Robert R. Edelman, MD • Heinrich P. Mattle, MD • Bernd Wallner, MD • Richard Bajakian, MD • Jonathan Kleefield, MD • Craig Kent, MD • John J. Skillman, MD • Jeffrey B. Mendel, MD • Dennis J. Atkinson, MS

Extracranial Carotid Arteries: Evaluation with "Black Blood" MR Angiography[1]

The authors evaluated the accuracy of "black blood" magnetic resonance (MR) angiography for depicting disease involving the extracranial carotid arteries. Two- and three-dimensional flow-compensated gradient-echo sequences were employed to create "bright blood" images. A thin-section spin-echo sequence with flow presaturation allowed the creation of black blood images. Projection angiograms were made from bright and black blood images with application of a maximum- or minimum-intensity projection algorithm, respectively. These methods were used in 13 healthy volunteers and 17 patients, and a prospective blinded comparison of MR angiography and conventional angiography was performed. Normal carotid arteries were well shown with both bright and black blood methods; in patients, both methods were sensitive for detecting carotid disease. However, bright blood angiography exaggerated the severity of carotid lesions in 13 of 33 arteries, mostly in severe disease; this problem was not encountered with black blood angiography. The authors conclude that bright blood angiography is a sensitive method for screening carotid disease; when a significant abnormality is found, black blood angiography should be performed for more precise delineation of the lesion.

Index terms: Carotid arteries, MR studies, 172.1214 • Carotid arteries, stenosis or occlusion, 172.721 • Magnetic resonance (MR), image processing, 172.1214 • Magnetic resonance (MR), pulse sequences, 172.1214

Radiology 1990; 177:45–50

ATHEROSCLEROTIC disease affecting the carotid arteries is a major cause of stroke. Several imaging modalities have been used for diagnosing carotid artery disease. Conventional angiography is considered the standard of reference but is invasive. Duplex sonography is a good noninvasive method for screening suspected carotid disease but has a limited field of view (FOV), is degraded by calcified plaque, and may not enable the distinction of severe stenoses from occlusions.

Recently, several techniques have been described for creating magnetic resonance (MR) angiograms that depict vessels in a projectional format similar to that of conventional angiograms. MR angiography has been used with some success in the evaluation of carotid artery disease (1–8). In these studies, "bright blood" imaging methods have been used (ie, flowing protons are made to appear more intense than surrounding tissues). However, there are substantial technical problems with bright blood methods. These problems include the exaggeration of stenoses due to flow recirculation and turbulence distal to the stenosis. In addition, very severe stenoses may cause low flow velocities and therefore poor flow contrast.

We report an alternative approach for evaluating the carotid arteries with "black blood' angiography. With black blood angiography, flowing protons are made to appear hypointense, to reduce artifacts created by abnormal flow patterns. In this study, black blood angiography was compared with conventional angiography to determine its accuracy for depicting disease of the carotid bifurcation.

SUBJECTS AND METHODS

All studies were performed at 1.5 T with a whole-body imaging system (Magnetom SP; Siemens Medical Systems, Iselin, NJ). A Helmholtz coil, which conforms to the shape of the neck, was used for signal detection, and the body coil was the transmitter. Thirty subjects were studied. These included 13 healthy volunteers (mean age, 35 years; range, 23–48 years) without any history of carotid artery disease. This group did not undergo conventional angiography and was used for sequence development. In addition, 17 patients (mean age, 58 years; range, 24–77 years) were studied who underwent selective carotid angiography within 1 day of the MR study (14 patients) and within 2, 6, and 17 days (three patients each, respectively). Cut-film or intraarterial digital subtraction angiography (9-inch image intensifier with a 1,024 × 1,024 matrix) was performed in all cases in at least two projections. Studies were performed within the guidelines of the hospital Committee on Clinical Investigations.

Bright Blood Angiography

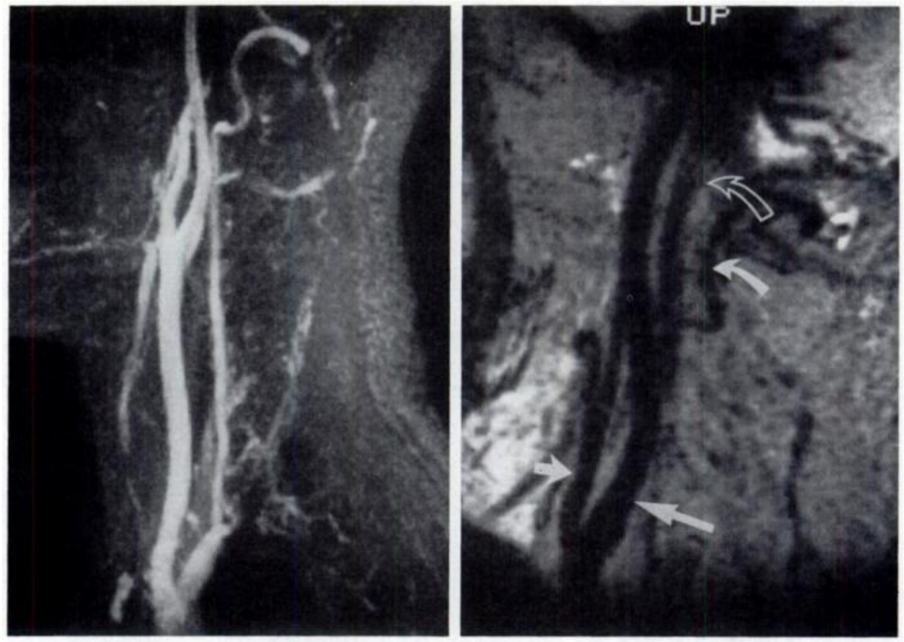
In all subjects, bright blood angiograms were obtained before black blood angiograms. Earlier studies employed a single- or two-slab sagittal three-dimensional gradient-echo (GRE) sequence (six patients). Imaging variables were a repetition time (TR) of 40 msec, echo time (TE) of 8 msec (TR/TE = 40/8), flip angle of 15°, and one excitation for a single slab or 70/8, 25° flip angle, and one excitation for a two-slab acquisition, with a 40-mm slab thickness, 32 partitions, 1.25-mm section thickness, first-order flow compensation, 256 × 192 matrix, and a 23-cm FOV. In two patient studies, a three-dimension-

[1] From the Departments of Radiology (R.R.E., H.P.M., B.W., R.B., J.K., J.B.M., D.J.A.) and Surgery (C.K., J.J.S.), Beth Israel Hospital and Harvard Medical School, 330 Brookline Ave, Boston, MA 02115; Department of Radiology, New England Deaconess Hospital, Boston (H.P.M.); and Siemens Medical Systems, Iselin, NJ (D.J.A.). Received March 15, 1990; revision requested April 19; revision received May 30; accepted May 31. **Address reprint requests to** R.R.E.

Abbreviations: FOV = field of view, GRE = gradient echo, RF = radio frequency, SE = spin echo, TE = echo time, TR = repetition time.

al sequence with an axial excitation and coronal readout was tested. This technique excites only a limited axial volume through the neck, without affecting the great vessels within the chest. As a result, flow contrast is improved. Imaging variables were 40/9, 20° flip angle, one excitation, 10-cm axial excitation volume, double presaturation slabs positioned to eliminate wraparound artifact from the anterior and posterior neck and to reduce jugular venous signal, first-order flow compensation, 256 × 192 matrix, 23-cm FOV, 64 partitions yielding a 1.5-mm section thickness, and an 8.2-minute imaging time for both carotid arteries. In 11 patients, sequential multisection two-dimensional acquisitions were performed. A series of sagittal multisection two-dimensional flow-compensated GRE images were obtained, with three sections per acquisition. Imaging variables were: 72/10, 35° flip angle, two excitations, 3-mm section thickness with a 6-mm intersection gap, and a 256 × 256 acquisition matrix with a 23-cm FOV. Two patients underwent both two- and three-dimensional bright blood angiography.

Bright blood images were postprocessed with a maximum-intensity projection algorithm. A series of projection images were generated and, along with the individual images, were photographed for evaluation.



a. b.

Figure 1. MR angiograms of healthy subjects. **(a)** Bright blood angiogram created from a series of sequential multisection two-dimensional bright blood images (72/10, 35° flip angle, two excitations, 3-mm sections). The left carotid artery is seen from its origin to the base of the skull. The left vertebral artery is also seen from its origin at the subclavian artery to the atlas loop. **(b)** Black blood angiogram postprocessed with a minimum-intensity projection algorithm. Long straight arrow = internal carotid artery, short arrow = external carotid artery, open curved arrow = jugular vein, solid curved arrow = vertebral artery.

Comparison of Results between Bright Blood and Black Blood MR Angiography

Category	No. of Arteries at Conventional Angiography	Bright Blood Angiogram Equal to Black Blood Angiogram	Black Blood Angiogram Superior to Bright Blood Angiogram
Normal	9	9	0
Mild stenosis	5	5	0
Moderate stenosis	5	4	1
Severe stenosis	10	1	9*
Occlusion	4	1	3

* In two arteries, findings at bright blood angiography were falsely suggestive of occlusion of the vessel.

Black Blood Angiography

Several methods were studied in healthy subjects, to create black blood images of the carotid bifurcation. The requirements for these sequences were that (*a*) they produce a uniform signal-intensity void within the carotid artery, (*b*) good contrast be maintained between the vessel and surrounding fat and muscle, (*c*) susceptibility and chemical shift artifacts be minimal so as not to interfere with plaque visualization, and (*d*) imaging times be sufficiently short that gross patient motion is unlikely to occur during the study. The two- and three-dimensional GRE sequences we tested with flow presaturation (9,10) failed to satisfy these requirements and therefore are not described in detail here.

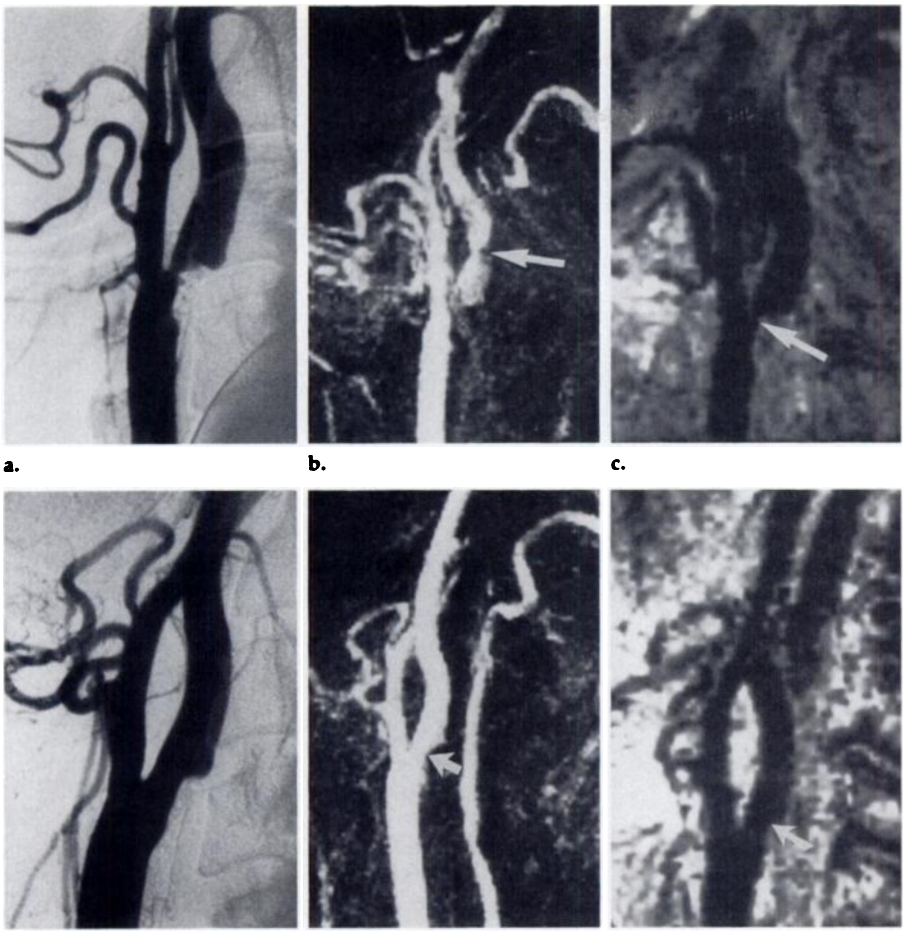
The most effective method tested was a two-dimensional spin-echo (SE) sequence with flow presaturation and thin sections. The use of a thin section exacerbates signal loss from washout, which occurs as flowing protons move out of the section during the time interval TE/2 between the 90° and 180° radio-frequency (RF) pulses. Initial sequence comparisons included variations in section thickness (1.2–2.0 mm), intersection gap (0%–40% of section thickness), and sampling times (7.7 vs 12.8 msec).

The resulting images were judged according to the four criteria listed previously. On the basis of these initial sequence comparisons, imaging variables considered to represent the "optimal" black blood technique were a double-echo SE sequence (1,600/20, 45), two excitations, 7.68-msec sampling time, 256 × 192 acquisition matrix, 23-cm FOV, 6-msec RF pulses with use of computer-optimized section profiles, 1.8-mm section thickness with no intersection gap, and sagittal acquisition with two groups of sections acquired simultaneously and each group centered over a carotid bifurcation. Flow presaturation of the carotid arteries was employed with a 5-cm axial slab applied just caudad to the bifurcation, presaturation selection gradient of 2 mT/m, and a constant spoiler gradient of 8-mT/m amplitude and 5-msec duration. The total imaging time of a study encompassing both carotid bifurcations was 10.2 minutes.

The black blood images were postprocessed with a minimum-intensity projection algorithm implemented on the host MicroVAX II computer (Digital Electronics, Maynard, Mass). This technique is similar to the maximum-intensity projection algorithm that has been previously described (11), except that the most hypointense, rather than the most hyperintense, pixel along a user-defined viewing angle is extracted into the projection image. A series of black blood projection images were generated with viewing angles of −30° to +30° and were photographed along with the individual images for evaluation.

Data Analysis

The studies of the carotid bifurcation were graded as follows: 1 = normal, 2 = mild stenosis of the internal carotid artery (less than 50% diameter reduction in the sagittal plane), 3 = moderate stenosis



a. b. c. d. e. f.

Figure 2. Comparison of bright and black blood angiography. **(a)** Conventional angiogram shows a severe stenosis at the origin of the left internal carotid artery. **(b)** Bright blood angiogram created with the sequential two-dimensional approach shows a lesion at the origin of the internal carotid artery but shows a finding falsely suggestive of a second stenosis more distally (arrow). **(c)** Black blood angiogram more correctly depicts a solitary stenosis (arrow). **(d)** Conventional angiogram in the same patient shows a mild stenosis of the right internal carotid artery. **(e)** Bright blood angiogram accurately depicts the mild stenosis (arrow). **(f)** Black blood angiogram also correctly depicts the stenosis (arrow).

of the internal carotid artery (50%–75% diameter reduction in the sagittal plane), 4 = severe stenosis of the internal carotid artery (more than 75% diameter reduction in the sagittal plane), and 5 = occlusion of the internal carotid artery.

Two authors (R.R.E., H.P.M.) prospectively interpreted the MR studies without knowing the results of conventional angiography. Both the bright and black blood studies were available for this interpretation; the projection angiograms and the individual sections were examined. Two other authors (J.K., J.B.M.) reviewed the conventional angiograms without knowing the results of MR angiography. In each case, the interpretation was made by consensus of the two observers. In one case, after a major discrepancy had been found between the conventional angiogram (which showed a carotid occlusion) and the MR angiograms (which showed a severe stenosis), MR angiography was repeated.

RESULTS

For black blood imaging, GRE sequences were ineffective for creating flow voids, despite the use of presaturation. Lengthening the TE to increase flow-related dephasing resulted in a loss of vessel detail and vessel-muscle contrast. Two-dimensional SE sequences proved effective for creating black blood images (Fig 1). The flow void was maximized with the use of very thin sections and no intersection gap. Because we desired to maintain imaging times of 10 minutes or less and images became noisier as the section thickness was reduced, a section thickness of 1.8 mm was found to represent a good compromise between minimizing partial volume averaging and an adequate signal-to-noise ratio. The sequence with a shorter sampling time was preferred because chemical shift artifact in images obtained with the lower-bandwidth sequence could be falsely interpreted as plaque.

The results of the clinical study are summarized in the Table. All disease found at conventional angiography was detected with MR angiography. In 20 arteries, the bright blood and black blood angiograms helped correctly grade and provide similar portrayals of normal carotid bifurcations and of mild to moderate stenoses (Figs 1, 2). Bright blood angiograms helped detect all stenoses of the internal carotid artery. However, in 13 arteries, only the black blood angiograms correctly depicted the disease, usually in severe stenoses or occlusions (Figs 2–4). The bright blood angiograms in these cases exaggerated the length and severity of the stenoses. In one severe stenosis of the proximal internal carotid artery (Fig 2b), findings at bright blood angiography suggested a second stenosis more distal; this was not shown at black blood or conventional angiography (Fig 2a, 2c). Generally, there was close correspondence between the appearance of the stenosis on the black blood and conventional angiograms.

In two patients, bright blood angiograms failed to demonstrate high signal intensity within the internal carotid artery and falsely suggested occlusion, whereas black blood and conventional angiograms demonstrated a severe stenosis. Bright blood images of another patient with an occluded internal carotid artery showed mildly high signal intensity within the vessel that could be incorrectly interpreted as slow flow. Black blood images showed uniform intermediate signal intensity within the vessel, a finding consistent with thrombus.

In one patient in whom both bright blood and black blood angiography showed severe bilateral stenoses of the proximal internal carotid artery, conventional angiography, performed 4 days later, showed a severe stenosis of the right internal carotid artery and an occlusion of the left internal carotid artery (Fig 4). Because of the discrepancy, a repeat MR angiogram was obtained 2 days later. Both bright and black blood angiography again showed a severe stenosis of the right internal carotid artery but an occlusion of the left internal carotid artery. Black blood images showed thrombus with a peripheral rim of moderately high signal intensity filling the lumen of the left internal carotid artery (Fig 4e).

DISCUSSION

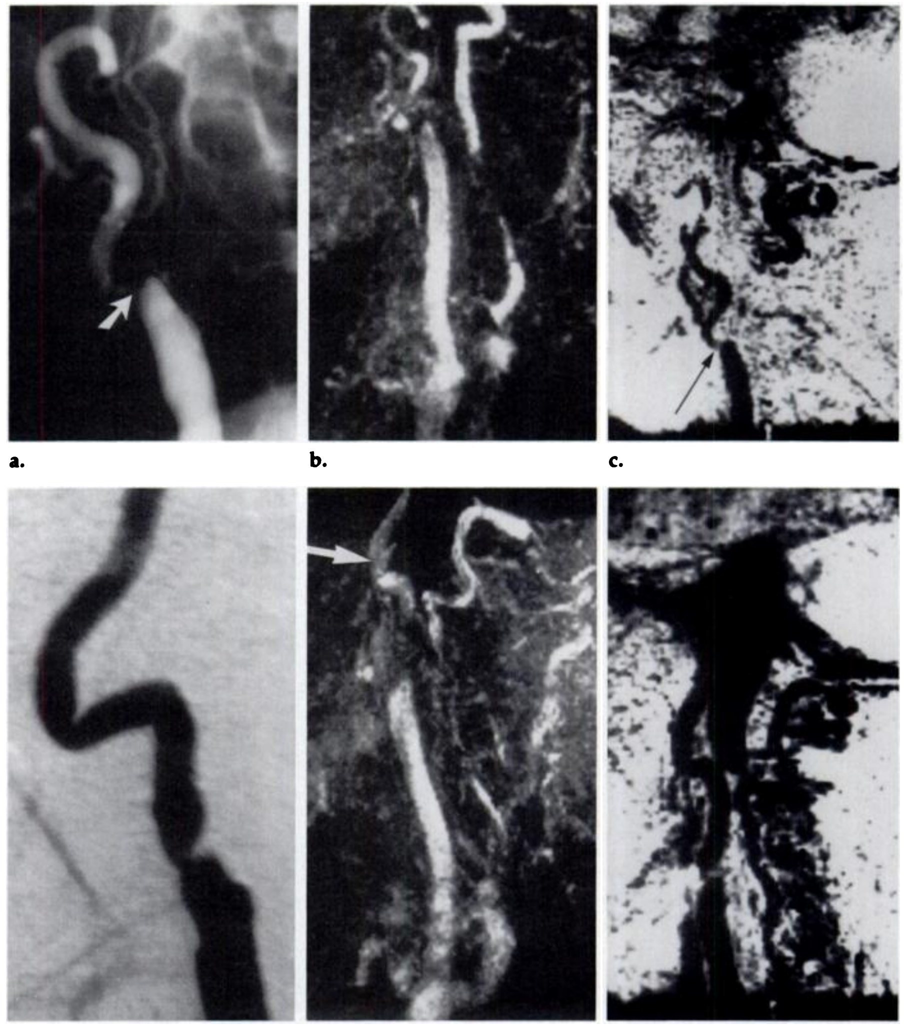
Bright blood angiography is a valuable tool for the depiction of vascular anatomy and function. The technique has proved advantageous for the evaluation of disease involving the intracranial vessels, such as arteriovenous malformations (12,13), aneurysms (14), and venous disorders (15). Recent work has suggested a potential role for MR angiography in the assessment of carotid bifurcation disease (16,17). However, the anatomic depiction of vascular lesions at bright blood angiography is imprecise, especially in severe stenoses, due to signal loss from flow turbulence, recirculation, or (in the case of three-dimensional acquisitions) slow flow.

In our study, bright blood angiography proved to be sensitive for depicting carotid disease in all cases but frequently exaggerated the degree of disease. An alternative approach was therefore developed that creates contrast between the blood vessel and perivascular tissue by rendering flowing blood as a signal-intensity void. We designated this technique as black blood angiography. Black blood angiography has an advantage in that the signal loss produced by flow turbulence does not degrade the images. Also, good flow contrast is preserved even at relatively low flow velocities. In our study, the best technique for producing black blood images combined flow presaturation with an SE sequence and very thin sections. For flow perpendicular to the section, the maximum flow velocity that will result in an observable signal intensity on an SE image is determined by the ratio v_{max} = (section thickness)/(TE/2). For instance, with a section thickness of 1.8 mm and a TE of 20 msec, the washout effect alone will ensure a complete flow void if the velocity is greater than 18 cm/sec. The availability of a second echo (TE = 45 msec) reduces the minimum velocity to 8 cm/sec, although the signal-to-noise ratio is suboptimal in the second-echo images. In comparison, the mean flow velocity measured in the internal carotid artery with Doppler sonography is 36.3 cm/sec ± 8.6 cm/sec (18).

Although the most washout is expected to occur for an axial section, an impractically large number of axial sections would be needed to encompass the carotid artery. Therefore, a sagittal orientation was employed (19).

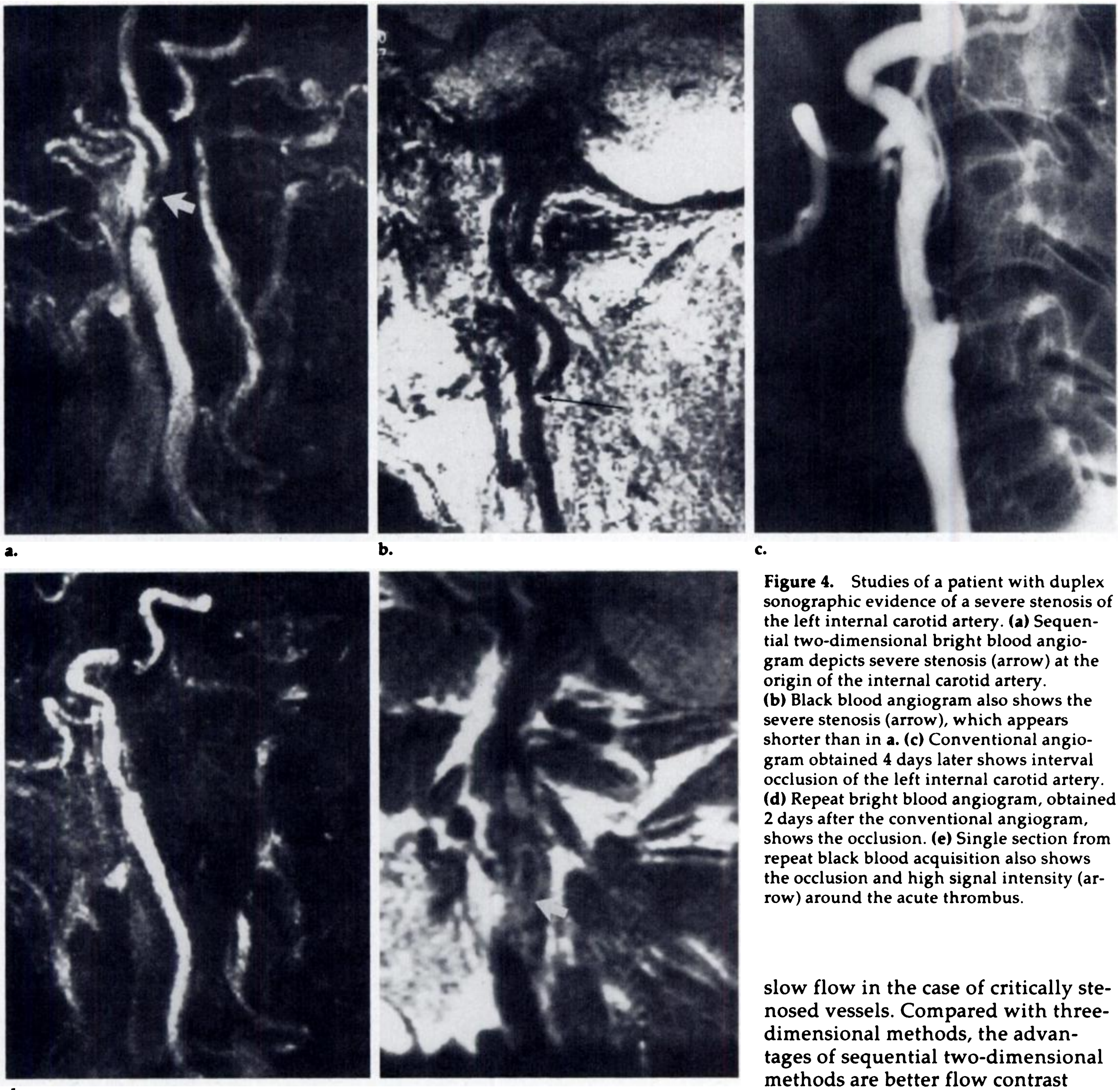
Because of the very thin (1.8 mm) sections, flowing protons are still likely to wash out of the section between the 90° and 180° RF pulses. Signal loss due to flow turbulence generally enhances, rather than degrades, the quality of black blood images, which is particularly relevant in the evaluation of severe stenoses. These factors may explain why the black blood techniques performed better than bright blood techniques in depicting severely stenotic vessels.

Several drawbacks of the black blood technique are also evident. First, the method cannot be applied to portions of the carotid artery that pass through bone (eg, the petrous portion), because of the absence of signal adjacent to the artery. Second, the useful field of view is limited; the bright blood images were much better for studying the common carotid artery. Third, in some projections, overlap of the carotid artery and jugular vein could limit evaluation. This problem is prevented by inspecting the individual black blood images as well as the projection angiograms;



a. b. c. d. e. f.

Figure 3. Studies in a patient with an occlusion of the left internal carotid artery and moderate stenosis of the right internal carotid artery. **(a)** Conventional angiogram of the left carotid artery shows occlusion of the internal carotid artery and stenosis (arrow) at the origin of the external carotid artery. **(b)** Sequential two-dimensional bright blood angiogram demonstrates occlusion of the internal carotid artery, but the external carotid artery is poorly seen at its origin. **(c)** Black blood angiogram shows occlusion of the internal carotid artery and the stenosis (arrow) at the origin of the external carotid artery. **(d)** Digital subtraction angiogram of the right carotid artery shows severe stenosis (approximately 75% reduction in diameter) at the origin of the internal carotid artery and occlusion of the external carotid artery. **(e)** Sequential two-dimensional bright blood angiogram shows reconstitution of flow signal intensity within the internal carotid artery (arrow), consistent with turbulent flow distal to a stenosis. The stenosis, however, is poorly depicted. **(f)** Black blood angiogram shows a severe stenosis at the origin of the internal carotid artery and occlusion of the external carotid artery. The stenosis appears slightly less severe in the individual black blood images (not shown). Both the maximum- and minimum-intensity projection algorithms tend to exaggerate the extent of vascular disease.



a. b. c. d. e.

Figure 4. Studies of a patient with duplex sonographic evidence of a severe stenosis of the left internal carotid artery. **(a)** Sequential two-dimensional bright blood angiogram depicts severe stenosis (arrow) at the origin of the internal carotid artery. **(b)** Black blood angiogram also shows the severe stenosis (arrow), which appears shorter than in **a.** **(c)** Conventional angiogram obtained 4 days later shows interval occlusion of the left internal carotid artery. **(d)** Repeat bright blood angiogram, obtained 2 days after the conventional angiogram, shows the occlusion. **(e)** Single section from repeat black blood acquisition also shows the occlusion and high signal intensity (arrow) around the acute thrombus.

multiplanar reconstructions can also be helpful. When care is taken to exclude the most lateral sections containing the jugular vein from postprocessing, overlap is seldom a problem in the projection angiograms either. Vessel overlap is more easily prevented in bright blood images by presaturating the jugular vein. Finally, there is the possibility that densely calcified plaque could be isointense with flowing blood in black blood images. Nonetheless, all the plaques seen in our study showed intermediate signal intensity and were readily distinguished from the lower-signal-intensity flowing blood within the vessel lumen.

A limitation of our study design was that the methods employed for bright blood imaging evolved over the course of the study, and an optimal bright blood imaging sequence has not yet been devised. For bright blood imaging, we preferred the sequential sagittal two-dimensional approach because imaging times were short and it was sensitive and moderately specific for depicting most carotid disease. The major advantage compared with sequential axial two-dimensional imaging (17) is a shorter study time, since much fewer sections are required. The sagittal orientation uniformly provided good flow contrast when thin sections were obtained. However, axial acquisitions might be better for detecting very slow flow in the case of critically stenosed vessels. Compared with three-dimensional methods, the advantages of sequential two-dimensional methods are better flow contrast (particularly in the setting of low flow velocities [20]) and less sensitivity to patient motion for the individual sections.

Three-dimensional sequences have the dual advantages of shorter TEs and smaller voxels (due to the thinner sections), so there is less signal loss from flow-related dephasing. Masaryk et al (16) obtained good results with a sagittal three-dimensional sequence by imaging their patients in a 30-cm-diameter, transmit-receive-mode, linearly polarized head coil. Since inflowing spins beyond the limit of the head coil are not affected by the RF pulses, flow contrast is generally adequate. Our experience with the linear head coil for carotid bifurcation imaging has been disappointing, because the bifurcation is not consistently positioned within the imaging volume of the coil in large patients or those with short necks. Also, the common carotid artery is poorly visualized. Therefore, we used a Helmholtz receiver coil with the body coil as transmitter. To overcome the saturation effects encountered with three-dimensional sequences, we tried a three-dimensional sequence with use of an axial excitation and coronal read-out. However, the resulting coronal images were suboptimal for interpreting carotid stenoses; also, the studies tended to be degraded if the patient swallowed. We currently supplement the sagittal sequential two-dimensional sequence with an axial three-dimensional sequence; this combination appears promising.

A final point is that projection angiograms created with the maximum-intensity projection algorithm show a loss of vascular detail due to random noise propagation (21). We have found this to be true of the minimum-intensity projection algorithm as well. Therefore, inspection of individual images is required for the most precise results. The projection angiograms are nonetheless useful as an overall guide to vascular anatomy, particularly for the clinician.

In conclusion, bright blood angiography is a good screening method and accurately portrays normal bifurcations and mild stenoses. Compared with bright blood angiography, black blood angiography provides more accurate depiction of severe carotid stenoses and plaque morphology. Bright and black blood angiography are complementary methods; the latter method should be employed when findings on the bright blood angiogram are suggestive of moderate or severe disease. The combination of these methods provides an accurate depiction of disease affecting the extracranial carotid arteries. ■

Acknowledgments: We are indebted to Gerhardt Laub, PhD, of Siemens Medical Systems, Erlangen, Federal Republic of Germany, for assistance in pulse sequence development, and Mark Haacke, PhD, of Case Western Reserve University, Cleveland, for helpful discussions.

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