Intraoperative digital subtraction neuroangiography: a diagnostic and therapeutic tool.

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Intraoperative Digital Subtraction Neuroangiography: A Diagnostic and Therapeutic Tool

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We report our experience with intraoperative digital subtraction neuroangiography to demonstrate its application as a diagnostic and therapeutic technique. Intraoperative neuroangiography was performed on 53 occasions in 43 patients using a portable imaging system. Thirty-two procedures were performed for diagnostic purposes after resection of arteriovenous malformations, clipping of aneurysms, or carotid endarterectomy. Unexpected problems were disclosed in seven cases and were surgically remedied immediately in four. In addition, angiography was used as a therapeutic tool in 21 cases to facilitate intraoperative embolization of a vascular lesion or to enable the angioplasty of a vessel inaccessible without direct surgical exposure.

We found that by allowing a combined interventional neuroangiographic and neurosurgical approach, intraoperative angiography opened new avenues for treatment of intracranial vascular abnormalities.

The value of intraoperative cerebral angiography in embolization therapy of arteriovenous malformations (AVMs) was first reported by Luessenhop and Spence [1] in 1960. Since then, other reports in both the radiology and neurosurgery literature have stressed the value of intraoperative neuroangiography as a diagnostic and therapeutic tool [2–17]. By allowing the neurosurgeon to intraoperatively visualize the cerebral vasculature after clipping an aneurysm or resecting an AVM, the decision to modify the operative procedure may be made immediately, thereby improving surgical outcome and obviating a repeat surgical procedure [2–6]. The immediate detection of an incomplete AVM resection, an incomplete aneurysm clipping, or the inadvertent clipping of a normal vessel may prevent potentially catastrophic results [7, 8]. Furthermore, intraoperative angiography may facilitate the performance of an otherwise impossible therapeutic procedure such as the selective embolization of AVMs by direct catheterization of intracranial feeding arteries that are otherwise inaccessible by angiographic techniques [9–12].

In the past, most intraoperative neuroangiography was performed by neurosurgeons, either by direct puncture of the carotid arteries or by retrograde surgical catheterization of the superficial temporal artery or other external carotid artery branches [1–9, 12–16]. More recently, interventional neuroradiologists have participated in embolization procedures requiring intraoperative angiography, but catheterization has also depended primarily on either carotid puncture, surgical exposure of the carotid artery, or surgical exposure of intracranial vessels [10, 11]. Images have been obtained in the operating room by using either rapid serial-film angiography or fluoroscopy. Most recently, Bauer [2] reported the development of an imaging system designed for intraoperative angiography that used a mobile C-arm fluoroscopy unit, a high-resolution television camera, and a video camera. Use of this system in 48 cases enabled the depiction and subsequent modification of several incorrectly placed aneurysm clips and incompletely resected AVMs. Although Bauer proposed the development of a digital subtraction angiography (DSA) system, until now there has been only one technical note reporting intraoperative

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cerebrovascular digital subtraction angiography [17]. In that technical note, our preliminary method for intraoperative angiography in a small number of patients was described. DSA offers the advantage of immediate image processing, thereby eliminating delays caused by processing of standard radiographic film. In addition to requiring a lower dose of contrast material, the subtraction technique allows the depiction of blood vessels unobscured by extraneous bony structures or partially radiopaque surgical hardware. We report herein our experiences in 53 cases of intraoperative digital subtraction neuroangiographic procedures. The technique has facilitated intraoperative angiography via a transfemoral approach and has opened new therapeutic options in the treatment of intracerebral vascular abnormalities.

Materials and Methods

From March 1985 to August 1986, 53 intraoperative neuroangiographic procedures were performed in 43 patients at the University of California, Los Angeles, Center for the Health Sciences. Intraoperative angiography was not performed on a routine basis, but instead was applied for diagnostic purposes when the successful surgical treatment of a vascular lesion was questioned, or it was applied for therapeutic reasons when a combined approach of transvascular embolization and surgery was deemed clinically necessary. Studies were performed by using a commercially available portable digital subtraction imaging system (OEC-Diasonics, Salt Lake City). The imaging system consisted of several components: (1) a portable C-arm fluoroscope with 0.3-mm focal spot, 40–120 kV, and 0.5–5.0 mA, with capability of a 20-mA boost; (2) a dual-mode 6- and 9-in. (15- and 23-cm) image intensifier; (3) a high-resolution, low-noise television camera; (4) two 15-in. (38-cm) video monitors, allowing simultaneous display of either two previously obtained images or display of a real-time image alongside a previously obtained image; (5) an image-processing system with real-time subtraction and "road-mapping" capabilities, which allowed the superimposition of a real-time subtracted image upon an angiographic image obtained immediately before; and (6) an image storage system with a hard disk video cassette recorder, and video disk recorder.

The portable system was stored in the radiology department and was transported to the operating room for each case only when the surgery had reached the stage where angiography was imminent. In nearly all cases, the patient had been previously positioned on a radiolucent operating-room table so that fluoroscopy of the aortic arch, neck, and head could be performed. To facilitate cerebral angiography, a radiolucent carbon-fiber head-holder was developed during the investigation and was used in a few of the later cases (Surgeons International, Los Angeles). Of 53 procedures, 30 were performed primarily as diagnostic tests to assess the cerebral vasculature after the clipping of an aneurysm or resection of a vascular lesion. In two instances, the procedure was performed to verify the success of a carotid endarterectomy. In 21 cases, angiography was used as a therapeutic tool in the intraoperative embolization of a vascular abnormality or angioplasty, frequently with a combined approach of intravascular embolization and neurosurgery. In 38 cases, angiography or embolization was performed via a right transfemoral approach. Except in rate instances when a sheath was placed in a femoral artery preoperatively, catheterization of the femoral artery and subsequent selective catheterization of the vertebral and/or carotid arteries was performed in the operating room by the neuroradiologist at the time of the angiogram. When an intraoperative angiogram was anticipated, the right groin was sterilely prepared and draped by the operating-room team before surgery, avoiding the inconvenience of doing this at the time of angiography. A 5-French polyethylene catheter was used in virtually every case in which a transfemoral approach was used.

In 17 cases, angiography was performed via direct surgical exposure and catheterization of a selected vessel, including the common carotid artery (six), middle cerebral artery branches (two), lenticulostriate arteries (two), external carotid artery (one), vertebral artery (one), axillary artery (one), cavernous carotid artery (one), posterior meningeal artery (one), pericallosal artery (one), and cavernous sinus (one). In two cases, both the transfemoral approach and a direct selective arterial puncture were performed. A variety of techniques was used for arterial access in the 17 cases in which the selected vessel was surgically exposed. These included (1) catheterization with a 3- or 5-French polyethylene catheter using the Seldinger technique, (2) direct puncture of the selected vessel with a 21-gauge butterfly needle or a 27- or 29-gauge lymphangiogram needle, or (3) catheterization of the vessel via a small arteriotomy and securing a 2- or 3-French catheter with a purse-string suture.

Catheters were intermittently hand-flushed with a small amount of solution of 5000 units of heparin per liter of saline to prevent thrombus formation. This solution mixed with equal amounts of 60% meglumine iothalamate was used as the contrast agent for angiography.

At the time of angiography, the craniotomy site and the C-arm of the fluoroscopy unit were both covered with sterile drapes. The movable C-arm allowed fluoroscopy and angiography to be performed in multiple planes.

In 17 cases, standard serial film angiograms were obtained within 1 month of the intraoperative angiogram.

Results

Technical Aspects

The portable digital system used for intraoperative angiography proved practical and reliable. In the group of cases in which intraoperative angiography was used primarily as a diagnostic tool to evaluate the success of an endarterectomy or an aneurysm clipping or a resection of a vascular abnormality, the procedure generally required 1–2 hr. When intraoperative angiography was used for a combined intravascular embolization and neurosurgical procedure, the technique required 1–5 hr. In two cases, intraoperative angiography was attempted but aborted, once because of an electrical failure and once because improper positioning of the patient on a radiopaque operating room table obviated fluoroscopy. All angiograms were of diagnostic quality. To avoid radiopaque surgical hardware, unorthodox oblique views were often required. The relatively radiolucent carbon-fiber head-holder was of significant value, since it could be digitally subtracted from the final image without obscuring underlying vessels.

The transfemoral approach of catheterization proved reliable and practical, often enabling the neuroradiologist to work beyond the surgical sterile field. Preparation of the angiographic field, catheters, guidewires, and syringes, and catheterization of the right femoral artery, could therefore be performed without interruption of the neurosurgical procedure.

A few pitfalls were encountered: (1) Puncture of the femoral artery was occasionally quite difficult, given that some patients were hypotensive and positioned in an oblique decubitus orientation. In a few instances when these factors were anticipated, preoperative placement of a 6-French sheath in the right femoral artery proved to be extremely valuable. (2) Fluoroscopy below the upper thorax was generally not possible, requiring "blind" passage of the catheter to the aortic arch. (3) Passage of a catheter directly into a surgically exposed artery sometimes proved to be difficult. In two cases (one lenticulostriate artery and one posterior cerebral artery), repeated attempts to directly enter the arteries led to their thrombosis.

Although few complications occurred in the group of patients in whom intraoperative angiography was performed primarily to monitor an embolization or other transvascular interventional angiographic procedure, no complications occurred in the diagnostic group and there were no complications related to angiography per se.

Diagnostic Procedures

The indications for the 32 intraoperative angiograms performed for diagnostic purposes included evaluation of AVMs after resection (12), a single aneurysm after clipping (nine), multiple feeding-artery aneurysms after clipping and resecting an AVM (two), multiple aneurysms after clipping without associated AVM (two), and the cervical carotid artery after endarterectomy (two) (Table 1). In addition, patency of the left middle cerebral artery in one case was confirmed angiographically after surgical embolectomy of a silicone balloon, which had inadvertently detached prematurely during earlier balloon occlusion of a cervical internal and common carotid artery (performed emergently to treat a carotid hemorrhage caused by tumor invasion). In one case, an intraoperative diagnostic angiogram was obtained after emergent evacuation of a spontaneous occipital hematoma to exclude the presence of an underlying vascular malformation. In another case, intraoperative angiography confirmed successful clipping of a congenital fistulous connection of the basilar artery tip and posterior mesencephalic vein and also confirmed patency of the posterior cerebral arteries and superior cerebellar arteries. In yet another case, surgery was performed to obliterate an internal carotid artery stump (remaining after spontaneous dissection and occlusion of the internal carotid artery), which was responsible for intermittent embolization of the ipsilateral external carotid artery. Intraoperative angiography confirmed obliteration of the stump and patency of the subsequently performed superficial temporal artery–middle cerebral artery bypass. Finally, in one case, intraoperative angiography was used to localize the site of hemorrhage in a large, unresectable deep right hemispheric AVM, enabling resection of this portion of the lesion.

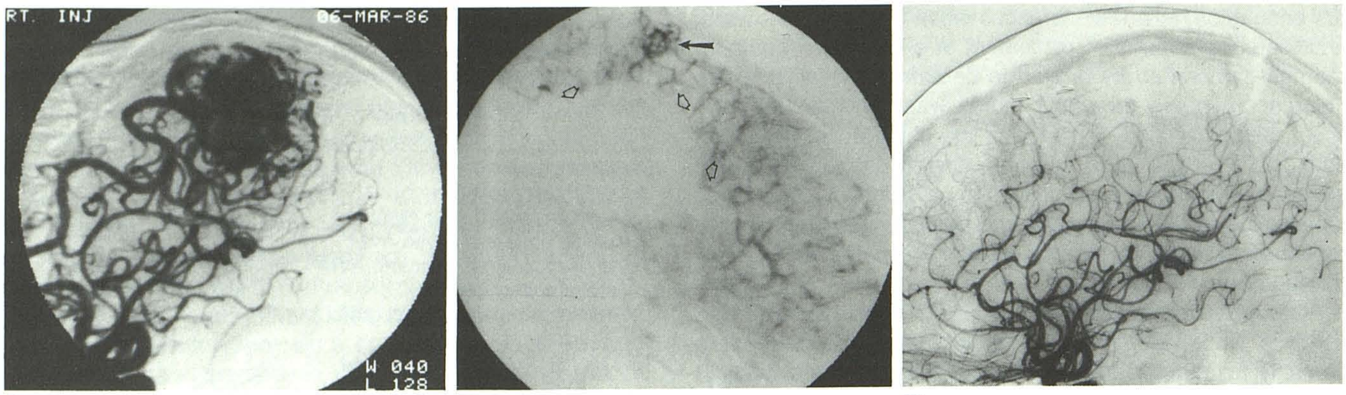
Among the 12 intraoperative angiograms obtained after resection of AVMs, significant findings were disclosed in three. In the first case, a residual right occipital AVM was disclosed, as was slow flow in neighboring normal and feeding arteries due to focal cerebral edema. Because of the severe edema, complete resection was not immediately possible, but subsequent repeat craniotomy led to complete resection of the lesion. In the second case, an unsuspected residual left frontoparietal AVM was disclosed (Fig. 1). Even after immediate reexploration of the region and resection of an additional portion of the lesion, a second intraoperative angiogram continued to disclose a small area of persistent arteriovenous shunting. Further reexploration of the lesion resulted in its complete extirpation, confirmed by intraoperative angiography and subsequent postoperative serial-film angiography. In the third case, intraoperative angiography after resection of a left sylvian AVM revealed unexpected proximal thrombosis of a large middle cerebral feeding branch, confirmed by subsequent reexploration of this vessel. Unfortunately, this situation could not be modified surgically and the patient developed a moderate aphasia. In a fourth case, intraoperative angiography was planned in conjunction with an AVM resection, but could not be performed because of an electrical failure. Postoperative serial-film angiography revealed some residual AVM in this case, requiring a second craniotomy to accomplish a repeat resection.

Of the nine patients undergoing intraoperative angiography after clipping of a single aneurysm, complete clipping of the

TABLE 1: Summary of Indications for Intraoperative Neuroangiography

Type of Study: Indication	No. of Patients	No. of Examinations
Diagnostic:		
AVMs after resection	10	12
Single aneurysm after clipping	9	9
Multiple aneurysms with AVM[a]	2	2
Multiple aneurysms without AVM	2	2
Carotid endarterectomy	2	2
Embolectomy of middle cerebral artery	1	1
Occipital hematoma to rule out AVM	1	1
Confirm clipping of congenital basilar tip fistula	1	1
Confirm obliteration of internal carotid artery stump	1	1
Localize site of hemorrhage in unresectable AVM	1	1
Total	30	32
Interventional:		
Embolization of carotid cavernous fistula	5	5
Balloon occlusion of internal carotid pseudoaneurysm	2	5
Embolization of pial AVMs[a]	5	5
Embolization of dural AVF	1	2
Balloon occlusion of cavernous carotid aneurysm	1	1
Balloon entrapment of cavernous carotid aneurysm	1	1
Subclavian angioplasty	1	1
Basilar angioplasty	1	1
Total	17	21

Note.—AVM = arteriovenous malformation; AVF = arteriovenous fistula.
[a] Four patients in these categories also underwent diagnostic intraoperative angiography associated with final resection of their AVMs.

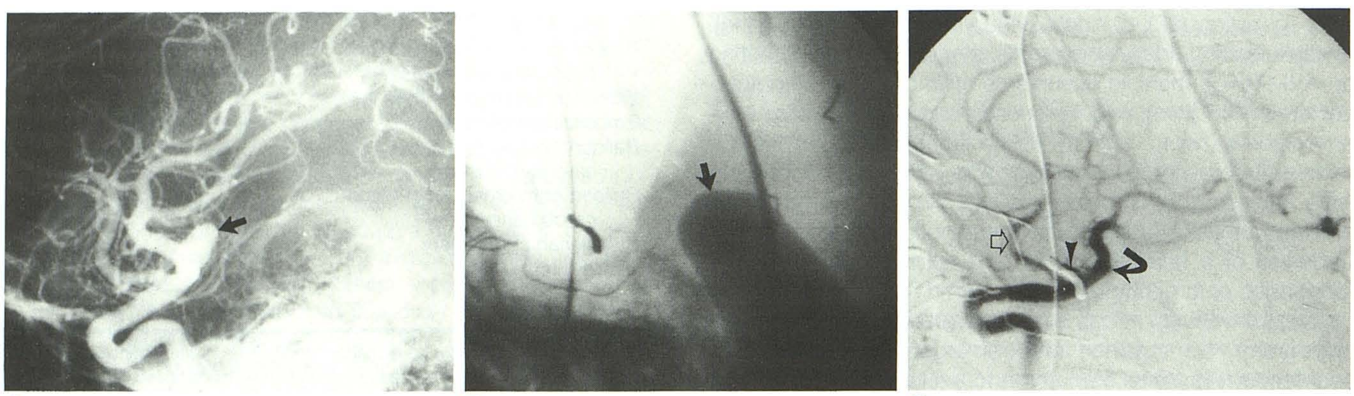


A B C

Fig. 1.—*A*, Preoperative digital subtraction angiogram, lateral projection, reveals large right frontoparietal arteriovenous malformation (AVM).

B, Intraoperative digital subtraction angiogram in same lateral projection. Residual AVM is seen (*solid arrow*), although large area is obscured by radiopaque head-holder (*open arrows*). Immediate surgical reexploration of region confirmed residual AVM, which was then completely resected.

C, Serial-film postoperative angiogram confirms complete resection of AVM.



A B C

Fig. 2.—*A*, Preoperative serial-film angiogram shows aneurysm at internal carotid artery bifurcation (*arrow*).

B, Intraoperative unsubtracted digital image reveals overlying surgical hardware and partly radiopaque head-holder (*arrow*).

C, Digital subtraction angiogram in same lateral oblique projection shows complete clipping of aneurysm (*arrowhead*) and normal filling of anterior (*open arrow*) and middle (*solid arrow*) cerebral arteries.

aneurysm was confirmed in six cases (Fig. 2); in three cases, other significant findings were disclosed. In one of these three cases, a residual portion of a basilar-tip aneurysm was revealed (Fig. 3). Since most of the aneurysm was obliterated by the clip and the difficult surgical exposure of the basilar tip made repositioning the clip unacceptably dangerous, this suboptimal position was accepted. In the second case, slow filling of a large carotid-ophthalmic artery aneurysm was seen. In the third case, the anterior communicating artery was found to be occluded after clipping an anterior communicating artery aneurysm. A brief surgical reexploration revealed marked spasm of the anterior communicating artery, and the vessel was again shown to be nonpatent on a postoperative serial-film angiogram obtained a few days later. While the significance of this finding was not initially appreciated, the patient experienced a second subarachnoid hemorrhage adjacent to the anterior communicating artery 1 month later. Angiography then revealed recanalization of the anterior communicating artery, suggesting that an undetected injury to the vessel caused both the intraoperative spasm and the subsequent hemorrhage when the vessel reopened.

Of two cases in which intraoperative angiography was performed after clipping of multiple aneurysms, a residual aneurysm was disclosed in one. In this patient, preoperative angiography demonstrated four aneurysms arising from the supraclinoid carotid artery. Although the neurosurgeon believed that each had been clipped, intraoperative angiography revealed that one still remained (Fig. 4). An additional clip was placed, and subsequent intraoperative angiography confirmed complete obliteration of the aneurysms. The AVM was resected in a subsequent surgical procedure, with complete resection confirmed by intraoperative angiography.

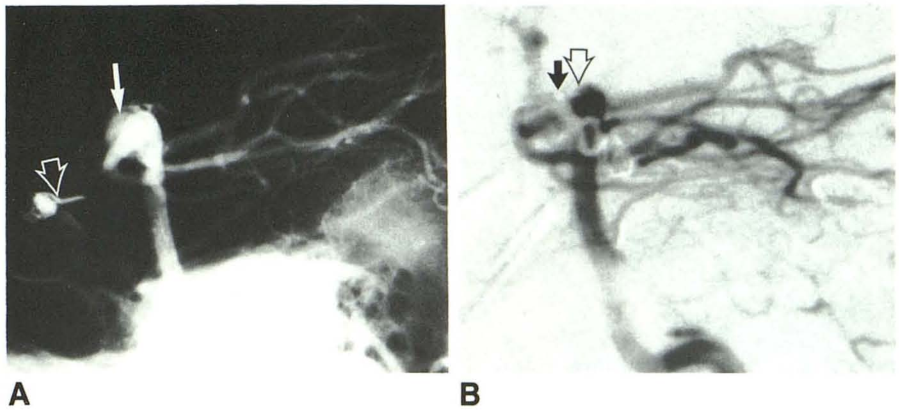


Fig. 3.—*A*, Preoperative serial-film lateral vertebral angiogram reveals basilar-tip aneurysm (*solid arrow*). Surgical clip (*open arrow*) had been placed on posterior communicating artery aneurysm several years before.

B, Intraoperative digital subtraction angiogram reveals placement of clip (*solid arrow*) 3–4 mm ventral to basilar artery tip (*open arrow*), suggesting residual interposed aneurysm neck.

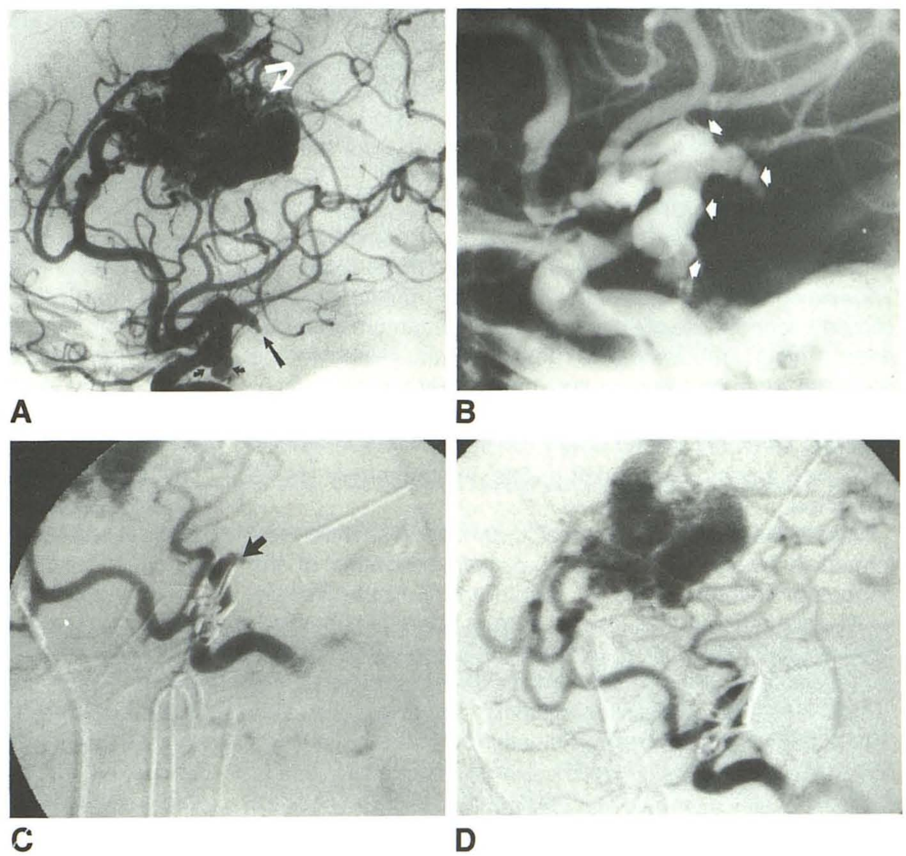


Fig. 4.—A, Preoperative serial-film internal carotid angiogram reveals corpus callosum arteriovenous malformation (*white arrow*) and multiple aneurysms of supraclinoid carotid artery (*black arrows*).

B, Magnified preoperative lateral view of supraclinoid carotid artery shows sites of four aneurysms (*arrows*), confirmed by angiography with multiple oblique views.

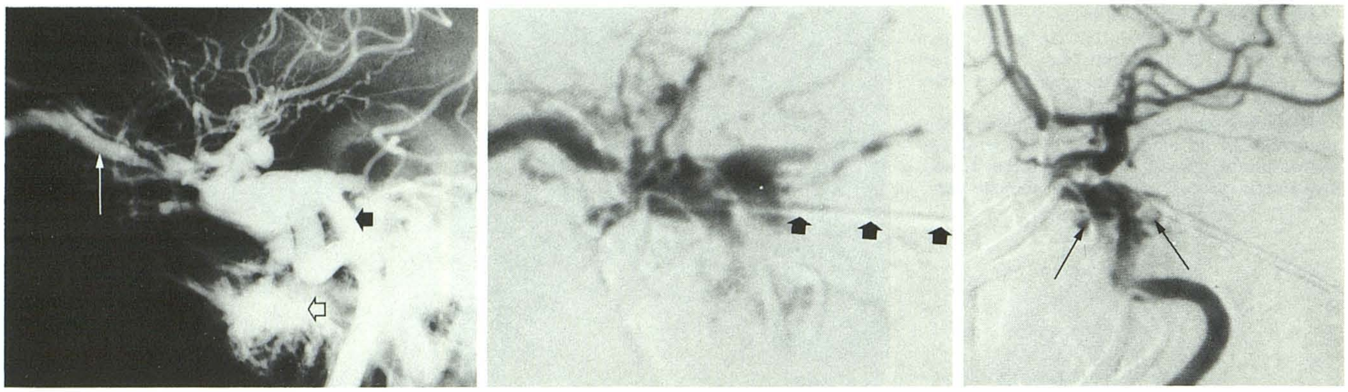
C, Intraoperative oblique lateral internal carotid angiogram via transfemoral approach reveals that one aneurysm remains (*arrow*) after placement of multiple surgical clips.

D, Final aneurysm was then clipped, as revealed by subsequent intraoperative angiogram.

Interventional Cases

Twenty-one intraoperative interventional angiographic procedures were performed for a wide range of indications (Table 1).

In five cases, intraoperative angiography was used in conjunction with embolization therapy of direct carotid cavernous fistulas (CCFs). In three of the five, marked atherosclerotic disease (two) or Takayasu's arteritis (one) prevented balloon occlusion of the CCF via a transfemoral approach. In these cases, direct surgical exposure of the common carotid artery facilitated safe catheterization of this vessel with the relatively large sheath (7.5 French) required to deliver the balloon catheter system. In one case, a CCF was successfully treated by angiographically monitored direct puncture of the cavernous sinus and injection of isobutyl-2-cyanoacrylate (IBCA) into the involved portion of the sinus (Fig. 5). This was considered necessary since numerous attempts at transvascular embolization of the lesion via catheterization of both the carotid artery and the inferior petrosal sinus had been unsuccessful.



A B C

Fig. 5.—*A*, Preoperative serial-film angiogram in lateral projection shows carotid cavernous fistula with drainage into superior ophthalmic vein (*white arrow*), inferior petrosal sinus (*solid arrow*), and pterygoid plexus (*open arrow*). Intraoperative embolization was performed after attempted transvascular embolization via arterial and venous approaches was unsuccessful.

***B*, Intraoperative digital subtraction angiogram through needle (*arrows*) placed in cavernous sinus. Injections of isobutyl-2-cyanoacrylate into multiple areas of sinus were monitored by intraoperative angiography.**

***C*, Intraoperative internal carotid angiogram in lateral oblique projection via transfemoral approach confirms obliteration of arteriovenous shunt, although a few noncommunicating pouches of cavernous sinus (*arrows*) continue to fill.**

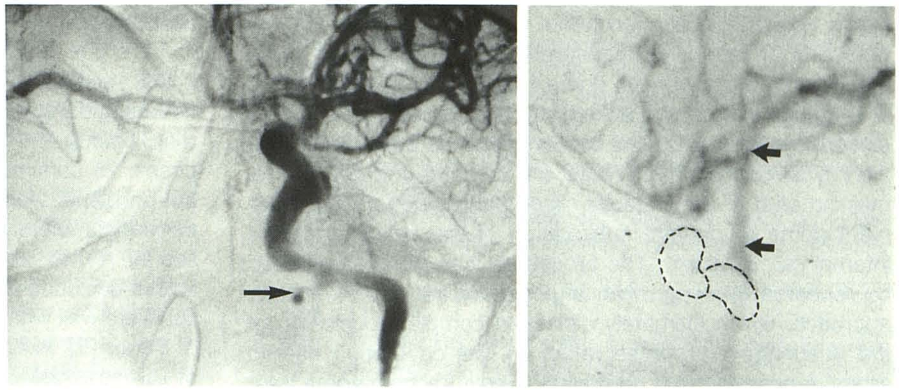
In the fifth case, an emergency diagnostic intraoperative angiogram was requested by a vascular surgeon after thrombectomy of an internal carotid artery with a Fogerty balloon. The angiogram revealed a new direct CCF, presumably occurring secondary to traction placed on the internal carotid artery during embolectomy. The CCF was closed in the operating room by using an angiographically guided detachable silicone balloon placed via catheterization of the surgically exposed common carotid artery. This patient nevertheless developed a postoperative left middle cerebral artery stroke syndrome.

Five intraoperative angiographic procedures were performed in two patients to treat pseudoaneurysms of the petrous or cavernous internal carotid artery. In the first patient, who had a petrous internal carotid artery pseudoaneurysm secondary to tumor invasion, a preoperative balloon test occlusion of the internal carotid artery had resulted in a reversible neurologic deficit, precluding therapeutic occlusion of the internal carotid artery. The patient was therefore taken to the operating room, a bypass from the external carotid to the internal carotid artery was performed, and balloons were placed in the internal carotid artery above and below the pseudoaneurysm (Fig. 6). The second patient had a cavernous carotid artery pseudoaneurysm that extended into the sphenoid sinus. This patient, too, was unable to tolerate test occlusion of the internal carotid artery neurologically. Two separate intraoperative procedures were performed in which temporary balloon occlusion of the internal carotid artery at the level of the pseudoaneurysm enabled surgical treatment of the lesion via a transsphenoidal approach. After each procedure, the pseudoaneurysm recurred, manifested by episodes of epistaxis and documented by serial-film angiography. In a third surgical procedure, intraoperative angiography helped identify a neck of the pseudoaneurysm that the neurosurgeon was able to clip via a craniotomy, despite the location of the lesion within the cavernous sinus. Although the intraoperative angiogram again demonstrated occlusion of the pseudoaneurysm and patency of the internal carotid artery, the lesion again recurred 1 month later. Finally, a superficial temporal artery to middle cerebral artery bypass was performed, followed immediately by intraoperative definitive balloon occlusion of the cavernous internal carotid artery above, below, and at the level of the lesion.

Five AVMs were embolized with intraoperative angiography. In two cases, intraoperative embolization of pial AVMs by direct puncture of feeding vessels facilitated their complete surgical resection. Three unresectable AVMs were embolized by direct puncture of feeding vessels and injection of either polyvinyl alcohol or IBCA (Fig. 7). These procedures, which were monitored by intraoperative angiography, resulted in subtotal obliteration of the lesions.

In one case, a dural arteriovenous fistula of the transverse sinus was completely obliterated by intraoperative embolization. Two separate procedures were performed in this patient, whose external carotid artery had been ligated 25 years earlier. In the first procedure, direct surgical exposure of the external carotid artery above the level of the ligation was followed by intraoperative catheterization and embolization of the middle meningeal artery and posterior auricular artery with IBCA. In the second procedure, a left occipital craniotomy was performed to enable direct puncture and embolization of a posterior meningeal artery branch feeding the fistula, resulting in total closure of the lesion.

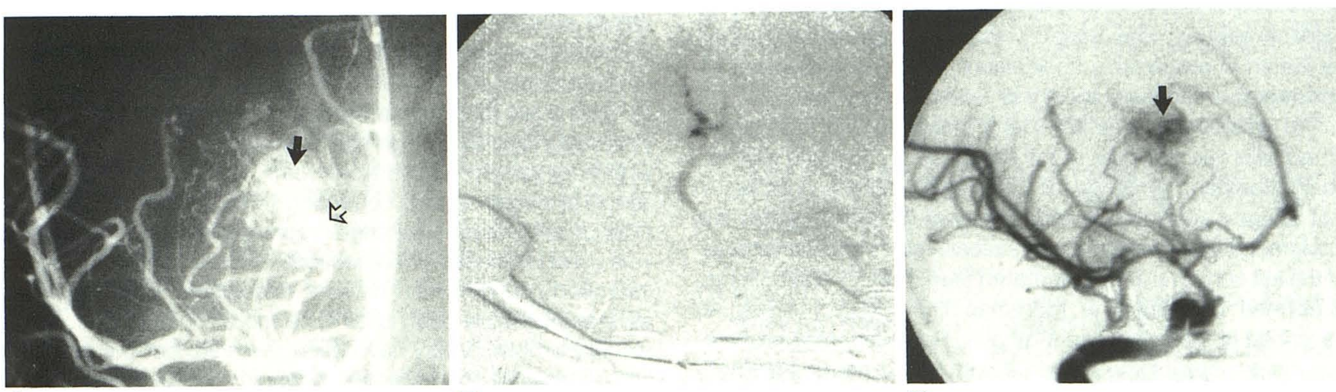
In one case, direct surgical exposure and catheterization of the common carotid artery facilitated balloon occlusion of the cavernous carotid artery above the level of a giant cavernous carotid aneurysm (Fig. 8). Severe atherosclerosis of the aortic arch required a direct carotid puncture rather than a transfemoral approach. The proximal internal carotid artery was then surgically clipped. The procedure was performed in



A B

Fig. 6.—*A*, Preoperative serial-film angiogram reveals pseudoaneurysm (*arrow*) of petrous internal carotid artery. "Test" balloon occlusion of internal carotid artery resulted in left hemispheric ischemic attack, which reversed when balloon was deflated. External carotid–middle cerebral artery bypass was therefore performed, followed immediately by balloon entrapment of pseudoaneurysm.

B, Intraoperative digital subtraction angiogram in lateral projection reveals patent bypass graft (*arrows*) supplying middle cerebral artery branches. Two balloons (*outlined*) are seen in cavernous segment of internal carotid artery. A third balloon in more proximal internal carotid artery is not seen.

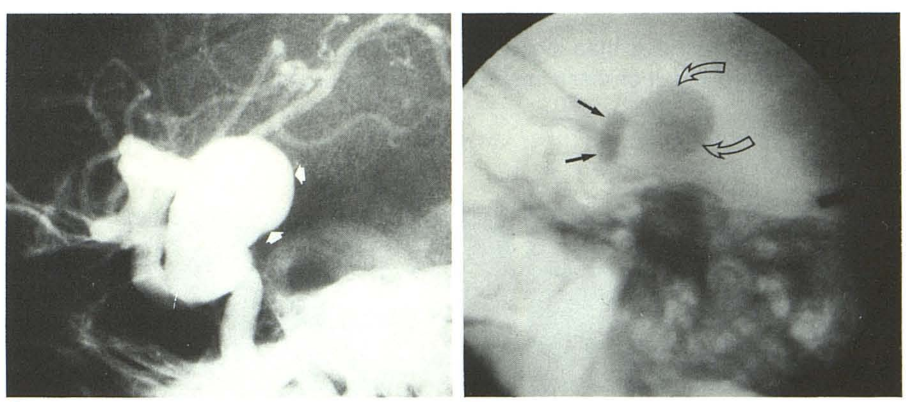


A B C

Fig. 7.—*A*, Preoperative serial-film right internal carotid angiogram reveals arteriovenous malformation (AVM) of basal ganglia (*solid arrow*), which had previously hemorrhaged. Aneurysm (*open arrow*) is identified within malformation.

B, Intraoperative angiogram via selective direct cannulation of lenticulostriate artery with 29-gauge needle. Multiple lenticulostriate arteries feeding AVM were thus identified and embolized with isobutyl-2-cyanoacrylate.

C, Intraoperative right internal carotid digital subtraction angiogram via femoral approach reveals residual AVM (*arrow*), but obliteration of aneurysm.



A B

Fig. 8.—*A*, Preoperative serial-film internal carotid angiogram in lateral projection reveals giant aneurysm (*arrows*) arising from cavernous carotid artery. Severe atherosclerosis prevented balloon occlusion via transfemoral approach. Direct surgical exposure of common carotid artery under local anesthesia enabled intraoperative "test" balloon occlusion of internal carotid artery in awake patient.

B, No neurologic deficit developed after 20-min "test" occlusion. Detachable balloon (*solid arrows*) was then placed distal to aneurysm (*open arrows*), which contains pooled contrast material. Proximal internal carotid artery was then ligated.

an awake patient under local anesthesia so that constant neurologic monitoring was possible. This patient sustained a transient ipsilateral ophthalmoplegia after the procedure.

A unique intraoperative treatment was performed for a large cavernous carotid aneurysm that previously had leaked, causing a well-documented subarachnoid hemorrhage. The patient was unable to tolerate balloon test occlusion of the internal carotid artery neurologically. The broad neck of the aneurysm made selective ballon occlusion of the aneurysm without occlusion of the cavernous carotid artery impossible. Via a craniotomy, the aneurysm dome was directly punctured with a 16-gauge needle and a Fogerty balloon catheter coaxially placed into the lesion. The balloon was inflated and solidified with hydroxyethylmethacrylate, the catheter cut, and the remaining stub of the catheter clipped and glued to the aneurysm dome to prevent subluxation of the balloon into the internal carotid artery. The procedure was greatly facilitated by repeated intraoperative angiography via a transfemoral approach, which ultimately disclosed complete occlusion of the aneurysm and preservation of the cavernous carotid artery. A postoperative contralateral epidural hematoma tragically occurred in this case, eventually leading to the patient's death.

A proximal subclavian angioplasty was performed intraoperatively in a patient with no femoral arterial access and no palpable axillary pulse. Surgical exposure of the axillary artery facilitated intraoperative angioplasty, which was required to perform an emergency axillary to femoral artery bypass.

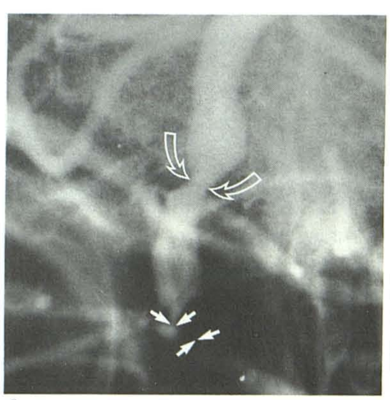
The final patient was an elderly man with two high-grade atherosclerotic stenoses of the basilar artery, causing severe, nearly constant posterior fossa ischemia despite anticoagulant therapy. Attempts at angioplasty of the basilar artery by the femoral approach were not successful. Surgical exposure of the left vertebral artery facilitated basilar artery angioplasty, performed by using the road-map fluoroscopic technique described in Materials and Methods. Road-mapping allowed superimposition of the real-time subtracted image obtained during balloon placement upon a basilar artery angiogram obtained immediately before, thus facilitating precise placement of the balloon. The angioplasty was approached with great concern, but the patient was severely disabled (unable to sit upright without ischemic symptoms), and bypass was not considered feasible. Although the basilar artery was successfully dilated (Fig. 9), the patient sustained a brainstem infarction, presumably caused by obstruction of pontine perforating branches.

No complications other than those summarized above occurred as a direct result of these interventional procedures.

Discussion

Our results indicate that intraoperative digital subtraction neuroangiography is valuable as a diagnostic and therapeutic tool. Among the 32 studies performed for diagnostic purposes, 25 confirmed the success of the surgical procedure, but problems were revealed in seven cases. These included three incompletely clipped aneurysms, two incompletely resected AVMs, an occluded anterior communicating artery, and an occluded middle cerebral artery branch. These findings correlate well with the intraoperative angiograms in the series of Bauer [2], in which clips were incorrectly placed in seven of 33 intracranial aneurysms, and three of 11 AVMs were incompletely resected. Smith [6] also reported residual AVMs in four of seven cases in which intraoperative angiography was performed. The obvious advantage of intraoperative angiography over postoperative angiography is that the detected problem may often be remedied immediately. A better clip position was achieved in two of the three cases in which residual aneurysms were disclosed, and intraoperative angiography led to complete resection of both residual AVMs. Prior reports indicate high morbidity and mortality in patients with incompletely clipped aneurysms, testifying to the significance of detecting and correcting this condition [7, 8]. The diagnostic intraoperative angiography performed in this series was used for most AVM resections, but usually requested by neurosurgeons for only "difficult" aneurysms. Had intraoperative angiography been used on a more routine basis, more surgical problems may have been revealed, but the percentage of "positive" cases probably would have decreased.

An important advantage of the currently available digital angiographic equipment in intraoperative angiography is its ability to provide immediate, subtracted images. This allows the rapid acquisition of multiple angiographic series in various projections without the delay inherent in the processing and subtraction of standard radiographic film [6]. This ability to obtain multiple subtracted series proved to be essential during one of our procedures, in which the bleeding point of a large unresectable AVM was found by angiographically localizing a small collection of extravasated constant medium. This allowed resection of that portion of the large AVM, which has



A

B

Fig. 9.—*A*, Highly magnified anteroposterior serial-film left vertebral angiogram reveals critical stenosis of proximal basilar artery (*solid arrows*) and second stenosis (*open arrows*) distal to origin of anterior inferior cerebellar artery. Attempted angioplasty of basilar artery via transfemoral approach was unsuccessful. Direct surgical exposure of suboccipital segment of left vertebral artery allowed access to basilar artery.

***B*, Angioplasty of proximal basilar stenosis was "angiographically successful," as shown on intraoperative digital subtraction angiogram, but patient sustained brainstem infarction.**

not rebled during a 17-month follow-up period. The ability of the neuroradiologist to work at the femoral site, where he is most comfortable, and away from the operative field probably contributes to the safety and speed of the procedure. No complications resulted from the diagnostic intraoperative angiograms in this series.

As a therapeutic tool, intraoperative neuroangiography opens new avenues for treatment of vascular abnormalities. On the basis of our limited experiences, we have formed several impressions: (1) Surgical exposure of an otherwise inaccessible vessel may facilitate transvascular embolization of carotid cavernous fistulae, AVMs, and aneurysms. This is corroborated by the work of Fox et al. [10, 11]. (2) Transfemoral intraoperative cerebrovascular angiography may be used to guide an intracranial embolization procedure. For example, in our series, intraoperative angiography facilitated embolization of a CCF by direct puncture of the cavernous sinus, balloon occlusion of a large cavernous aneurysm by direct puncture of the aneurysm dome, and surgical exploration of a cavernous carotid artery pseudoaneurysm. (3) In patients who are unable to tolerate a needed therapeutic carotid occlusion neurologically, a combined procedure of extracranial-intracranial vascular bypass followed by internal carotid artery balloon occlusion is both feasible and practical. (4) Direct surgical exposure of otherwise angiographically inaccessible vessels may facilitate an angioplasty procedure.

The neuroradiologist may encounter conditions in the operating room less optimal than those in the angiography suite, requiring imaginative improvisation. While often challenging and time-consuming, intraoperative digital subtraction neuroangiography may be extremely rewarding for all physicians involved and, most importantly, for the patient.

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