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Photoelectronic Radiology

Bruce J. Hillman, Janice R. L. Smith, Gerald D. Pond, Theron W. Ovitt, and M. Paul Capp

Application of the computer to radiological imaging is a relatively new concept, which has become clinically applicable only during the past decade. However, the enthusiasm for and acceptance of these modalities among radiologists and other physicians have spawned increasing avidity for further innovations in computer-based radiological technology.

Our own research program in photoelectronic imaging was catalyzed by an informal 1971 discussion between University of Arizona Professor Sol Nudelman and J. W. Motz of the United States Bureau of Standards (1). Formal work here commenced in 1974 and has recently culminated in the development and dissemination of technology for digital video subtraction angiography. We believe that digital angiography represents a significant development in radiology. Nonetheless, we similarly believe that it is only a precursor to the rapid expansion of the role photoelectronic technology will play in radiology's future.

DIGITAL VIDEO SUBTRACTION INTRAVENOUS ANGIOGRAPHY

Digital video subtraction intravenous angiography is an image enhancement technique designed to amplify low contrast iodine signals to suitable contrast levels for diagnosis of major vascular abnormalities. The image acquisition system consists of a specially designed x-ray image intensifier-video chain with which images are obtained. Images are continuously obtained before and after the intravenous injection of contrast, converted into a digital format via an analog/digital (A/D) converter, and stored. Images before the appearance of contrast are then subtracted from those obtained after so that the resultant image contains contrast only. The image is then electronically contrast-enhanced to demonstrate the final image of arterial structures which are displayed on a video screen (Figure 1). Studies are modern and sophisticated; the underlying principles are not. One of the earliest examples of image enhancement is that of subtraction techniques first used by Ziedses des Plantes (2) in the early 1930s. He applied the use of photographic subtraction to radiography to enhance contrast studies, and it has been a useful and commonly performed procedure since that time.

Intravenous angiography is also not a new technique and was first performed in the 1930s. Robb and Steinberg (3) described, in 1939, their technique for visualization of the chambers of the heart and great vessels. Their procedure consisted of bilateral venous cutdowns, with insertion of 14-gauge needles in the antecubital veins and bilateral hand injection of high volumes of contrast. This produced very satisfactory angiograms of the aorta and major vessels (3). However, it was a time-consuming procedure that never achieved great popularity even though there was a revival of this technique in the early 1950s (4–6). The procedure was at that time somewhat simplified, requiring the use of only a single vein; however, again intravenous angiography enjoyed only a short period of popularity probably because of the rapid advancements in the techniques of catheter angiography.

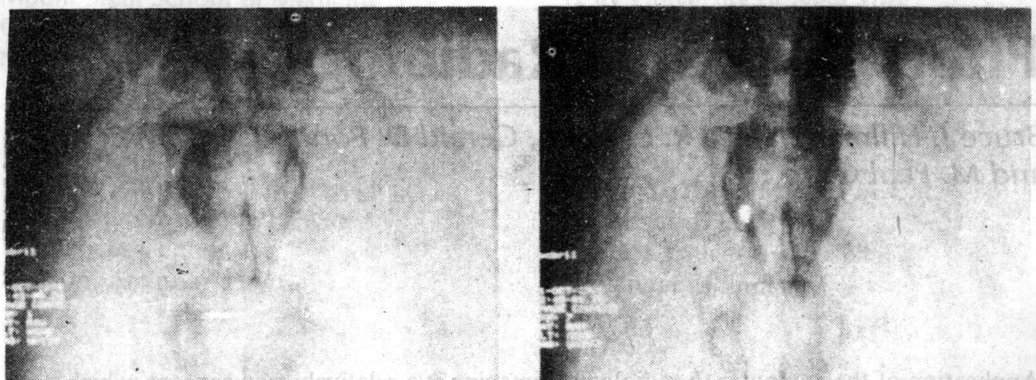


Figure 1. Images exposed on a 27-year-old potential renal donor, demonstrating digital video subtraction. (*A*) Precontrast raw data image exposed 2 seconds following contrast injection but prior to its arrival in the abdominal circulation. (*B*) Postcontrast raw data image exposed 7 seconds after contrast injection. Contrast is faintly seen in the vasculature. (*C*) Subtraction image. (*D*) Enhanced subtraction image suitable for diagnosis.

In the early 1970s, Dr. Charles Mistretta and his group (7), at the University of Wisconsin, started working on energy subtraction to enhance low concentrations of iodine. Using nuclear medicine phantoms, with low concentrations of nonradioactive iodine, he investigated energy subtraction techniques (i.e., x-ray beams of different kilovoltages above and below the K-edge of iodine) to determine if further information could be obtained with planar x-rays. For his image receptor, he was the first to use an image intensifier TV system rather than film. At that time, his images were fed into a subtraction device employing two analog storage tubes. By integrating fluoroscopic images over 1–2 seconds and using subtraction, he was successful in detecting iodine concentrations of approximately 1 mg/cm^3 in thyroid phantoms (7). He later modified his equipment so that the images could be digitized in real time from the output of the image intensifier detector, so that he could begin in vivo iodine imaging.

In 1974, the University of Arizona started work on a completely digital video subtraction unit. This equipment was designed to perform clinical intravenous angiographic studies using sequential temporal subtraction and contrast enhancement techniques (1, 8). Both institutions started experimental clinical work on a limited basis in the late 1970s. The first clinical series reported was by Dr. Peter Christenson at the American Society of Neuroradiology in May, 1979 (9, 10). In 1980, The Cleveland Clinic reported the first large patient series comparing intravenous angiography with conventional arteriography (11, 12). They judged their results to be quite satisfactory and indicated that intravenous angiography was already a major new diagnostic tool.

Within the last year, all major x-ray manufacturers have begun research into or production of digital intravenous angiographic units. In addition, several nuclear medicine companies are providing add-on units for existing radiological equipment. In addition, there have been new variations on the theme of intravenous angiography. Dr. Brody and coworkers (13, 14), at Stanford, have used the scout view system of a computerized tomography (CT) scanner to produce subtraction images of contrast containing vessels (Figure 2). This has been primarily an experimental tool, and it is not presently advocated for clinical use. Ducos de Lahitte and coworkers (15), in France, have reintroduced film subtraction, using intravenous injection techniques for the study of extracranial carotid vessels. Images obtained are satisfactory, except when vessels are superimposed over bone, where film subtraction techniques appear to be not as effective as electronic methods. This may be a major limiting factor of this technique. Dr. Kramann (16), in Germany, has used xeroradiography subtraction techniques for peripheral vessels in the same manner. He has produced some excellent images of the vessels of the legs and arms; again, nonetheless, the major limitation is that of bone subtraction.

Methods of Performance

Our earliest examinations were performed by inserting a short 16-gauge angiocatheter into an antecubital vein and mechanically injecting 76% meglumine diatrizoate, 20 ml/second, for 2

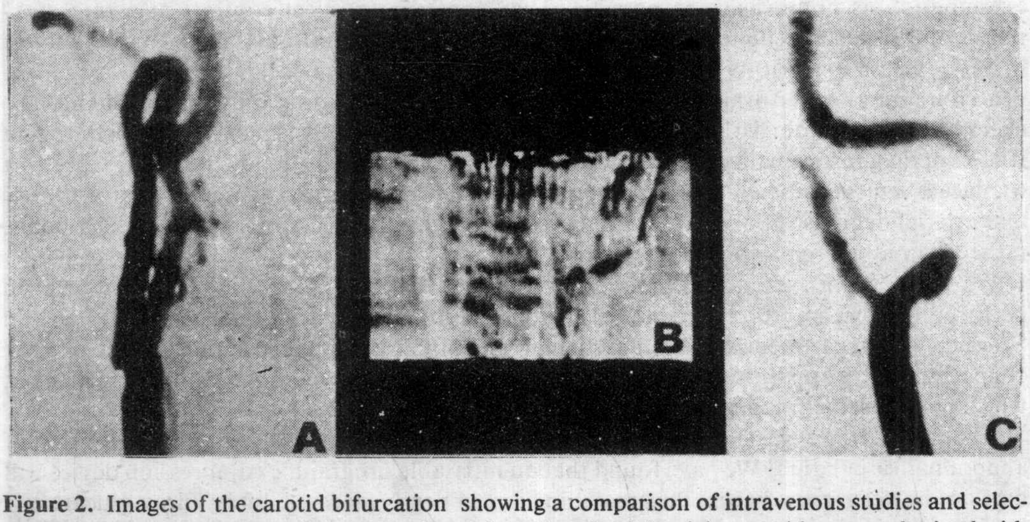


Figure 2. Images of the carotid bifurcation showing a comparison of intravenous studies and selective arteriography by catheter. (*A*) Selective catheter image of the right carotid artery obtained with conventional radiographic subtraction. (*B*) Temporal subtraction image obtained with line-scanned radiography. Diatrizoate was injected intravenously. (*C*) Selective catheter image of the left carotid artery, obtained with conventional radiographic subtraction.

seconds. The result was, in most cases, adequate imaging of the areas of interest; however, in obese patients, or patients with poor cardiac function, images were often unsatisfactory. In addition, 1 patient who had had previous administration of chemotherapy via her antecubital veins suffered venous rupture and extravasation. Fortunately, this resulted in no lasting morbidity. This problem of venous rupture, when contrast is administered from a distal site, has been reported by others (11, 17) and is largely responsible for our developing our current technique.

At present, we first bathe the antecubital fossa with antiseptic solution and drape the region, then numb the skin with 1% lidocaine and insert a 16-gauge angiocatheter. By Seldinger technique, we pass a 7 French (Fr) pigtail catheter with end and side holes into the distal superior vena cava. There follows the mechanical injection of 76% meglumine sodium diatrizoate at a rate of 20-30 ml/second to a maximum of 45 ml per injection. One to five injections, in different projections, are required to complete the examination, depending on the area of interest and indication.

Immediately following injection, we begin exposing images, 1 per second, and continue for 20 seconds. Images are exposed directly onto an image intensifier, then transmitted via a high signal:noise video camera to an A/D converter.

The resultant information is then sent to a digital memory. The computer plays a central role in integrating the functions of our system. It signals the exposure of an image and its snapping into memory. It also controls the process of digital subtraction via an interactive keyboard. All postprocessing is also handled in this fashion. Our system differs in some respects from others, in which digital memories or processors (18) may play a role in subtraction. Finally, finished images are recorded on digital disks and available for video display and postprocessing. Permanent storage is on magnetic tape.

As we have indicated, injection techniques vary among those institutions which pioneered this technology. We have chosen our own method with an eye toward optimizing image quality while minimizing risk. Like us, the group at the University of Wisconsin is now advancing a catheter into a central vein prior to injection. This catheter, however, is smaller than ours (5 Fr), and they administer a more prolonged injection, delivering a similar contrast load (18). Buonocore and coworkers, at The Cleveland Clinic, have focused their efforts on keeping the examination as noninvasive as possible. They continue to inject contrast at a rate of 12 ml/second via an antecubitally-placed 8-inch angiocatheter. Contrast is layered onto a volume of 5% dextrose to assist its transit centrally (19). The advantage of this technique is that the procedure may be performed by nurses or technologists, requiring only that the images be checked by the radiologist prior to the conclusion of the study. Despite this, we believe that studies of diagnostic quality may be more consistently achieved by taking the additional effort to place a central catheter. In addition, our work indicates that intravascular contrast levels and arterial demonstration may be improved by administering contrast as a compact bolus, rather than by more prolonged injection.

We have found several techniques particularly helpful in specialized situations. In performing cervicocerebral intravenous angiography, a head holder, designed by Dr. Joachim Seeger of our department, has been particularly helpful in arresting head motion; the bite bar connected to this apparatus perhaps helps in minimizing the hyoid bone swallowing artifact, which may obscure findings on oblique views.

Abdominal bowel gas motion may be an extreme problem in obscuring demonstration of abdominal vasculature. We have found that an inflatable urographic compression device will displace bowel gas away from the area of interest in nearly all cases. Intravenous glucagon, 1 mg, routinely has been less effective but may have value in examining renal allografts.

Finally, small degrees of ambient patient motion, respiratory motion, and motion resultant of cardiovascular pulsation have all been correctable by a computer software program we have termed "reference shift." Using the interactive keyboard, the radiologist may shift the mask image as needed to improve mask-subtraction image registration. This has been particularly helpful in eliminating confusing artifacts which may masquerade as arterial abnormalities.

Equipment

The equipment for digital intravenous angiography is a combination of x-ray and computer components (Figure 3). The x-ray source should be a high flux, high heat x-ray tube so that relatively short exposures can be performed with sufficient photon flux for cardiac examinations. Calculations indicate that a 1 milliroentgen (mr) exposure to the intensifier face is needed, per exposure, to obtain satisfactory images.

Most of the video systems in use consist of an Amperex frogshead Plumbicon, incorporated into a Sierra camera, optically coupled to the image intensifier. Its most important feature is a high signal output of 2.5 to 3 microamps with a preamplifier noise of 1 to 2 nanoamps, at a 5 megahertz (MHz) video band width, so that there is no degradation of the signal emanating from the image intensifier. In our system, the camera can operate in either the interlaced or noninterlaced mode. This allows images to be obtained with a single snapshot exposure or by the integrated interlaced mode of operation.

The A/D converter is a high speed instrument, capable of 10 megawords per second at 13 bit accuracy. This allows digitization in real time, with 512 x 512 pixels. The image is digitized and then transferred to a digital image storage unit. The digital image store is a memory device that holds the digitized image before it is transferred to either a digital or analog disk. Memories in sequence can be used for real-time subtraction, or they can also be used to integrate images before transfer.

The major limiting factor in the performance of intravenous angiography is the limited size and limited resolution of the image intensifier. Most intensifiers in use for this procedure are

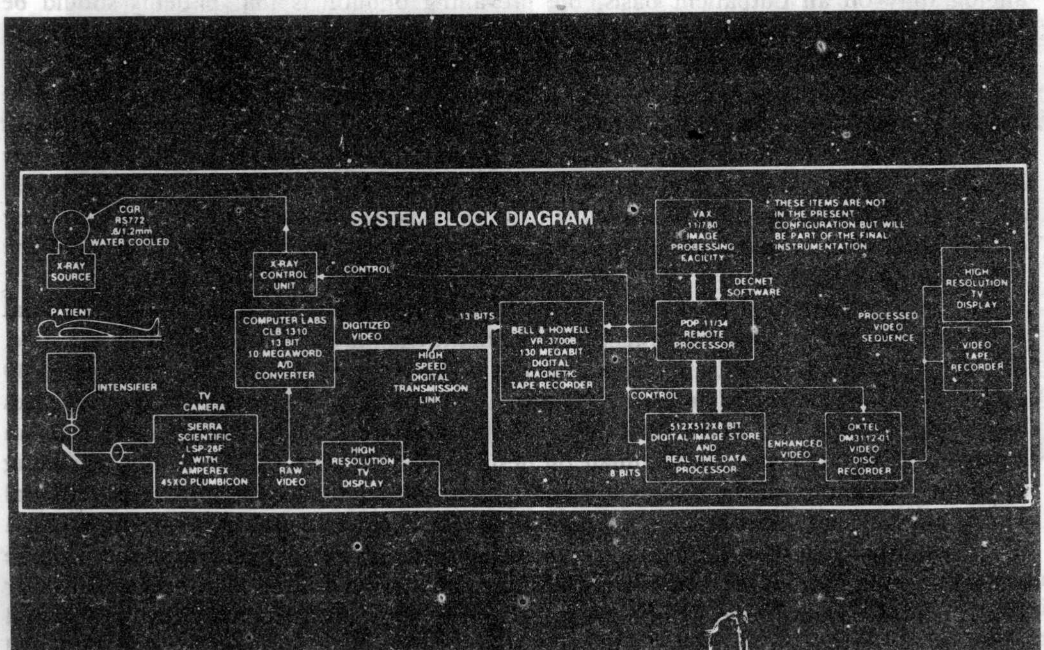


Figure 3. Block diagram of the University of Arizona digital video subtraction angiography system.

9-inch intensifiers. They are scanned by a 512 x 512 television system, at a 5 MHz bandwidth, which limits resolution to approximately 1.8 line pairs at 20% modulation transfer function (MTF). Because the iodine concentrations are relatively low on the arterial side, and there is considerable amplification of this signal, the remainder of the system is designed to add as little electrical noise to the x-ray image as possible. Most systems incorporate a TV camera system with a high signal output to maintain the signal-to-noise obtained with the intensifier. The signal-to-noise ratio from the intensifier is approximately 300:1. Thus, it is desirable to have the television system signal-to-noise considerably higher than this figure to preserve the image. Depending on the system, the image from the television camera is stored either on an analog or a digital disk. Images may be stored in their subtracted form or in their raw data form, then redisplayed and electronically manipulated to obtain a high contrast, high fidelity subtracted image.

Digital Intravenous Angiography of the Head and Neck

The most common request for intravenous angiography related to the circulation of the head and neck involves the evaluation of atherosclerotic disease in the cervical carotid arteries. Various Doppler techniques are reasonably sensitive for the detection of high grade stenoses but falter as the degree of stenosis decreases (20). Real-time and duplex ultrasound (combining real-time and Doppler capabilities) improve the noninvasive diagnostic accuracy, detecting atheromatous plaques, which do not produce significant stenosis and some ulcerations in plaques (21, 22). Unfortunately, these ultrasound modalities are operator-dependent; cannot image intrathoracic, high cervical, or intracranial vessels; and are difficult to utilize in the early postoperative period because of the need for direct application of a contact medium and the transducer in the region of a fresh incision (22). The most definitive diagnostic test currently available is arteriography. In experienced hands, the risks of morbidity or mortality from this study reach a low but irreducible level. While some neuroradiologists will perform cerebral angiography on an outpatient basis, the prevailing opinion is that patients should be hospitalized. Added to the expenses of this procedure are the materials, equipment, and specialized personnel required.

Digital intravenous angiography is an outpatient procedure, which offers an alternative means of studying cervical and cerebral vessels comparable in informational content to an aortic arch injection, but with minimal risk, at a far lower cost (11, 17, 23, 24). In our institution, the intravenous study often has obviated the need for a selective intra-arterial angiogram either by clearly demonstrating that the suspected pathology is not present or by delineating the disease process to the satisfaction of both the neuroradiologist and the requesting physician.

As concerns studies of the cervical carotids, positioning the patient to obtain optimal projections is often the most challenging portion of the examination. At The Cleveland Clinic, the routine is to obtain left and right posterior oblique views, with the patient rotated 40 degrees, and the tube angled another 25 degrees. A third view was performed in 36 of 98 cases and a fourth view in 7 of 98 (25). For our standard cervical studies, we start with an anteroposterior (AP) view, then estimate the desired obliquity for each bifurcation depending upon the appearance of the bifurcation and its position relative to the ipsilateral vertebral artery. Initially, we superimposed the mandible and occiput for the AP run; however, a modified basilar view used for the study of the vertebrobasilar system has shown some promise and may become part of the routine carotid study. Other views utilized for the vertebrobasilar study include a right posterior oblique projection to show the proximal great vessels and vertebral origins and a lateral view of the posterior fossa. For routine frontal intracranial studies, we have used the same projection as Strother and coworkers (24), projecting the top of the petrous ridge into the center of the orbit. Recently, we have returned to the more standard angiographic projection with superimposition of the top of the petrous ridge and the roof of the orbit. Basal views are helpful for evaluation of sellar masses, and oblique transorbital projections have been used for demonstration of anterior communicating aneurysms. Examinations for various tumors, such as chemodectomas and meningiomas, and evaluations of extra-to-intracranial bypasses are generally tailored at the time of the study. A second C-arm on our unit will soon be functional, allowing us to obtain two projections per injection, thereby giving us much more flexibility for our examinations.

Chilcote and coworkers (25) have compared image quality and diagnostic content obtained by conventional and digital intravenous arteriography in studying the common carotid artery bifurcations in 100 patients (Figure 4). Visualization with the intravenous study was good or excellent for both bifurcations in 60%, for one side in 23%, and was poor for both sides in 17%. In 42 of 57 bifurcations poorly imaged, the cause was related to artifact from swallowing or superimposition of the vessels. Other causes were failure to catheterize an arm vein, venous reflux superimposed on the carotid bifurcation, poor contrast density, patient motion, and failure of the power injector (25).

Among the 143 bifurcations with good or excellent images, the diagnostic correlation with conventional angiography was quite good. The degree of stenosis was divided into 7 categories from normal (0) to occluded (6). The grade assigned to each bifurcation on each study was the same or only one category different in 139 of 143 arteries. Also, 4 ulcerations were accurately identified by both modalities. Predictably, there was a significant decrease in the diagnostic accuracy of the 57 bifurcations, which were not well seen, with sensitivity falling from 95% to 54%, specificity from 99% to 79%, and accuracy from 97% to 64%. This controlled

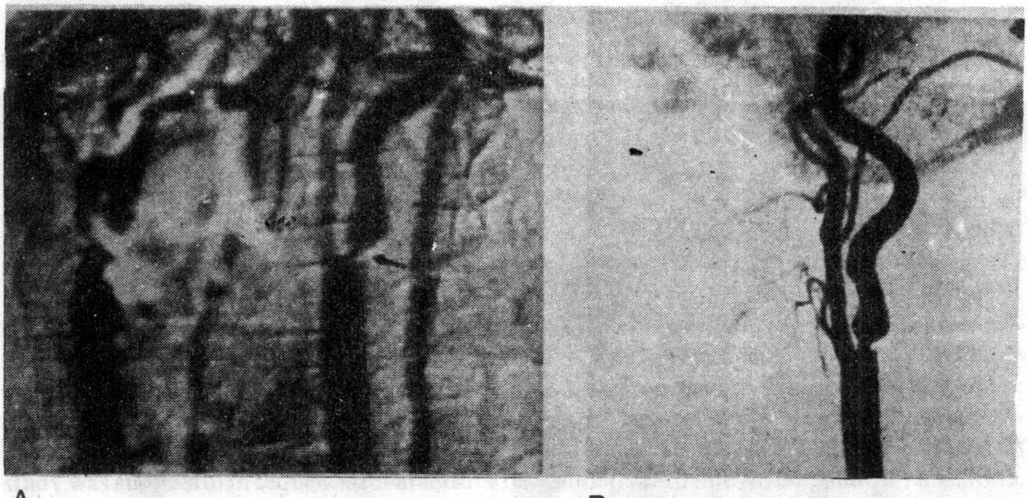


Figure 4. A 68-year-old woman with dizziness had right homonymous hemianopia. (*A*) The right posterior oblique position shows a severely stenotic left internal carotid artery (*arrow*). The origin of the left external carotid artery is normal. The right common carotid artery bifurcation is obscured by a misregistration subtraction artifact caused by the patient swallowing between the mask image and the contrast image. (*B*) Conventional angiography demonstrates severe stenosis of the left internal carotid artery.

comparative study confirms our strong clinical impression that a technically good intravenous angiogram is diagnostically highly reliable.

In our series of 116 neck studies, 101 (87%) were of good or excellent quality. There was motion in 9 cases, low cardiac output in 2, and technical difficulties in 3. In 1 patient, the injection of contrast induced a cough reflex with the resultant motion making the study of no diagnostic value. Ducos de Lahitte and coworkers (26) suggest that contrast kept at a temperature between 10° and 20° C avoids the cough reflex, and we may experiment with this method in future difficult cases. Of our 112 intracranial examinations, 99 (88%) were of good or excellent quality. There was motion in 10 cases, low cardiac output in 2, and both motion and poor output in 1. We have recently been using a head immobilizer designed by a member of our group, and the initial results have been very promising. In this same series, we had difficulty catheterizing the veins of 11 patients. Five patients required more than one venous puncture, because the first vein entered either developed spasm or divided into a plexus of small vessels, which could not be traversed. In the remaining 6 patients, femoral venous punctures were performed. When this was necessary in an outpatient, we simply kept the patient in the department for several hours observation to assure proper hemostasis before discharge.

Seventy-five percent of our neck studies were performed to evaluate the cervical carotid arteries and the regions of the bifurcations in particular (Figures 5 and 6). The technique has also been very helpful in the evaluation of the vertebrobasilar system and proximal great vessels. The vertebrobasilar arteries have been evaluated for atherosclerotic disease, for patency and pseudoaneurysm after trauma, and for follow-up of spasm after a subarachnoid hemorrhage. Studies of the great vessels have demonstrated an aberrant right subclavian artery (Figure 7), 2 instances of occluded proximal left subclavian artery with subclavian steal, and a significant stenotic lesion at the origin of a saphenous vein graft from the left subclavian artery to a branch of the left middle cerebral artery.

A B

Figure 5. Bilateral pulsatile neck masses were noted in this 70-year-old male. Aneurysmal dilatation of both common carotid bifurcations are demonstrated. (*A*) Left posterior oblique view showing the right common carotid artery bifurcation to best advantage. (*B*) Right posterior oblique view showing the left bifurcation.

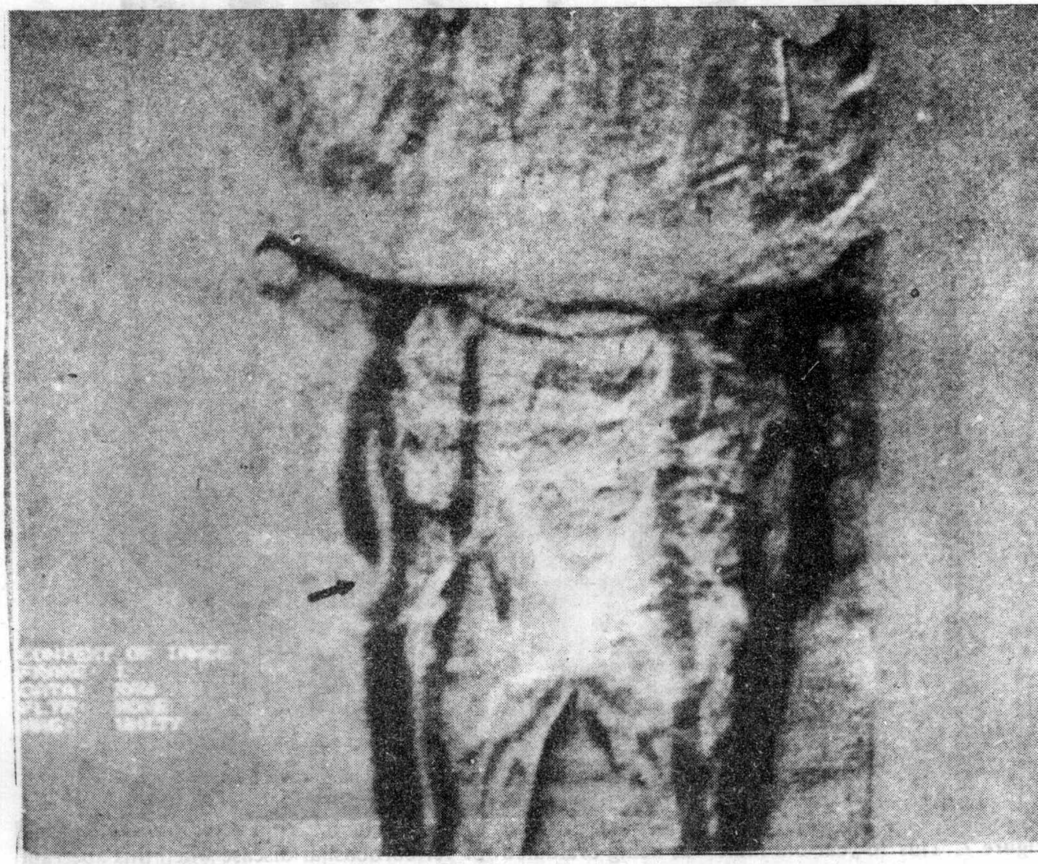


Figure 6. An elderly woman presented with a history of transient ischemic attacks. The digital intravenous angiogram demonstrated a severe stenosis of the right internal carotid artery (*arrow*).

Although occasional examples of intracranial applications have appeared in the work of Chilcote and coworkers (25) and Carmody and coworkers (27), Strother and coworkers (28) from Wisconsin were the first to devote an article to the topic. We have performed 112 intracranial studies to date and share Strother's enthusiasm for the potential of this technique (Figure 8). We have also shared some very similar experiences. Out of the 5 cases they presented, 3 demonstrated aneurysms—1 giant internal carotid artery aneurysm (Figure 9), 1 berry aneurysm of the right middle cerebral artery, and 1 combination of a giant aneurysm of the internal carotid and berry aneurysm of the middle cerebral artery. We have studied 9 patients specifically for intracranial aneurysms. Two patients had normal studies. The intravenous study was successful in sequential evaluations of 3 patients with known berry aneurysms, while yet another was diagnosed with intravenous angiography after it was suggested on a CT scan. Two giant aneurysms were studied—one postoperatively and one both before and after therapeutic thrombosis by copper wire insertion. A CT examination suggested the diagnosis of a thrombosed giant internal carotid artery aneurysm in our ninth case; an intravenous angiogram showed occlusion of the internal carotid artery, and a thrombosed fusiform aneurysm was confirmed at surgery. We have concluded that conventional angiography is still the procedure of choice in evaluation of subarachnoid hemorrhage but that intravenous angiography is an excellent procedure for postoperative follow-up or to further assess CT

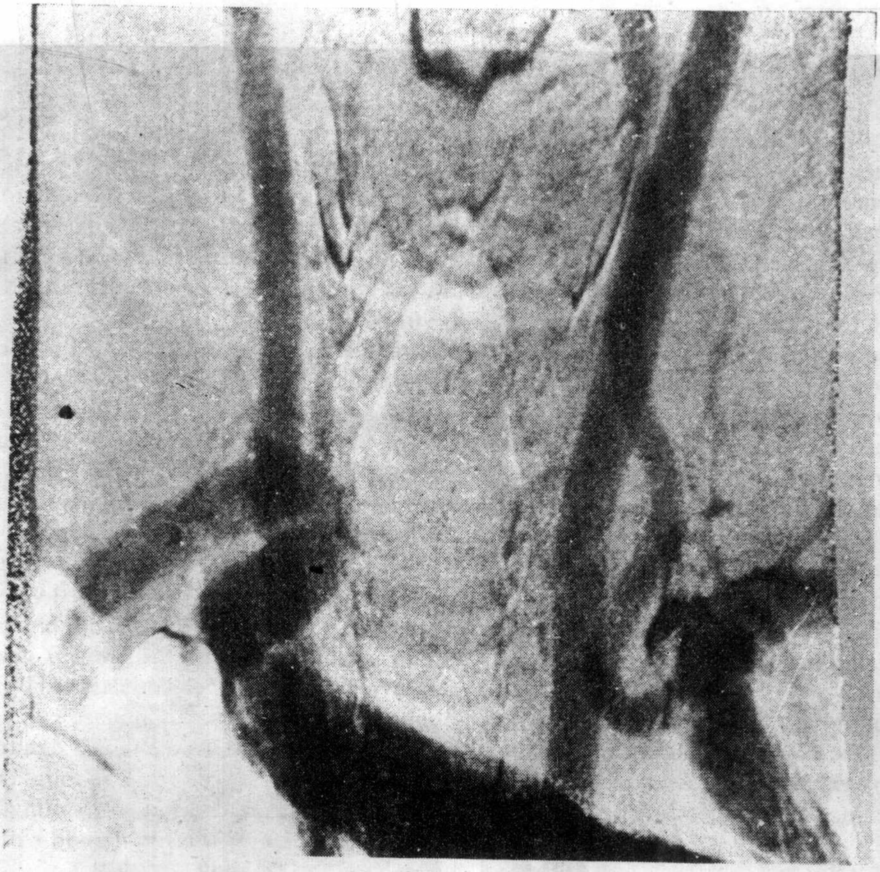
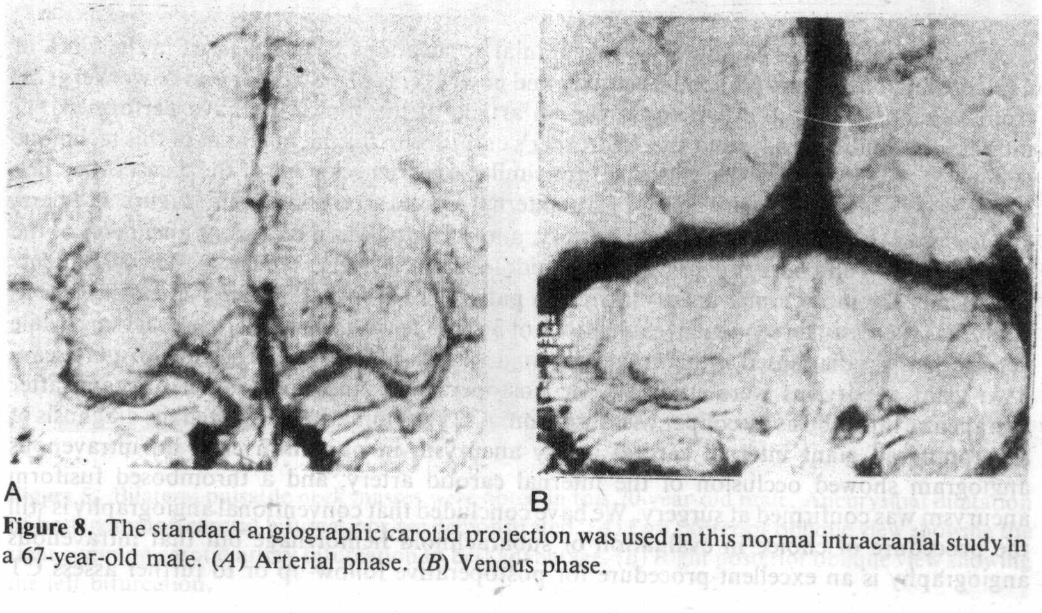


Figure 7. This 76-year-old male was being evaluated for vertebrobasilar disease when this aberrant right subclavian artery was documented. The small right vertebral artery projects just medial to the right common carotid artery. The left vertebral artery is clearly dominant.



A B

Figure 8. The standard angiographic carotid projection was used in this normal intracranial study in a 67-year-old male. (*A*) Arterial phase. (*B*) Venous phase.

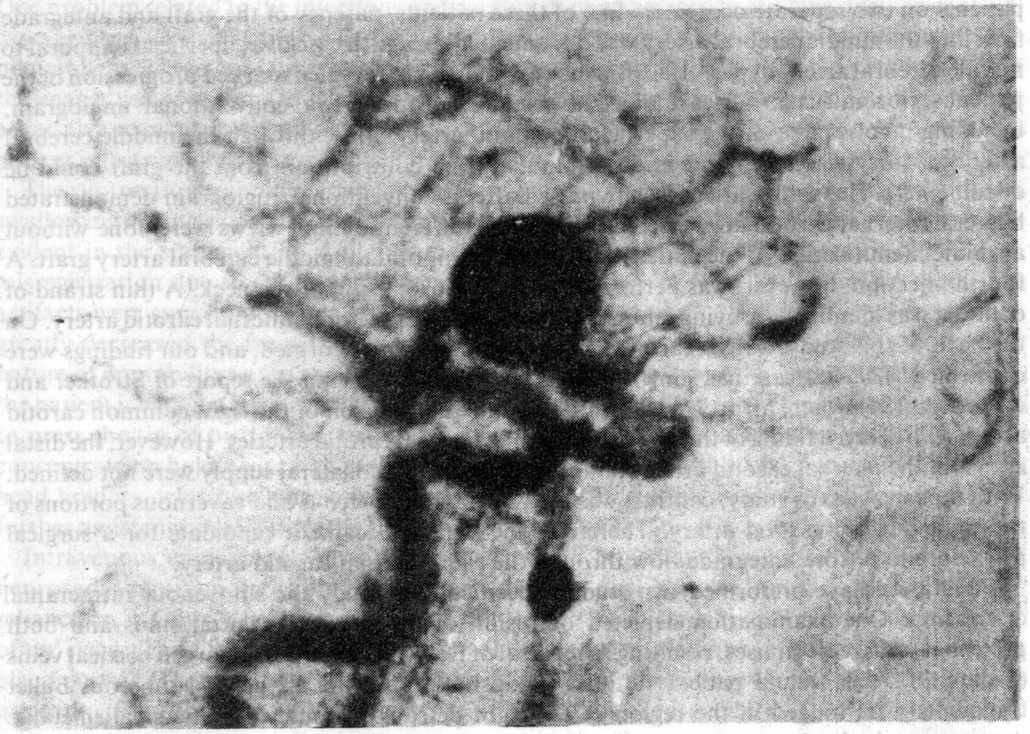


Figure 9. This oblique intracranial projection demonstrates a giant aneurysm at the apex of the left internal carotid artery.

findings, which may be suspicious for aneurysm. This same philosophy holds true for arteriovenous malformations.

Another indication for digital intravenous angiography has been reported by the Wisconsin group. They have shown the value of this technique in demonstrating the relationship of the carotid arteries to the sphenoid sinus and sella before a transphenoidal hypophysectomy (28). Evaluation of 2 of our patients preoperatively for sellar masses has shown some lateral displacement of the cavernous segment of at least 1 internal carotid artery; patency of the cavernous sinuses was clearly demonstrated in 1 case. The vessels of the circle of Willis were also well delineated, with mass effect on one posterior communicating artery seen and later documented at surgery.

We have evaluated 10 other patients for intracranial neoplasms. Six patients were studied for possible glomus jugulare or glomus tympanicum tumors. In the 3 positive examinations, the extent of the lesions and the status of the ipsilateral jugular vein were well documented. One patient with von Hippel-Lindau disease and a sibling of this patient had combined renal and posterior fossa intravenous angiograms as part of their baseline evaluations. Both posterior fossa studies were of excellent quality with no evidence of hemangioblastoma. Intravenous angiograms confirmed the CT diagnosis of meningiomas in 2 patients.

In recent years, neurosurgical techniques have been developed to bypass high grade distal internal carotid artery or proximal middle cerebral artery stenoses by constructing a shunt to a branch of the ipsilateral middle cerebral artery. The superficial temporal artery itself. or a venous graft from the external carotid artery or subclavian artery can be used. We have