The Cadaveric Perfusion and Angiography as a Teaching Tool: Imaging the Intracranial Vasculature in Cadavers

Erhan Turkoglu[1] Hakan Seckin[1] Bora Gurer[1] Azam Ahmed[1] Kutluay Uluc[1] Kari Pulfer[2] Anıl Arat[2] David Niemann[1,2] Mustafa K. Baskaya[1]

[1] Department of Neurological Surgery, University of Wisconsin, School of Medicine and Public Health, Madison, Wisconsin, United States
[2] Department of Radiology, University of Wisconsin, School of Medicine and Public Health, Madison, Wisconsin, United States

Address for correspondence Mustafa K. Baskaya, MD, Department of Neurological Surgery, University of Wisconsin, School of Medicine, CSC K4/822, 600 Highland Avenue, Madison, WI 53792, United States (e-mail: m.baskaya@neurosurgery.wisc.edu).

J Neurol Surg B 2014;75:435–444.

Abstract

Background and Study Aim To enhance the visualization of the intracranial vasculature of cadavers under gross examination with a combination of imaging modalities.

Material and Methods A total of 20 cadaver heads were used to test two different perfusion techniques. First, fixed cadaver heads were perfused with water; second, fresh cadavers were perfused with saline and 10% formalin. Subsequently, brains were removed and fixed. The compounds used were silicone rubber, silicone rubber mixed with powdered barium sulfate, and silicone rubber mixed with tantalum dioxide prepared by the first perfusion technique and gelatin mixed with liquid barium prepared with the second technique. Conventional X-ray imaging, computed tomography (CT), dynamic computed tomography (dCT), and postprocessing three-dimensional (3D) images were used to evaluate all the heads.

Results Gelatinized barium was better visualized when compared with tantalum dioxide in conventional X-ray images. The blood vessels injected with either tantalum dioxide or gelatinized barium demonstrated a higher enhancement than the surrounding soft tissues with CT or dCT. The quality of the 3D reconstruction of the intracranial vasculature was significantly better in the CT images obtained from the gelatinized barium group.

Conclusions Radiologic examinations of the heads injected with gelatinized barium facilitates the 3D understanding of cerebrovascular anatomy as an important tool for neuroanatomy training.

Keywords
- angiography
- barium sulfate
- cadaver
- computed tomography angiography
- liquid barium
- neuroanatomy
- tantalum dioxide
- three dimensional
- X-ray

Introduction

Neuroanatomical and microsurgical training have become an integral part of neurosurgical training in institutions of excellence.[1–9] Cadaver dissections simulating complex neurosurgical approaches help the training of residents with respect to surgical neuroanatomy, improve manual dexterity, and facilitate the development of new microsurgical techniques. Knowledge of the complex anatomy of the cerebral vasculature coupled with a precise and accurate microsurgical technique is the mainstay for success in cerebrovascular surgery.[9] The well-described technique of injecting colored silicone into the cerebral vessels has been demonstrated to facilitate the identification and dissection of the cerebral

received November 4, 2013
accepted May 27, 2014
published online August 11, 2014

DOI http://dx.doi.org/10.1055/s-0034-1386653.
ISSN 2193-6331.

vessels from the surrounding tissues.[1,5,6,10,11] In most centers, this technique is the basis for training, planning, practicing, developing, and refining neurosurgical approaches.

Computed tomography angiography with three-dimensional (3D) reconstruction (3D-CTA) is used in the diagnosis of brain lesions and cerebrovascular diseases.[12,13] It also provides detailed information about vascular relationships that is useful for preoperative planning. Zhao et al examined cadaveric specimens after injecting the vessels with a silicone rubber and a contrast agent mixture.[14] Their method allowed static and dynamic CT scanning of the neurosurgical anatomy. The objectives of this study were to use a technique that allows better perfusion and visualization of the vessels of interest and to visualize these vessels by conventional X-ray imaging in addition to conventional CT, dynamic computed tomography (dCT), and postprocessing 3D images.

Materials and Methods

Preparation of the Cadaver Heads

Initial Preparation

We used two different perfusion techniques for our study. In the first technique, cadaveric head and neck specimens were fixed in 50% alcohol for 4 weeks. Bilateral internal carotid arteries (ICAs), vertebral arteries (VAs), and internal jugular veins (IJVs) were isolated and cannulated with appropriate size tubing. The cannulated vessels were irrigated with water until no blood clot was visible in the effluent. Points of leakage were ligated with 2–0 silk sutures, and further irrigation was performed manually with a 60-mL syringe. These specimens were injected with three different compounds: (1) silicone rubber ($n = 3$), (2) silicone rubber mixed with powder barium sulfate ($n = 6$), and (3) silicone rubber mixed with tantalum oxide ($n = 6$). Each specimen was fixed in 50% alcohol for an additional 24 hours after the injection to allow the silicone to cure.[2,15] In the second technique, bilateral common carotid arteries, carotid bifurcations, and IJVs were dissected. We elected to use one-way Foley urinary catheters for tubing of the vessels because they are available in various sizes (range: 8–32F) and have adequate stiffness to cannulate and enough flexibility to permit manipulation. For the ICA, a number 10 Foley catheter (5 cm^3 inflatable balloon; Rochester Medical, Stewartville, Minnesota, United States) was optimal because the use of balloon occlusion prevented backflow from the ICA. The external carotid arteries were then tied with 2–0 silk suture. The ICAs were irrigated with a $\sim$ 3000-mL saline drip suspended 1.5 m above the cadaveric head until no visible blood or clots drained from the IJVs. Then a 10% formaldehyde (Sigma-Aldrich, St. Louis, Missouri, United States) drip was initiated via the same route for 1 hour; this step resulted in brain perfusion and fixation. Brains were removed and further fixed in 10% formaldehyde for 2 weeks. After 2 weeks of fixation, ICAs were cannulated with appropriate size cannulas and vessels further washed out to ensure removal of the intravascular blood clots. After satisfactory cleaning of vessels, gelatinized barium was injected into the cerebral vessels.

Experimental Groups and Contrast Agent Preparations

Silicone Rubber Only

Three cadaver heads were injected with the silicone rubber. Silicone rubber was prepared following a well-described protocol [1]. Because the factory has terminated the production of Crayola powder paint, we used a different powder paint that provided the same quality of colors (Powder Tempera Paint, Discount School Supply, Illinois, United States). This noncontrast group was used as a reference for comparison with the other groups in which a contrast agent was also used.

Silicone Rubber Mixed with Powder Barium Sulfate

Powder barium sulfate (Sigma-Aldrich Co., St. Louis, Missouri, United States) was dissolved in tap water by heating to 70°C and continuously stirring for 8 hours. The solution was filtered and the filtrate further grounded. The fine barium sulfate powder was then mixed with the previously prepared silicone mixture in a ratio of 1:1. This solution was then injected into the cerebral vessels of the cadaveric heads ($n = 6$).

Silicone Rubber Mixed with Tantalum Dioxide

Silicone compound and black tantalum dioxide powder (Onyx, eV3, Plymouth, Minnesota, United States, and Trufill NBCA, Cordis, Miami Lakes, Florida, United States) were mixed to yield a 10% w/w mixture. This mixture was then injected into the cerebral vessels of the cadaveric heads ($n = 6$).

Gelatin Mixed with Liquid Barium (Gelatinized Barium)

A gel-based mixture was experimented with for better penetration over the silicone mixtures. Gelatin is a water-soluble material and therefore a hydrophilic substance such as liquid barium (Entrobar Barium Sulfate Suspension, Tyco, New Mexico, United States). Therefore this type of barium was used in this mixture. A total of 4 g of gelatin type-A (MP Biomedicals, Solon, Ohio, United States) was dissolved in 30 mL of 70°C water by continuous stirring on an electromagnetic heater. Then 25 mL of liquid barium sulfate was added and stirred until a uniform homogeneous liquid mixture was obtained with a specific gravity of 0.95 g/mL at 24°C. This mixture was then injected with a 60-cm^3 syringe into the cadaveric heads via the cannulated ICAs and VAs ($n = 5$).

Angiographic Imaging

For all imaging methods, the cadaveric head was positioned with the orbitomeatal line and the sagittal plane perpendicular to the floor.

Conventional Computed Tomography

This technique was performed on all specimens using a 64-row multislice computed tomographic machine (V scanner; GE Medical Systems, Milwaukee, Wisconsin, United States). The CT data acquisition was performed with the following parameters: 120 kV, 300 mA, slice thickness of 1.25 mm, and reconstruction interval of 0.5621 mm.

X-ray and Dynamic Computed Tomography

Conventional X-ray and C-arm dCT images were obtained using a biplane fluoroscopy unit (Axiom Artis dBA; Siemens Medical Solutions, Erlangen, Germany). For C-arm dCT images, a "Hi-Dose Dyna" was performed using the following parameters: 20-second acquisition, 0.4-degree increment, 512 matrix projections, 220-degree total angle, 20 deg/s, and 15 to 30 frames/s, for a total of 538 projections (DynaCT; Siemens Medical Solutions, Forchheim, Germany).

Postprocessing

The CT images were postprocessed and analyzed on an Advantage Windows Workstation (v.4.4). Postprocessing and analysis of the C-arm dCT data was performed on a Leonardo workstation. The images were reconstructed into multiplanar reformat, maximal intensity projection, and 3D images. The images were also postprocessed in a dual-volume mode creating images where disparate densities (e.g., calcium, silicone, and silicone with tantalum or barium particles) are represented by different colors. No postprocessing was performed for the X-ray images.

Dissection of the Cadaver Heads

After the imaging process was completed, the cadaveric heads were dissected to study the specimens under operating microscope and gross examination. Bilateral ICAs, the arterial circle of Willis, bilateral IJVs, and vertebrobasilar arteries were exposed under microscopic magnification and illumination (Leica, Wild M 695 surgical microscope). In several cadaver heads, further surgical dissections and alterations were made to imitate common pathologic processes such as ischemic stroke and aneurysms. In one cadaver head an artificial aneurysm was implanted surgically into the anterior communicating artery (AcomA) to imitate an AcomA aneurysm. The artificial aneurysm was made by sculpturing the solidified silicone rubber mixed with tantalum oxide. The aneurysm was then sutured to the AcomA with 3–0 silk sutures. In another specimen, anterior temporal lobectomy was performed to imitate an ischemic infarct.

Results

There were no differences between the penetration ability of the compounds used by different imaging modalities. The visualization of the vascular tree with the mixture containing gelatinized barium was more detailed compared with the other three mixtures: silicone rubber only, silicone rubber mixed with powdered barium sulfate, and silicone rubber mixed with tantalum dioxide in all imaging modalities (►**Table 1**).

The homogeneity of the mixtures varied by the type of the contrast agent used, and the most homogeneous mixture could be obtained by the use of gelatinized barium (►**Fig. 1**). Among the silicone mixtures; silicone rubber and silicone rubber mixed with tantalum dioxide resulted in a homogeneous mixture; the silicone rubber mixed with powdered barium sulfate ended up by clumping the barium despite vigorous efforts (►**Figs. 2–4**). The densities of the four in-

Table 1 Comparisons of the homogeneity of mixture, density, and penetration ability of the compounds and visualization of the vascular tree with different imaging modalities

	Homogeneity of mixture	Density and penetration ability of the compounds	X-ray	CTA	3D-CTA
Silicon rubber only	Homogeneous	Satisfactory	No visualization	Degradation of image quality	Poor overall visualization
Silicon rubber with powdered barium sulfate	Granularity	Satisfactory	Clumping of the barium	Nonopacified irregularities; poor overall visualization	Nonopacified irregularities; poor overall visualization
Silicon rubber with tantalum dioxide	Homogeneous	Satisfactory	No visualization	Adequate overall visualization	Adequate overall visualization
Gelatin mixed with liquid barium	The most homogeneous	More satisfactory and more detailed	More detailed visualization	More detailed visualization	More detailed visualization

Abbreviations: 3D, three-dimensional; CTA, computed tomography angiography.

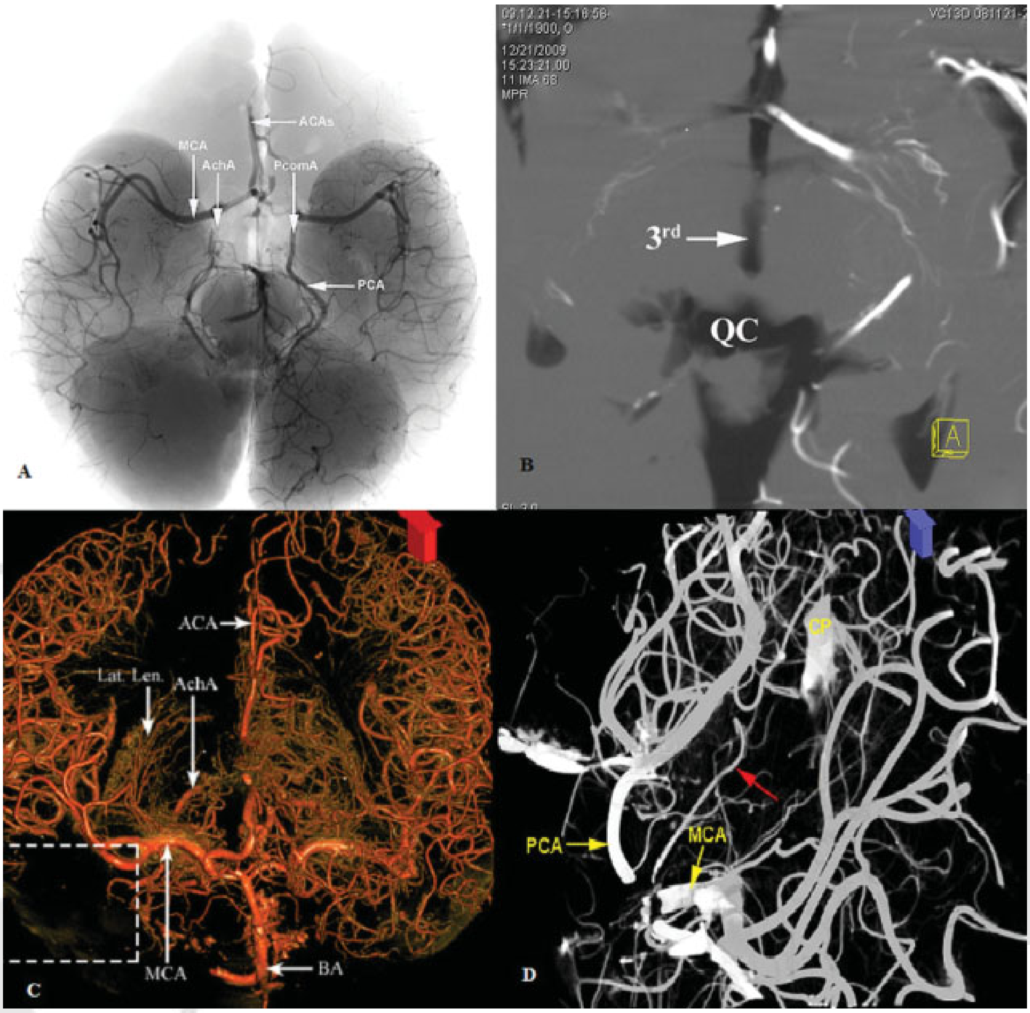

Fig. 1 (A) Fluoroscopic inferior-superior view of a cadaveric brain perfused with liquid barium sulfate. Note the visualization of the anterior choroidal artery (AchA) on the right and posterior communicating artery (PcomA) on the left. (B) Axial dynamic computed tomography imaging of the same cadaveric brain. Note that the capillary network feeding the diencephalon and basal ganglia on the left side are visualized. Also note the air in the 3rd ventricles and cisterns. (C) Three-dimensional computed tomography angiography (3D-CTA) imaging of the same cadaveric brain. The arterial tree is artificially colored to obtain a detailed view of the fine vasculature. Note especially the detailed and fine demonstration of the perfusion of lenticulostriate territories. In this cadaveric specimen, anterior temporal lobectomy has been performed to mimic stroke in this region (dotted lines). Dotted lines show the region of anterior temporal lobectomy. (D) 3D-CTA view providing the anatomy of both the middle cerebral artery and posterior cerebral arteries. Red arrow: anterior choroidal artery; 3rd, third ventricle; ACA, anterior cerebral artery; BA, basilar artery; CP, blush of choroid plexus; Lat. Len., lateral lenticulostriate arteries; MCA, middle cerebral artery; PCA, posterior cerebral artery; QC, quadrigeminal cistern.

jected mixtures were satisfactory for visualization of the vasculature under both gross and imaging examination. Both contrast substances (barium sulfate, either powder or liquid, and tantalum dioxide) increased the density of the colored silicone as evidenced by their imaging quality on the X-ray images.

The quality of the images varied based on the type and the concentration of the contrast agent of the injected mixture and the imaging modality. The density of the 1:1 ratio of powdered barium and silicone rubber was appropriate for a clear rendering of the vessels with all three imaging modalities. As mentioned earlier, the silicone rubber mixed with powdered barium ended up clumping the barium; in our study this granularity was seen in all imaging modalities but was most conspicuous in the X-ray images where granules of barium appeared as higher density areas (►**Fig. 3A**). Even though it is hard to appreciate this granularity on CTA or 3D-CTA images, some nonopacified irregularities were noted on these CT images (►**Fig. 3B**, **C**). Liquid barium (80% concentration) was more appropriate for a clear rendering of the vessels with all three imaging modalities (►**Fig. 1**). Granularity was not apparent in any of the imaging modalities with gelatinized barium.

Tantalum dioxide powder was useful for obtaining conventional and 3D-CTA images (►**Fig. 4B**, **C**). However, its darkening effect (shift in the color of the silicone rubber) limited its concentration to 10% that was adequate for CT but insufficient for X-ray images (►**Fig. 4A**). Granularity was not noted on imaging of the silicone rubber mixed with tantalum dioxide.

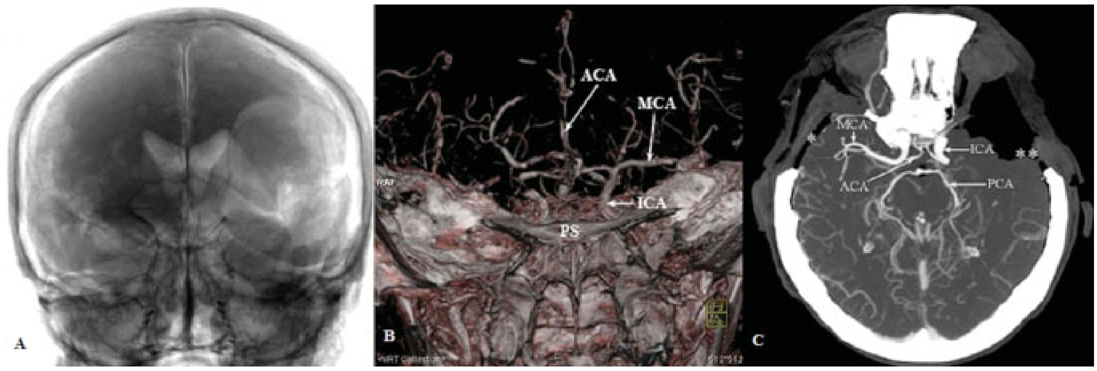

Fig. 2 (A) Anteroposterior conventional X-ray of the silicone rubber–only injection of a cadaveric head. Note no visualization of any vasculature. (B) Three-dimensional computed tomography angiography (3D-CTA) of the silicone rubber–only injection of cadaveric head. Note the poor overall visualization of vasculature and good visualization of the anterior skull base. (C) Axial CTA of the silicone rubber–only injection of cadaveric head. Note the better visualization of vasculature in this imaging modality. ACA, anterior cerebral artery; ICA, internal carotid artery; MCA, middle cerebral artery; PCA, posterior cerebral artery; PS, planum sphenoidale; right-sided craniectomy defect (asterisk); left-sided craniectomy defect (double asterisk).

The silicone rubber only did not allow for visualization of the vasculature on X-ray imaging but did allow for visualization of the vasculature in CTA and 3D-CTA images (►**Fig. 2**). The image quality was degraded in areas where a full column of silicone was not present. This degradation of image quality occurred to a greater extent in the specimens injected with silicone rubber only.

The specimen with a sutured artificial aneurysm underwent a 3D-CTA imaging that showed the aneurysm clearly (►**Fig. 5**). A right-sided anterior temporal lobectomy was performed in one specimen to imitate the temporal territory ischemic stroke (►**Fig. 1C**).

The colored silicone was obvious upon gross examination after the dissection of all specimens. The addition of powdered barium resulted in a lightening of the color of the silicone rubber. The red color gained a pinkish hue and the blue color gained a whitish hue after addition of the powdered barium. The same effect was observed after addition of the liquid barium to the gel mixture. Tantalum dioxide has a black color, which resulted in a darkening of the original color of the silicone rubber mixture. After addition of the tantalum dioxide, the blue color turned into a darker blue and the red color turned into dark red to brown color (►**Fig. 6**). However, these discolorations did not interfere with identification of the vessels under gross examination.

We used two different techniques to clean the cerebral vasculature from blood clots. The first technique performed on fixed cadavers was found to be challenging due to the difficulty of the breaking down and removal of already formed blood clots. The second technique was superior to the first technique. We cleaned the vasculature as soon as possible in fresh cadavers. This provided better clot removal and consequently better penetration of the perfused material.

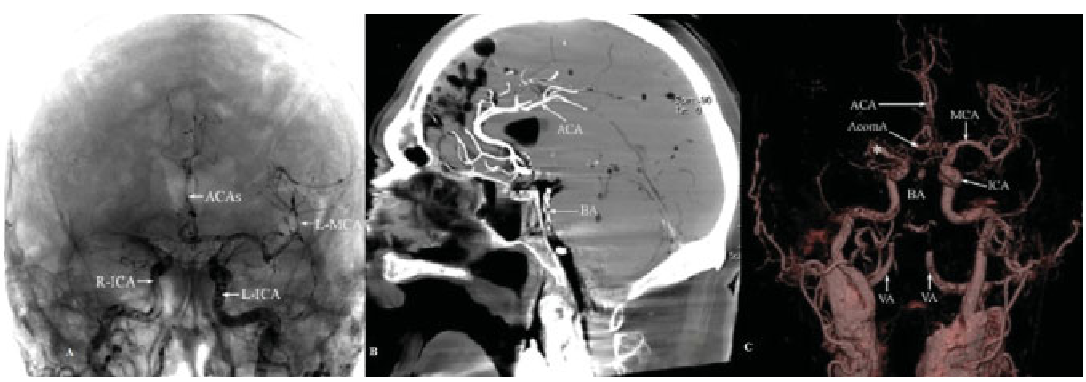

Fig. 3 (A) Anteroposterior conventional X-ray of the silicone with powdered barium injection of the cadaveric head. Note the clumping of the barium within the arteries. (B) Sagittal computed tomography angiography (CTA) imaging of the silicone with powdered barium injection of the cadaveric head. Note that clumping of barium is not seen in this imaging modality. (C) Three-dimensional CTA imaging of the silicone with powdered barium sulfate injection of the cadaveric head. Note that all arteries but the basilar artery are well visualized in this imaging modality. Right middle cerebral artery (MCA) is not filling beyond the M1 segment, which can be used to mimic M1 occlusion. This resulted in no filling of the MCA territory in contrast to the contralateral region. ACA, anterior cerebral artery; AcomA, anterior communicating artery; BA, basilar artery; L-ICA, left internal carotid artery; R-ICA, right internal carotid artery; L-MCA, left middle cerebral artery; VA, vertebral artery; right M1 stump (asterisk).

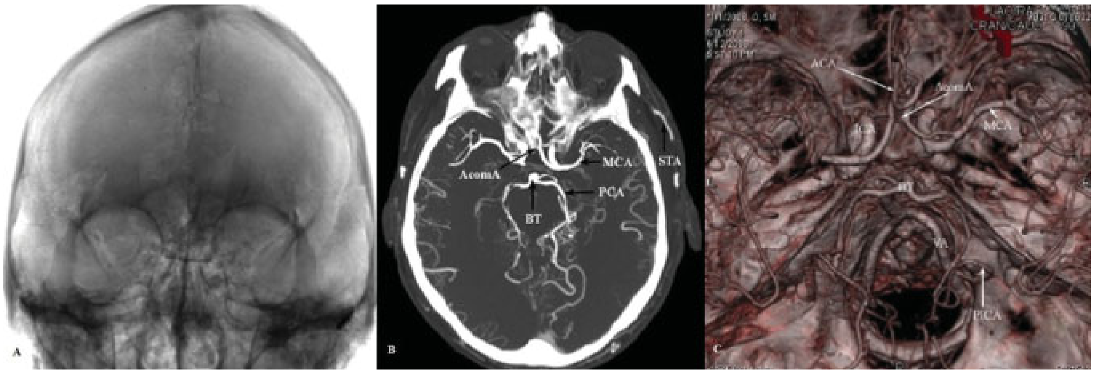

Fig. 4 (A) Anteroposterior conventional X-ray of the silicone with tantalum injection of the cadaveric head. (B) Axial computed tomography angiography (CTA) of the silicone with tantalum injection of the cadaveric head. (C) Three-dimensional CTA imaging of anterior and posterior vasculature and neighboring bony structure of the tantalum-injected cadaveric head. ACA, anterior cerebral artery; AcomA, anterior communicating artery; BT, basilar tip; ICA, internal carotid artery; MCA, middle cerebral artery; PCA, posterior cerebral artery; PICA, posterior inferior cerebellar artery; STA, superficial temporal artery; VA, vertebral artery.

Discussion

Cadaver dissections are an important training tool for understanding and developing dexterity and skills for basic and complex neurosurgical procedures.[8] Traditionally, surgical skills were acquired via an apprenticeship model where the model of "see one, do one, teach one" was the accepted form. However, learning neuroanatomy and microsurgical skills by this model presents some disadvantages during actual neurosurgical procedures. In these cases, time is of the essence, the surgical field is restricted depending on the type of operation, and, most importantly, learning is influenced and limited by the experience of the resident, as well as the ethical responsibilities of the senior neurosurgeon toward the patient. To overcome these problems, animal models and cadaver dissections have been used to practice fine manipulation, dissection, and anastomosis of cerebral vessels.

Computed-assisted imaging techniques allow superior imaging of the nervous system and its blood vessels.[8,12,15,16] Dissections of colored silicone-injected cadaver heads have been effectively used as a method for studying neuroanatomy and neurosurgical approaches.[1,17] Injections of the vascular structures with radiopaque substances such as strontium bromide, lead oxide, sodium iodide, calcium sulfate, mercury, bismuth, sodium bromide, colloidal silver, lead chromate, mercuric sulfide, iodized oils, barium sulfate, and latex have been used previously.[6,18–20] Some of these substances have also been used exclusively for the imaging of the cerebrovascular tree.[21] Zhao et al reported that combining a colored silicone compound with a radiopaque substance included 3D-CT imaging of the cerebrovascular tree of the cadaveric specimens before microsurgical dissection.[14] However, 3D-CT imaging was the only imaging modality described using this technique. The ability to use conventional X-ray imaging for visualization of the vascular tree may widen the use of this technique as a training tool and improve the understanding and correlating capacities of the trainees of angiography and neuroanatomy in departments where there are no advanced imaging modalities such as 3D-CT or dCT.

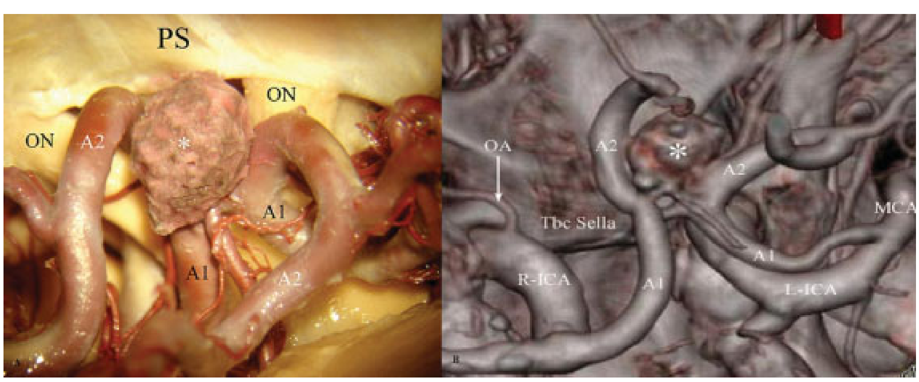

Fig. 5 (A) Three-dimensional computed tomography angiography (3D-CTA) shows the aneurysm with respect to bony structures. (B) Cadaveric dissection of artificially created anterior communicating artery aneurysm. Note the aneurysm projecting superiorly between two A2s. This dissection correlates with angiography in terms of projection. A1, first segment of the anterior cerebral artery; A2, second segment of the anterior cerebral artery; L-ICA, left internal carotid artery; OA, ophthalmic artery; ON, optic nerve; PS, planum sphenoidale; R-ICA, right internal carotid artery; Tbc Sella, tuberculum sella; artificially created anterior communicating artery aneurysm (asterisk).

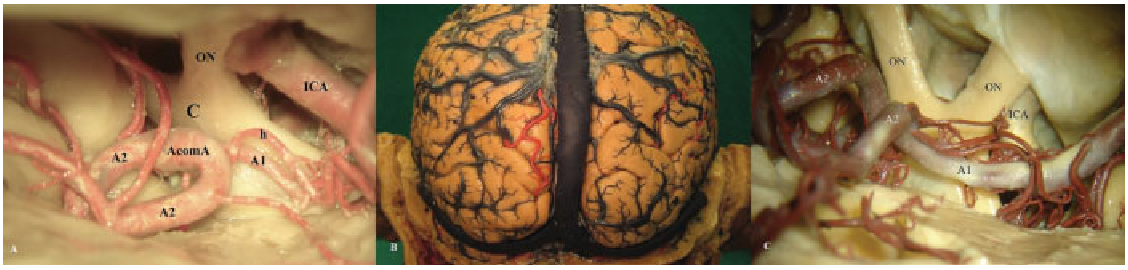

Fig. 6 (A) Dissection of the brain injected with silicone and powdered barium sulfate into the arterial system. Note the white punctuate granularity of the perfused arteries due to white barium sulfate powder. (B) Dissection of the brain injected with tantalum into the venous system. (C) Dissection of the cadaveric head injected with tantalum into the arterial system. Note the black discoloration of the veins and arteries. A1, first segment of the anterior cerebral artery; A2, second segment of the anterior cerebral artery; AComA, anterior communicating artery; C, optic chiasm; h, recurrent artery of Heubner; ICA, internal carotid artery; ON, optic nerve.

We used powder barium sulfate, liquid barium sulfate, and tantalum dioxide due to their wide application in medicine. Powder barium sulfate is a white crystalline substance insoluble in water. It is frequently used clinically as a radio contrast agent for X-ray imaging and other diagnostic procedures. Barium sulfate suspensions are provided by a radiologist in advance of a CT scan to allow for a higher quality CT of the gastrointestinal tract. The suspension is homogeneous and perfectly smooth. With white substances whose densities are similar to that of normal tissue, the volume of the substance alone precludes its visualization based on evaluation of its density. Barium suspension is an excellent alternative to other media for injection of cadaveric brains because of its predictable resistance, deep penetration into small distal vessels, and faster consolidation. X-ray imaging provides some insight into the cerebral vascular anatomy, but postprocessing of 3D images allows rotation of the images in any desired axis thereby improving the understanding of complex vascular relationships. Bony elements can be removed digitally, which enables the surgeon to study the tantalum dioxide commonly used as a density enhancer of a craniotomy plan, potential surgical approaches, and bony drilling scenarios.

Intravascular flow of silicone is one of the greatest technical hurdles in perfusing cadaver heads. Silicone penetration is further limited by the ability to cleanse the vessels prior to perfusion. Our protocols for preparation of the barium and tantalum silicone mixtures resulted in homogeneous pastes with viscosities similar to that of the silicone alone. Achieving the best result meticulous cleaning of the cerebral vasculature is crucial. We recommend cleaning of the cerebral vascular tree while a cadaver is fresh. In this way, a blood clot could be easily removed and consequently achieve better penetration of the perfused material. You may achieve the best result in the visualization of microvascular anatomy with cleaning of the vasculature before fixing the cadaver in alcohol or formaldehyde.

Among the injected material, gelatinized barium was the best penetrating material and gave the best image quality in all imaging modalities. This result was due to two factors. The first was the better clot cleaning technique, and the second was the improved viscosity and homogeneity of the mixture. These advantages made penetration of the smallest vessels possible. The result was satisfactory both in terms of obtaining a relatively consistent barium sulfate/gelatin mixture to allow microsurgical dissection and imaging the cerebrovascular tree to allow sufficient visualization. This cleaning technique and perfusing with gelatinized barium was able to demonstrate fine vasculature and eliminated the formation of clumps of barium visualized as granular densities on the X-ray, CT, and dCT images. We attribute this to the smoothing effects of the postprocessing algorithms. Furthermore, because this technique allowed perfusion of very small arteries, we tested two different colors to demonstrate arterial territories of neighboring vessels. This may allow a better understanding of the vascular territories supplied by different arteries for less experienced residents and fellows training in neurosurgery, neuroradiology, or interventional neuroradiology fields (►**Fig. 7**).

The addition of the adjuvant contrast substances resulted in improved image quality, particularly as it relates to the CT and, to a greater degree, the 3D-CT images

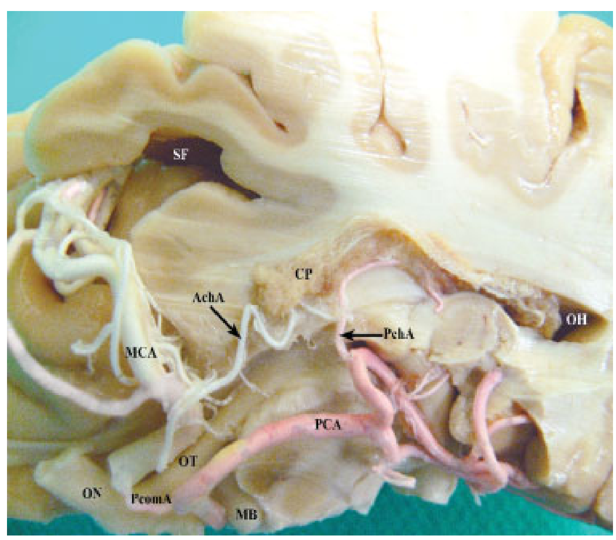

Fig. 7 Cadaveric dissection of the right anterior choroidal artery (AchA) and choroid plexus of a brain in which middle cerebral artery (MCA) and posterior cerebral artery (PCA) were perfused with two different colors (white for MCA, red for PCA) to study collateralization between two different arterial systems. CP, choroid plexus; MB, mamillary body; OH, occipital horn of the lateral ventricle; ON, optic nerve; OT, optic tract; PchA, posterior choroidal artery; PcomA, posterior communicating artery; SF, Sylvian fissure.

(►Figs. 1B–D, 2B, C, 3B, C, and 4B, C). However, the adjuvant contrast substances did alter the integrity of the color of the silicone on gross examination. Barium, which is white, lightened the red and blue in silicone perfusions. This was improved by increasing the concentration of the powder paint. However, the concentration of tantalum in the mixture could not be increased more because it significantly darkened the silicone colors with the current concentration.

Correlation of radiologic and surgical anatomy is often difficult, particularly in the submillimeter environment of microneurosurgery.[9] Neuroradiologists are often forced to make educated guesses on the location of the aneurysm if it is truly intradural or the relationship of a vascular structure to surrounding tissues without the luxury of direct visualization. The main objective of this study was to describe a technique that allows neurosurgery residents to understand and correlate the radiologic and surgical anatomy. We implanted an artificial aneurysm in the anterior communicating artery to imitate common neurosurgical pathology and aneurysms of the AcomA. Studying this specimen with the imaging studies and under direct visualization provides an invaluable tool for understanding and improving the correlation of radiology to actual anatomy. Moreover, a thorough understanding of the projection of an AcomA aneurysm and its relationship to the surrounding structures might be difficult for neurosurgery residents. Performing a cadaveric angiography with an aneurysm, followed by dissection of the same specimen by a neurosurgery resident, would result in better understanding by direct correlation.

The different densities of silicone, gelatinized barium, silicone mixed with powder barium, and silicone mixed with tantalum can be exploited to study the relationships between arteries and veins. This method can also be applied to the study of the cisternal, ventricular, or sulcal anatomy by injecting these mixtures into these spaces. Images obtained from 3D CT and dCT using this method can help neurosurgery residents in their understanding of real anatomy during actual operations. By perfusing cadaveric heads with different colored mixtures in the different anatomical "compartments" of the brain, these relationships may be better understood (►Fig. 7).

There are certain limitations of this study. These procedures may be insufficient for simulating the actual surgical anatomy and its associated challenges because there can be differences between the imaging modalities and the real anatomy. A second limitation may be the variations in the visualization of the fine vessels because the cadaveric heads generally belonged to elderly people, some of them with obstructive cerebrovascular disease.

Conclusion

In this study we demonstrated a method and compared different techniques and perfusion mixtures for studying the cadaveric cerebrovascular tree. This cleaning and perfusion method allows for two-dimensional as well as 3D digital subtraction angiography imaging of the cerebrovascular tree of cadaveric specimens, and it should prove to be a valuable tool for studying cerebrovascular and skull base anatomy, as well as for surgical training. This technique also may provide a preoperative surgical view of vascular pathologies with complex anatomy and locations such as the carotid cave or paraclinoid aneurysms. Overall, cadaveric perfusions and angiography may offer a better understanding of normal and pathologic neuroanatomy for residents and fellows in training by allowing them to create pathology such as an aneurysm with direct visualization, followed by a study of associated angiographic images.

Conflict of Interest
The authors have nothing to disclose.

References

1 Sanan A, Abdel Aziz KM, Janjua RM, van Loveren HR, Keller JT. Colored silicone injection for use in neurosurgical dissections: anatomic technical note. Neurosurgery 1999;45(5):1267–1271; discussion 1271–1274
2 Day JD, Kellogg JX, Fukushima T, Giannotta SL. Microsurgical anatomy of the inner surface of the petrous bone: neuroradiological and morphometric analysis as an adjunct to the retrosigmoid transmeatal approach. Neurosurgery 1994;34(6):1003–1008
3 Aboud E, Al-Mefty O, Yaşargil MG. New laboratory model for neurosurgical training that simulates live surgery. J Neurosurg 2002;97(6):1367–1372
4 Wen HT, Rhoton AL Jr, de Oliveira E. Transchoroidal approach to the third ventricle: an anatomic study of the choroidal fissure and its clinical application. Neurosurgery 1998;42(6):1205–1217; discussion 1217–1219
5 Rhoton AL Jr. The cerebrum. Anatomy. Neurosurgery 2007; 61(1, Suppl):37–118; discussion 118–119
6 Alvernia JE, Pradilla G, Mertens P, Lanzino G, Tamargo RJ. Latex injection of cadaver heads: technical note. Neurosurgery 2010;67 (2, Suppl Operative):362–367
7 de Notaris M, Prats-Galino A, Cavallo LM, et al. Preliminary experience with a new three-dimensional computer-based model for the study and the analysis of skull base approaches. Childs Nerv Syst 2010;26(5):621–626
8 de Notaris M, Topczewski T, de Angelis M, et al. Anatomic skull base education using advanced neuroimaging techniques. World Neurosurg 2013;79(2, Suppl):e9–e13
9 Djulejić V, Marinković S, Maliković A, et al. Morphometric analysis, region of supply and microanatomy of the lenticulostriate arteries and their clinical significance. J Clin Neurosci 2012;19(10): 1416–1421
10 Seoane E, Rhoton AL Jr. Suprameatal extension of the retrosigmoid approach: microsurgical anatomy. Neurosurgery 1999;44(3): 553–560
11 Rhoton AL Jr. The cerebellar arteries. Neurosurgery 2000; 47(3, Suppl):S29–S68
12 Macchi V, Porzionato A, Stecco C, Parenti A, De Caro R. Clinical neuroanatomy module 5 years' experience at the School of Medicine of Padova. Surg Radiol Anat 2007;29(3):261–267
13 Matsumoto M, Kodama N, Endo Y, et al. Dynamic 3D-CT angiography. AJNR Am J Neuroradiol 2007;28(2):299–304
14 Zhao JC, Chen C, Rosenblatt SS, et al. Imaging the cerebrovascular tree in the cadaveric head for planning surgical strategy. Neurosurgery 2002;51(5):1222–1227; discussion 1227–1228
15 Day JD. Cranial base surgical techniques for large sphenocavernous meningiomas: technical note. Neurosurgery 2000;46(3):754–759; discussion 759–760

16 Balogh AA, Preul MC, László K, et al. Multilayer image grid reconstruction technology: four-dimensional interactive image reconstruction of microsurgical neuroanatomic dissections. Neurosurgery 2006;58(1, Suppl):ONS157–ONS165; discussion ONS157–ONS165
17 Katsuta T, Rhoton AL Jr, Matsushima T. The jugular foramen: microsurgical anatomy and operative approaches. Neurosurgery 1997;41(1):149–201; discussion 201–202
18 Wen HT, Rhoton AL Jr, de Oliveira E, et al. Microsurgical anatomy of the temporal lobe: part 1: mesial temporal lobe anatomy and its vascular relationships as applied to amygdalohippocampectomy. Neurosurgery 1999;45(3):549–591; discussion 591–592
19 Bergeron L, Tang M, Morris SF. A review of vascular injection techniques for the study of perforator flaps. Plast Reconstr Surg 2006;117(6):2050–2057
20 Barrs TJ. Overview of radiopaque drugs: 1895–1931. Am J Health Syst Pharm 2006;63(22):2248–2255
21 Salomon G. Microangiographic studies of injected brain specimens in normal and pathologic states. In: Hilal S, ed. Small Vessel Angiography. St. Louis, MO: Mosby; 1973:183–206