE 1. The questionnaire administered after completion of the training course*

Question	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
This model was a true simulation of the conditions of live surgery on aneurysms		1.09	2.19	28.57	68.13
This model promotes the acquisition of microsurgical skills			6.59	21.97	71.42
This model offers benefits not available in existing training models			6.59	21.97	71.42
The tissue characteristics in this model are very similar to those of living tissues	3.29	1.09	3.29	32.96	59.34
The scenario of aneurysm clipping and intraoperative rupture is realistic			7.69	30.76	61.53
This model could significantly improve current training in the management of intraoperative cerebrovascular complications				24.17	75.82
This model could add significantly to training in microneurosurgical techniques				26.37	73.62
This model will be a valuable addition to the medical device development and testing process	1.09	2.19	7.69	23.07	65.93
This model is superior to existing models for cerebral revascularization		1.09	4.39	27.47	67.03
This model could replace the use of live animals in microanastomosis training	3.29	5.49	15.38	30.76	45.05

* All values given as percentages.

Team Practice of Adverse Events

As a surgical crisis, the intraoperative rupture of an aneurysm requires swift and decisive action, not only by the surgeon himself but also by the whole team in the operating room. The trend today is to use a simulated environment to teach safety principles and train staff to adhere to crisis checklists during the management of a surgical crisis.^{3,18} A significant proportion of complications may be avoided by using practices that encourage standardized protocols, improved teamwork, and communication.²³ The live cadaver model, which combines real human anatomy and the ability to achieve hemostasis and address hemorrhage, is an ideal training modality to simulate a surgical crisis and allow the teamwork training required for crisis management. During training sessions in our courses and after 2 or 3 attempts to control bleeding from a ruptured aneurysm, trainees reacting to a sudden hemorrhage from a rupture began to develop a sequence of actions and precise moves shaped by the repetitive training on the model. In future studies, we intend to elaborate on the acquisition of skills and the development of learning curves during these courses.

With the live cadaver model, participating residents, including those who had never clipped an aneurysm or even applied a clip to a vessel, have developed the skill and ability to clip aneurysms and address an intraoperative rupture in a short period of time (Video 7).

VIDEO 7. Clip showing development of simple skills, i.e., clipping of an aneurysm by a resident, after several attempts, who had never

clipped an aneurysm before. Copyright Emad Aboud. Published with permission. Click here to view with Media Player. Click here to view with Quicktime.

The ability to have the scrub nurse help the trainee, and the presence of a third person to control the pump and pressure (playing the role of the anesthesiologist), make the live cadaver model appropriate for practicing teamwork during an intraoperative crisis. In fact, this is a common practice in our institution, where scrub nurses attend the lab every 2–3 months, and whenever a new member joins the team, to practice teamwork management of adverse intraoperative events, including aneurysmal rupture (Fig. 4).

Potential Applications

The live cadaver model can be the main training model used in workshops for training and practice. With this model, the participants can cover all neurosurgical and neurovascular procedures in a period of 5 days to 1 week. During such workshops, each participant has his/her own specimen, and we can arrange the sequence of procedures to maximize the benefits of the specimens and resources provided and include all possible surgical procedures and approaches. Participants can practice all types of maneuvers and techniques, particularly those that require circulating blood in the vessels and CSF in the cisterns. These procedures include, but are not limited to, endovascular techniques, extradural dissection, unlocking the cavernous sinus, and managing dural sinus bleeding. We can also include intracranial pressure reduction maneuvers, such as

FIG. 4. Scrub nurses and operating room team in the lab, helping trainees during training sessions and working under the microscope to get used to the microscopic world. The nurses are also shown working on the aneurysms themselves and addressing the bleeding so they can fully understand the situation from the surgeon's point of view.

releasing CSF through cisternal and arachnoidal dissection, opening Meckel's cave, opening the lamina terminalis, inserting ventricular cannulas, and splitting the sylvian fissure. The model also allows trainees to practice bypass techniques, repair vascular injuries, dissect artificial tumors, create and clip artificial aneurysms, and manage intraoperative aneurysmal rupture. All these maneuvers need a lifelike situation, with CSF in the cisterns, and have already been practiced with the live cadaver model.

With only a few limitations, such as the quality of tissue and the properties of artificial blood, the live cadaver model provides great benefits and unique opportunities that are not offered by any other training model. Since we first described it in 2002,¹ this model has been established for training and evaluating new techniques and devices in neurosurgery.^{12,13,19,22} The preparation of the model, including the creation of the aneurysm, might appear complex and time consuming; to the contrary, the preparation of the specimen for this model is similar to what is usually done for preparation of a latex injection routinely used. The establishment of aneurysms and bypasses in the model is, in itself, an addition to beneficial microsurgical training.

Similarly, the live cadaver model can be used to practice all types of procedures in other surgical disciplines. Elsewhere, we describe the use of the whole live cadaver for training with traumatic injuries and penetrating wounds,² and several groups have begun to use this model for training and experimental surgeries in different areas of surgery.^{6,20} To our knowledge, there have been no prior reports describing the use of a model such as the live cadaver. Garrett¹⁰ has described a technique to create a lifelike model of the human arterial tree, in which an arterial-to-arterial circulation was created in major vessels for endovascular training and research.

Conclusions

The live cadaver model combines real human anatomy with lifelike conditions. It presents a true simulation of the conditions of live surgery on cerebral aneurysms and intraoperative aneurysmal rupture. This model could significantly improve the current training in neurosurgery, particularly team management of an intraoperative cerebrovascular crisis. It is readily available, cost effective, and of great value for training for all types of surgical procedures. This model can also be evaluated using precise performance measurements that would assess its effectiveness.

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References

1. Aboud E, Al-Mefty O, Yaşargil MG: New laboratory model for neurosurgical training that simulates live surgery. *J Neurosurg* **97**:1367–1372, 2002
2. Aboud ET, Krisht AF, O'Keeffe T, Nader R, Hassan M, Stevens CM, et al: Novel simulation for training trauma surgeons. *J Trauma* **71**:1484–1490, 2011
3. Arriaga AF, Bader AM, Wong JM, Lipsitz SR, Berry WR,

- Ziewacz JE, et al: Simulation-based trial of surgical-crisis checklists. *N Engl J Med* **368**:246–253, 2013
4. Batjer H: Comment on "Effect of the neurosurgeon's surgical experience on outcomes from intraoperative aneurysmal rupture." *Neurosurgery* **57**:13–14, 2005
5. Batjer H, Samson D: Intraoperative aneurysmal rupture: incidence, outcome, and suggestions for surgical management. *Neurosurgery* **18**:701–707, 1986
6. Carey JN, Rommer E, Shekter C, Minneti M, Talving P, Wong AK, et al: Simulation of plastic surgery and microvascular procedures using perfused fresh human cadavers. *J Plast Reconstr Aesthet Surg* **67**:e42–e48, 2014
7. Chowdhry SA, Spetzler RF: Genealogy of training in vascular neurosurgery. *Neurosurgery* **74** (Suppl 1):S198–S203, 2014
8. Coon AL, Paul AR, Colby GP, Lin LM, Pradilla G, Huang J, et al: Comparison of tertiary-center aneurysm location frequencies in 400 consecutive cases: Decreasing incidence of posterior communicating artery region aneurysms. *Surg Neurol Int* **2**:152, 2011
9. Fridriksson S, Säveland H, Jakobsson KE, Edner G, Zygmunt S, Brandt L, et al: Intraoperative complications in aneurysm surgery: a prospective national study. *J Neurosurg* **96**:515–522, 2002
10. Garrett HE Jr: A human cadaveric circulation model. *J Vasc Surg* **33**:1128–1130, 2001
11. Giannotta SL, Oppenheimer JH, Levy ML, Zelman V: Management of intraoperative rupture of aneurysm without hypotension. *Neurosurgery* **28**:531–536, 1991
12. Gragnaniello C, Nader R, van Doormaal T, Kamel M, Voormolen EH, Lasio G, et al: Skull base tumor model. *J Neurosurg* **113**:1106–1111, 2010
13. Güvencer M, Sayhan S, Ay Dereli N, Tetik S, Yücesoy K, Arda MN: Simulation of cerebrovascular circulation in the human cadaver for surgical neuroanatomy training. *Türk Neurosurg* **17**:243–246, 2007
14. Houkin K, Kuroda S, Takahashi A, Takikawa S, Ishikawa T, Yoshimoto T, et al: Intra-operative premature rupture of the cerebral aneurysms. Analysis of the causes and management. *Acta Neurochir (Wien)* **141**:1255–1263, 1999
15. Lawton MT, Du R: Effect of the neurosurgeon's surgical experience on outcomes from intraoperative aneurysmal rupture. *Neurosurgery* **57**:9–15, 2005
16. Leipzig TJ, Morgan J, Horner TG, Payner T, Redelman K, Johnson CS: Analysis of intraoperative rupture in the surgical treatment of 1694 saccular aneurysms. *Neurosurgery* **56**:455–468, 2005
17. Madhugiri VS, Ambekar S, Pandey P, Guthikonda B, Bollam P, Brown B, et al: The pterional and suprabrow approaches for aneurysm surgery: a systematic review of intraoperative rupture rates in 9488 aneurysms. *World Neurosurg* **80**:836–844, 2013
18. Moorthy K, Munz Y, Forrest D, Pandey V, Undre S, Vincent C, et al: Surgical crisis management skills training and assessment: a simulation[corrected]-based approach to enhancing operating room performance. *Ann Surg* **244**:139–147, 2006
19. Olabe J, Olabe J, Sancho V: Human cadaver brain infusion model for neurosurgical training. *Surg Neurol* **72**:700–702, 2009
20. Russin JJ, Mack WJ, Carey JN, Minneti M, Giannotta SL: Simulation of a high-flow extracranial-intracranial bypass using a radial artery graft in a novel fresh tissue model. *Neurosurgery* **71** (2 Suppl Operative):ons315–ons320, 2012
21. Seifert V, Stolke D, Trost HA, Brüning A, Schäffer J: Incidence, management, and outcome of patients with rupture of cerebral aneurysms during surgery, in Frowein RA, Brock M, Klinger M (eds): *Advances in Neurosurgery*. Berlin: Springer-Verlag, 1989, Vol 17, pp 203–207

22. van Doormaal TP, van der Zwan A, Aboud E, Berkelbach van der Sprenkel JW, Tulleken CA, Krisht AF, et al: The sutureless excimer laser assisted non-occlusive anastomosis (SELANA); a feasibility study in a pressurized cadaver model. **Acta Neurochir (Wien)** **152**:1603–1609, 2010
23. Wong JM, Ziewacz JE, Ho AL, Panchmatia JR, Kim AH, Bader AM, et al: Patterns in neurosurgical adverse events: open cerebrovascular neurosurgery. **Neurosurg Focus** **33(5)**:E15, 2012
24. Yasargil MG: **Microneurosurgery**. New York: Thieme, 1984

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Supplemental Information

Previous Presentation

This work was previously presented as a poster (“Artificial aneurysms in live cadavers. A new realistic model for practicing the management of intraoperative rupture.”) at the 2014 Annual CNS Meeting in Boston, Massachusetts, October 18–22.

Videos

Video 1, Media Player. http://mfile.akamai.com/21490/wmv/digitalwbc.download.akamai.com/21492/wm.digitalsource-na-regional/jns14-1551_video_1.asx.

Video 1, Quicktime. http://mfile.akamai.com/21488/mov/digitalwbc.download.akamai.com/21492/qt.digitalsource-global/jns14-1551_video_1.mov.

Video 2, Media Player. http://mfile.akamai.com/21490/wmv/digitalwbc.download.akamai.com/21492/wm.digitalsource-na-regional/jns14-1551_video_2.asx.

Video 2, Quicktime. http://mfile.akamai.com/21488/mov/digitalwbc.download.akamai.com/21492/qt.digitalsource-global/jns14-1551_video_2.mov.

Video 3, Media Player. http://mfile.akamai.com/21490/wmv/digitalwbc.download.akamai.com/21492/wm.digitalsource-na-regional/jns14-1551_video_3_new.asx.

Video 3, Quicktime. http://mfile.akamai.com/21488/mov/digitalwbc.download.akamai.com/21492/qt.digitalsource-global/jns14-1551_video_3_new.mov.

Video 4, Media Player. http://mfile.akamai.com/21490/wmv/digitalwbc.download.akamai.com/21492/wm.digitalsource-na-regional/jns14-1551_video_4.asx.

Video 4, Quicktime. http://mfile.akamai.com/21488/mov/digitalwbc.download.akamai.com/21492/qt.digitalsource-global/jns14-1551_video_4.mov.

Video 5, Media Player. http://mfile.akamai.com/21490/wmv/digitalwbc.download.akamai.com/21492/wm.digitalsource-na-regional/jns14-1551_video_5.asx.

Video 5, Quicktime. http://mfile.akamai.com/21488/mov/digitalwbc.download.akamai.com/21492/qt.digitalsource-global/jns14-1551_video_5.mov.

Video 6, Media Player. http://mfile.akamai.com/21490/wmv/digitalwbc.download.akamai.com/21492/wm.digitalsource-na-regional/jns14-1551_video_6.asx.

Video 6, Quicktime. http://mfile.akamai.com/21488/mov/digitalwbc.download.akamai.com/21492/qt.digitalsource-global/jns14-1551_video_6.mov.

Video 7, Media Player. http://mfile.akamai.com/21490/wmv/digitalwbc.download.akamai.com/21492/wm.digitalsource-na-regional/jns14-1551_video_7.asx.

Video 7, Quicktime. http://mfile.akamai.com/21488/mov/digitalwbc.download.akamai.com/21492/qt.digitalsource-global/jns14-1551_video_7.mov.

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