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Intracranial Vascular Stenosis and Occlusion: MR Angiographic Findings

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PURPOSE: To investigate whether obtaining axial source images from three-dimensional Fourier transform (3DFT) time-of-flight MR angiography improves the detection of intracranial vascular stenosis and occlusion if added to maximum-intensity projection (MIP) images. **METHODS:** The angiograms of 103 patients who had MR angiography for evaluation of possible intracranial vascular disease were reviewed retrospectively in a quantitative and nonquantitative fashion. Diameters of vessels on MR angiograms were measured quantitatively by two reviewers using a magnifying loupe and compared with the results from conventional angiograms. Degrees of stenoocclusive disease were categorized into five classes; an artery with stenosis of 50% or greater was considered to be diseased. Another five observers also reviewed the MIP images with and without source images in a blinded fashion by means of nonquantitative visual inspection. **RESULTS:** In all, 23 stenoocclusive lesions of 50% or greater were available for review. In the quantitative analysis, with MIP images alone, 14 (78%) of 18 moderate and severe stenoses and four (80%) of five occlusions were identified correctly. The addition of the source images increased the sensitivity to 100% for moderate and severe stenoses and to 100% for occluded vessels. In the visual inspection study, however, no statistically significant differences were found between interpretations of MIP images alone and those of MIP images in combination with source images. **CONCLUSION:** In the quantitative study, interpretation of source images rather than MIP images reduced the tendency to overestimate stenosis seen with MR angiography and improved the sensitivity for detecting stenosis of 50% or greater. There was a discrepancy between the quantitative study and visual inspection. Experienced observers had a tendency to underestimate the degree of stenosis.

Index terms: Arteries, stenosis and occlusion; Magnetic resonance angiography

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Magnetic resonance (MR) angiography offers a noninvasive means to evaluate vascular disease without the use of contrast agents. Recent studies have documented the clinical efficacy of two- and three-dimensional Fourier transform (2DFT and 3DFT) time-of-flight MR angiography in the evaluation of narrowing of the carotid artery bifurcation (1–5). Despite the good correlation of MR angiography and conventional angiography in depicting extracranial vessel disease, a consistent overestimation of stenosis on maximum-intensity projection (MIP) images has plagued MR angiography (6). In several recent reports (5–7), when the source images were read in combination with projection images, the residual lumen appeared wider, resulting in significantly increased accuracy.

Clinical application of MR angiography in intracranial stenoocclusive disease has been limited (8–11). To our knowledge, no studies have systematically evaluated the accuracy of MR angiography with both MIP and source images in depicting intracranial stenoocclusive disease. We hypothesized that the source images would

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depict the low-contrast, flow-related enhancement seen at the margins of the vessels better than standard MIP images and that the vessel margins would be better defined on the source images, improving the ability to measure arterial stenosis.

The purpose of this study was to compare the diagnostic accuracy of 3DFT time-of-flight MR angiography with that of conventional angiography in the identification of intracranial stenoocclusive disease and to investigate whether axial source images improve the detection of intracranial vascular stenosis and occlusion if added to MIP images.

Materials and Methods

Study Group

The imaging findings of 103 patients who had had MR angiography within 1 month of conventional angiography for evaluation of possible intracranial vascular disease were reviewed retrospectively. The patients were studied on a standard superconductive MR imaging system operating at 1.5 T. A spoiled GRASS (gradient-recalled acquisition in the steady state) sequence was used in axial orientation with the following parameters: 45/4.9/1 (repetition time/echo time/excitation), 25° flip angle, 32-mm slab thickness, 64 partitions, 14-cm field of view, 128 × 256 matrix size, and 6 minute 10 second acquisition time.

The angiographic findings were normal in 19 patients, showed aneurysms in 60 patients, and depicted vascular stenoses or occlusions in 28 patients (four patients had both an aneurysm and stenosis). Seventy-five patients, consisting of those with angiographically normal findings and those with aneurysms only, served as the control group.

The axial source images were postprocessed by means of the MIP algorithm to produce multiple projections rotated about the section axis. Both the MIP and source images were reviewed on hard-copy films (film size, 43 × 35 cm) after they were reviewed at the MR console so that optimal windows could be selected to better assess the aneurysms and occlusive lesions. Twelve MIP images (11 projection images and one axial “collapse” projection image; image format, 12 on 1) and 24 source images (image format, 24 on 1) were reviewed on each hard copy. All MIP images were arranged so as to be seen stereoscopically.

Conventional arteriography was performed via femoral artery catheterization using the film-screen technique. In one patient, only one carotid artery was examined for clinical reasons.

Reviewing Methods

Conventional Angiography.—The presence or absence of stenoocclusive disease and its grading were established by consensus of two experienced reviewers (who did not participate in the blinded MR angiographic study) using the conventional angiograms as the standard. For the conventional angiographic studies, anteroposterior and lateral images from the selective carotid injections were supplied. Diameters on the conventional angiograms were measured with a ×10 magnifying loupe with 0.1-mm divisions. The projection that showed the greatest stenosis was chosen.

The degrees of stenoocclusive disease as determined quantitatively from the conventional angiograms were categorized into five classes: normal (0% to 29% diameter stenosis), mildly stenotic (30% to 49%), moderately stenotic (50% to 79%), severely stenotic (80% to 99%), or occluded. Internal carotid artery (C4, juxtasellar segment; C1, terminal carotid segment) and middle cerebral artery (M1, horizontal segment; proximal one third of M2; insular segment) were scored segment by segment bilaterally. A total of 410 arteries (204 right and 206 left) were assessed. For the purposes of this study, vessels on the left and right sides were considered equivalent, and the results were pooled. From these data, tables were constructed that compared the scoring of a given vessel.

Quantitative Analysis.—Diameters on both the MIP images and source images were measured quantitatively by two reviewers using a ×10 magnifying loupe with 0.1-mm divisions. Under magnification, the vessel margins no longer appeared sharp but rather blended softly into the background. To maintain uniformity in choosing the location of the vessel wall, the outermost margin of the vessel was selected on both MR angiographic and source images (7). When measurements were made on the MIP images, the projection that showed the greatest stenosis was chosen. When measurements were made on the source images, it was often necessary to measure the stenosis on one section and the more distal vessels on another.

The degrees of stenoocclusive disease as determined from the MR angiograms were categorized into the same five classes as for the conventional angiograms. When taking measurements on the MIP images alone and on the MIP plus source images, reviewers were blinded to the results of conventional angiography.

Visual Inspection.—MR angiograms and source images were also reviewed, usually retrospectively, by five trained observers who were blinded to the results of conventional arteriography. All assessments were done by means of visual inspection without use of magnifying lenses or measuring devices, because visual inspection is the most commonly used method for clinical evaluation of arterial stenosis. The order in which the images were reviewed was varied systematically among observers as follows: observer A started MR angiographic interpretation from case 1, observer B started from case 20, observer C from case 60, and so on. Initially, MIP images alone were presented. At the second reading, both MIP and source images were read simultaneously. To minimize a possible learning effect by the observers, the order in which the images were reviewed was varied from one reading to the other and there was a time interval of 6 weeks between the readings.

TABLE 1: MR angiography versus conventional angiography: quantitative analysis

Results at MR Angiography*	Results at Conventional Angiography*					
	Normal (n = 361)	Mild Stenosis (n = 26)	Moderate Stenosis (n = 12)	Severe Stenosis (n = 6)	Occluded (n = 5)	**Total (n = 410)**
Normal	300/338	0/0	0/0	0/0	0/0	**300/338**
Mild stenosis	43/20	17/21	1/0	0/0	0/0	**61/43**
Moderate stenosis	16/3	7/5	6/12	1/1	0/0	**31/21**
Severe stenosis	2/0	2/0	5/0	2/5	1/0	**12/6**
Occluded	0/0	0/0	0/0	3/0	4/5	**8/5**

* (MIP images)/(MIP plus source images).

Data Analysis

Quantitative Analysis.—The sensitivities of MIP images alone and MIP plus source images for detection of significant stenosis were determined by using the interpretations of the conventional arteriograms as the standard. An artery with stenosis of 50% or greater was considered to be diseased; otherwise, an artery was considered normal.

Visual Inspection.—MIP images were compared with the combined evaluation (MIP plus source images) for the detection of stenoocclusive disease by means of receiver operating characteristic (ROC) curves (12) as determined from the confidence scores of each observer's first and second reading of the images. Data from the five observers were not pooled; hence, two ROC curves were calculated for each observer. ROC curves were fit to the data points with a software program (ROCFIT and CORROC2) (12, 13) that also calculates the area under the curves, A_z (14). The A_z values of the ROC curves for the MIP images and for the combined image sets were then compared by means of a paired Student's *t* test.

To assess the interobserver variability in the interpretation of images, κ statistics were used to measure agreement between two observers. The extent of interobserver agreement among five observers for each imaging technique was also determined by means of the method reported by Fleiss (15). κ values greater than 0 were considered to indicate positive agreement; values up to 0.4 were considered to indicate positive but poor agreement; values of 0.41 to 0.75 were considered to indicate good agreement; and values greater than 0.75 were considered to indicate excellent agreement.

Results

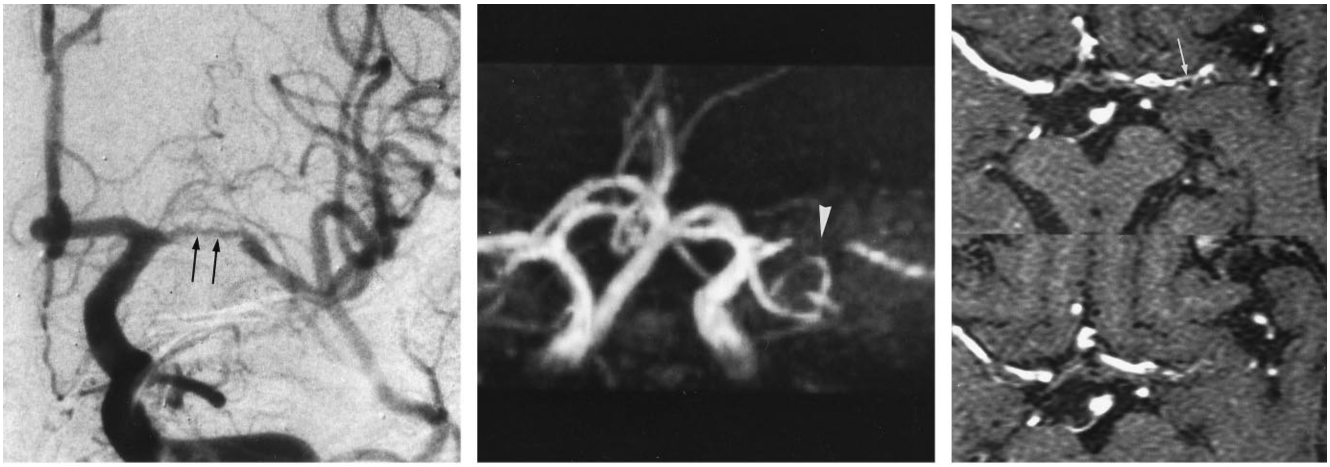
A total of 23 angiographic stenoocclusive lesions of 50% or greater were available for review: six lesions were in the internal carotid artery and 17 lesions were in the middle cerebral artery. The internal carotid lesions included five moderate and one severe stenosis. The lesions of the middle cerebral artery included five occlusions, five severe stenoses, and seven moderate stenoses. Another 26 mildly stenotic lesions (less than 50% reduction in diameter), including 16 in the internal carotid and 10 in the middle cerebral arteries, were not considered to be clinically significant.

Quantitative Analysis

Table 1 presents a summary of the scoring data for quantitative analysis. The rows correspond to MR angiographic scores and the columns represent conventional angiographic scores. Values along the diagonal represent exact matches of the conventional and MR angiographic scores. Interpretations of MIP images mainly overestimated the degree of stenosis, except for complete occlusion; although three of 23 lesions were underestimated (Figs 1–4). Eighteen (5%) of 361 normal vessels were interpreted as having moderate or severe stenosis. Three of six severe stenoses were interpreted as complete occlusion on the basis of MIP images alone. The rate of complete agreement between conventional and MR angiography as to the degree of stenosis was 80%. When MIP images and source images were combined, overestimation decreased significantly, and the rate of complete agreement was 93%. Even with the addition of source images, one of the 23 lesions was underestimated. With MIP images alone, 14 (78%) of 18 moderate and severe stenoses and four (80%) of five occlusions were identified correctly (Table 2). The addition of the source images increased the sensitivity to 100% for moderate and severe stenoses (18 of 18) and for occluded vessels (five of five).

Visual Inspection

Table 3 presents a summary of the scoring data for each reader. Each observer consistently underestimated the degree of stenosis by one or two ranks with visual inspection of MIP images. Even with combined evaluation of MIP



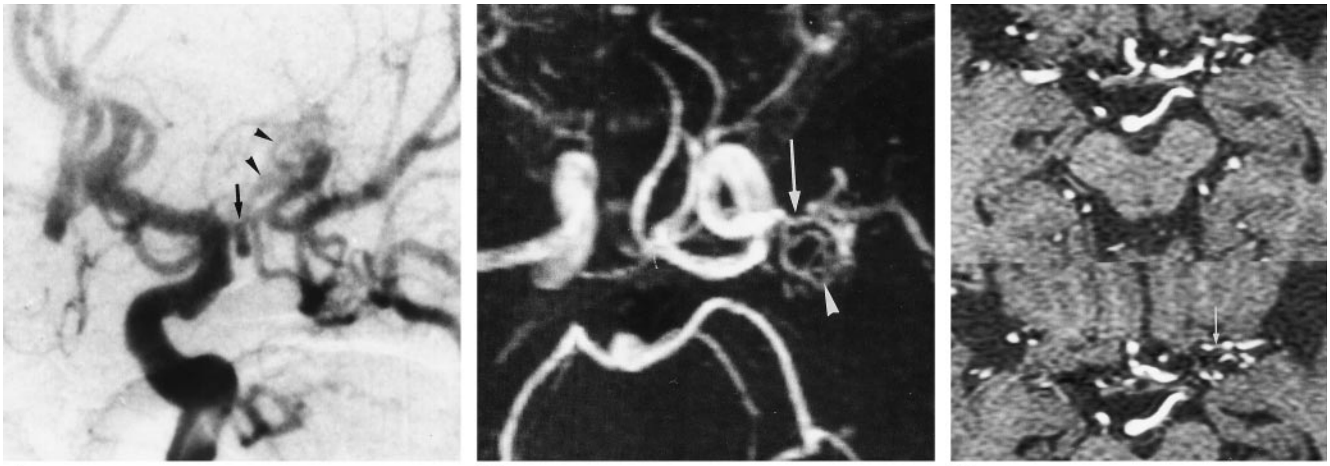
A B C

Fig 1. Stenosis of the middle cerebral artery.

A, Anteroposterior arteriogram of left carotid artery shows severe stenosis at the M1 segment of the left middle cerebral artery (*arrows*).

B, Anteroposterior MR angiogram shows short segmental signal loss simulating occlusion (*arrowhead*) with visibility of distal middle cerebral arteries. The stenosis of the M1 segment is exaggerated on MIP images.

C, Adjacent sections of the source images show the severity of the lesion more exactly (*arrow*).



A B C

Fig 2. Severe stenosis of the middle cerebral artery with collateral vessels.

A, Anteroposterior arteriogram of left carotid artery shows severe stenosis at the M1 segment of the left middle cerebral artery (*arrow*). Collateral vessels are markedly developed (*arrowheads*).

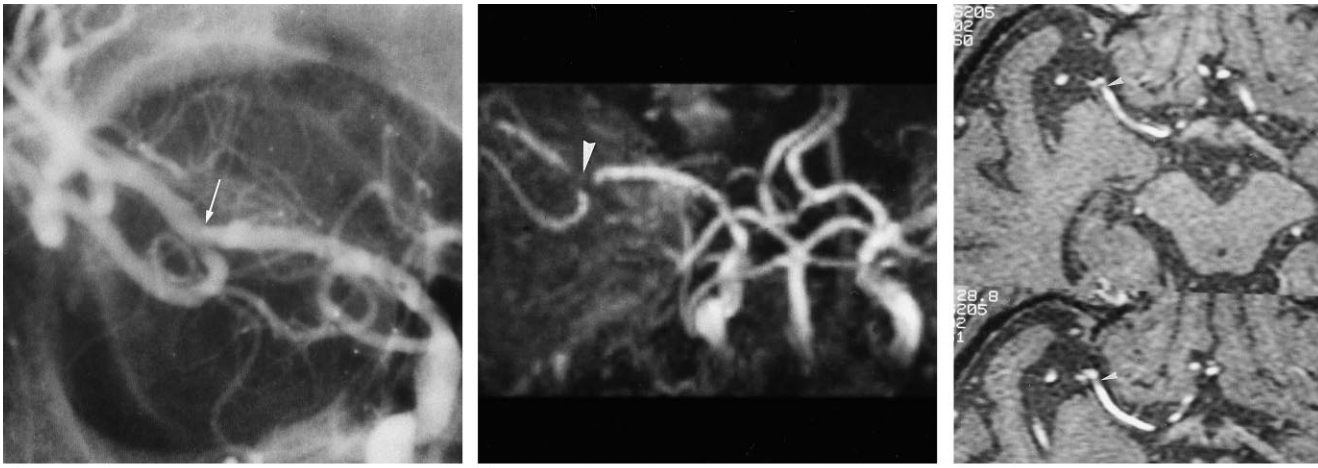
B, Axial collapsed MR angiogram shows short segmental signal loss (*arrow*) with poor visibility of distal middle cerebral arteries. Collateral vessels are also seen (*arrowhead*).

C, Adjacent sections of the source images. Severe stenosis is seen in the M1 segment of left middle cerebral artery (*arrow*).

and source images, the tendency toward underestimation for each observer did not change. Four of five observers interpreted severe stenosis as normal or mild stenosis in three or more of six lesions on both MIP images alone and on MIP plus source images.

The areas under the ROC curves (A_z index) for all observers are given in Table 4. There were no statistically significant differences in the overall performance among observers in the detection of stenosis of 50% or greater (Fig 5). The paired Student's *t* test of the A_z values revealed that the detection of stenosis was not improved significantly by the addition of the source images ($P > .05$).

In assessing interrater variability, five pairs for MIP images and six pairs for MIP plus source images indicated good agreement (κ value $\geq$ 0.40) (Table 5). Otherwise, positive but poor agreement was observed (κ value $<$ 0.40).



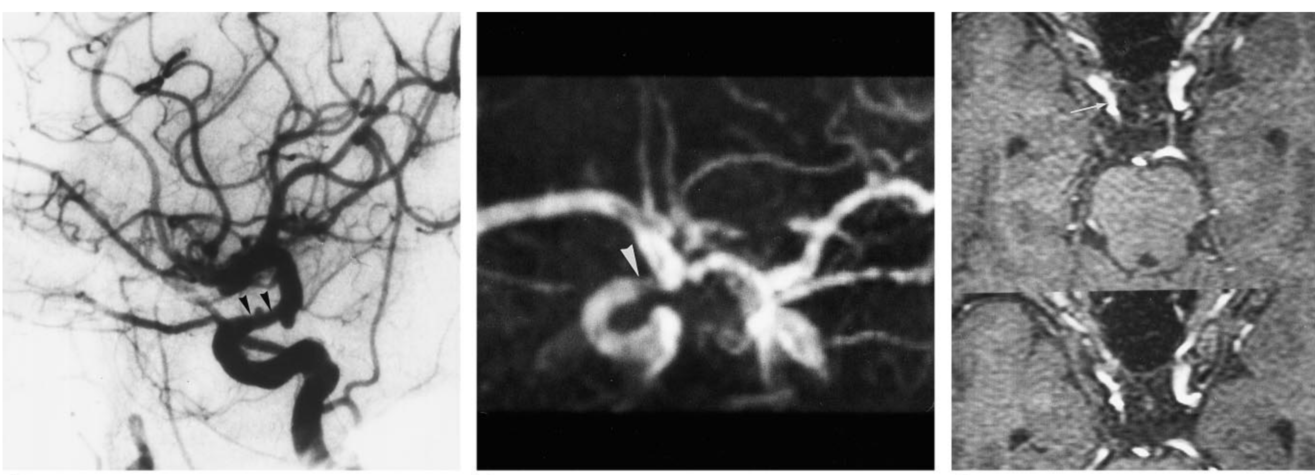
A B C

Fig 3. Mild stenosis at the bifurcation of the middle cerebral artery.

A, Anteroposterior arteriogram of right carotid artery shows mild stenosis at the distal M1 and proximal M2 segments of the right middle cerebral artery (*arrow*).

B, Anteroposterior MR angiogram shows short segmental signal loss (*arrowhead*), simulating occlusion.

C, Adjacent sections of the source images. Mild stenosis is seen at the bifurcation of left middle cerebral artery (*arrowheads*).



A B C

Fig 4. Moderate stenosis of the internal carotid artery.

A, Lateral arteriogram of right carotid artery shows the irregularity of the arterial walls and moderate stenosis in the right C2 segment (*arrowheads*).

B, Oblique MIP image shows artifactual signal loss simulating severe stenosis in the C2 segment of the right internal carotid artery (*arrowhead*).

C, Adjacent sections of the source images. Moderate stenosis is seen in the C2 segment (*arrow*).

Agreement among reviewers was better for combined interpretation than for MIP images alone.

Discussion

Recent studies have documented the clinical efficacy of 2DFT and 3DFT time-of-flight MR angiography in the evaluation of narrowing of the carotid artery bifurcation (1–5). Results of MR angiography of the carotid bifurcation have corresponded well to results of conventional angiography. However, a persistent problem has been the tendency to overestimate the degree of high-grade stenosis on MR angiograms. This overestimation results from disturbed patterns of blood flow within and beyond a stenotic channel leading to intravoxel phase dispersion and reduction in blood signal (16). Intravascular signal is much more perceptible on unprojected

TABLE 2: Detectability of 23 stenoocclusive lesions: quantitative analysis

Results at MR Angiography*	Results at Conventional Angiography*	
	Moderate and Severe Stenosis (n = 18)	Occluded (n = 5)
Moderate and severe stenosis	14/18	1/0
Occluded	3/0	4/5

* (MIP images)/(MIP plus source images).

source images than on MIP images (17). Furthermore, vessels appear wider on individual source images than on projections. This effect results from the choice of the highest background signal, which may be more intense than weak intravascular signal (7). Low-intensity regions of a vessel, such as the margins and areas of stenosis, may disappear on an MIP image (7).

In terms of the carotid artery bifurcation, Huston et al (5) reported a profound tendency to overestimate the degree of stenosis on 2D time-of-flight images. When interpreters reread the MR angiographic data from source images rather than from projections, the residual lumen appeared wider, resulting in an increase from 67% to 86% in the specificity for an interpretation of 50% stenosis. Likewise, according to Anderson et al (7), sensitivity and specificity for an interpretation of 70% to 99% stenosis significantly increased with the use of source images. De Marco et al (6) also reported the usefulness of source images and multiplanar reconstruction (MPR) images of 3D time-of-flight MR angiograms.

Clinical application of MR angiographic studies in intracranial stenoocclusive disease has been more limited than that of extracranial carotid artery studies (8–11). Heiserman et al (18) evaluated the usefulness of MR angiography of the intracranial vasculature in 29 patients. Another blinded study with a much larger population (131 patients, including 32 stenoocclusive lesions) also compared the accuracy of MR angiography and conventional angiography in the assessment of intracranial vascular stenosis (8). In that study, the sensitivity and specificity of the five observers for interpretations of MIP images obtained from MR angiography were 85% and 96%, respectively.

In this study, interpretations based on source partitions were more accurate than interpretations based on MIP images alone for the diagnosis of intracranial arterial stenosis. Specificity for high-grade lesions improved, because several lesions that were invisible on MIP images could be measured on individual sections. Use of a magnifying loupe further assisted in visualizing a weak intravascular signal, as reported by Anderson et al (7). With visual inspection, however, the degree of stenosis was frequently underestimated rather than overestimated. We used experienced observers who routinely interpret MR angiograms in their clinical work. Nevertheless, the observers consistently underestimated the degree of stenosis by one or two ranks. For the cases of severe or moderate stenosis, more than two thirds of lesions were underestimated. It is surprising that a number of occluded vessels on conventional angiograms were graded as mild, moderate, or severe stenosis on MR angiograms. Even with the use of source images and MIP data, none of the readers accurately detected all five occlusions.

Several types of artifacts cause problems in the identification of stenosis. First, vessels that lie near the sphenoidal sinus are subject to artifactual narrowing or to lack of visibility owing to the large susceptibility gradient present in this area (18). Second, acceleration of flow in the carotid siphon and loss of laminar flow and resultant intravoxel dephasing also contribute to artifactual signal loss, affecting the paracavernous internal carotid arteries and making it difficult to evaluate narrowing of this segment of the vessel (18). Third, the MIP algorithm has been known to create some artifacts on images of patients with stenosis (17). In general, it causes an apparent decrease in vessel diameter as well as an artificial lengthening of the stenotic portion of the vessel (2). MR angiograms of severely stenotic vessels often do not show the region of stenosis well. Usually, an apparent discontinuity in a vessel on the MR angiogram with a clearly defined proximal and distal portion of the vessel corresponds to a severe stenosis on a conventional angiogram. This discontinuity results from intravoxel spin dephasing (2). The flow void caused by the rapid acceleration of spins through the area of stenosis will also contribute to the discontinuity (2). In our study, experienced observers, who had knowledge of these physiological signal losses, seemed to use the appearance of signal void to estimate the degree of stenosis; they tended to interpret signal loss in the vessels as

TABLE 3: MR angiography versus conventional angiography: visual inspection

Results at MR Angiography*	Results at Conventional Angiography* Normal (n = 361)	Mild Stenosis (n = 26)	Moderate Stenosis (n = 12)	Severe Stenosis (n = 6)	Occluded (n = 5)	**Total (n = 410)**
			Observer 1			
Normal	351/348	20/12	4/4	1/0	0/0	**376/364**
Mild stenosis	9/10	4/6	5/3	0/2	0/0	**18/21**
Moderate stenosis	1/3	2/8	3/4	3/2	0/1	**9/18**
Severe stenosis	0/0	0/0	0/1	2/1	1/0	**3/2**
Occluded	0/0	0/0	0/0	0/1	4/4	**4/5**
			Observer 2			
Normal	359/359	21/24	5/7	2/4	0/0	**387/394**
Mild stenosis	2/2	5/2	6/4	2/0	0/0	**15/8**
Moderate stenosis	0/0	0/0	1/1	1/1	1/0	**3/2**
Severe stenosis	0/0	0/0	0/0	1/1	1/1	**2/2**
Occluded	0/0	0/0	0/0	0/0	3/4	**3/4**
			Observer 3			
Normal	339/343	15/18	2/3	2/0	0/0	**358/364**
Mild stenosis	18/14	8/4	6/3	1/3	0/0	**33/24**
Moderate stenosis	4/4	3/4	4/6	3/2	0/1	**14/17**
Severe stenosis	0/0	0/0	0/0	0/1	1/1	**1/2**
Occluded	0/0	0/0	0/0	0/0	4/3	**4/3**
			Observer 4			
Normal	353/357	21/23	6/7	1/1	0/0	**381/388**
Mild stenosis	6/3	5/3	5/4	3/3	0/0	**19/13**
Moderate stenosis	0/1	0/0	0/1	0/2	1/1	**1/5**
Severe stenosis	0/0	0/0	0/0	0/0	0/0	**0/0**
Occluded	2/0	0/0	1/0	2/0	4/4	**9/4**
			Observer 5			
Normal	358/356	26/24	6/3	2/1	1/0	**393/384**
Mild stenosis	2/4	0/2	5/7	2/2	0/1	**9/16**
Moderate stenosis	1/1	0/0	1/2	1/3	0/0	**3/6**
Severe stenosis	0/0	0/0	0/0	1/0	0/0	**1/0**
Occluded	0/0	0/0	0/0	0/0	4/4	**4/4**

* (MIP images)/(MIP plus source images).

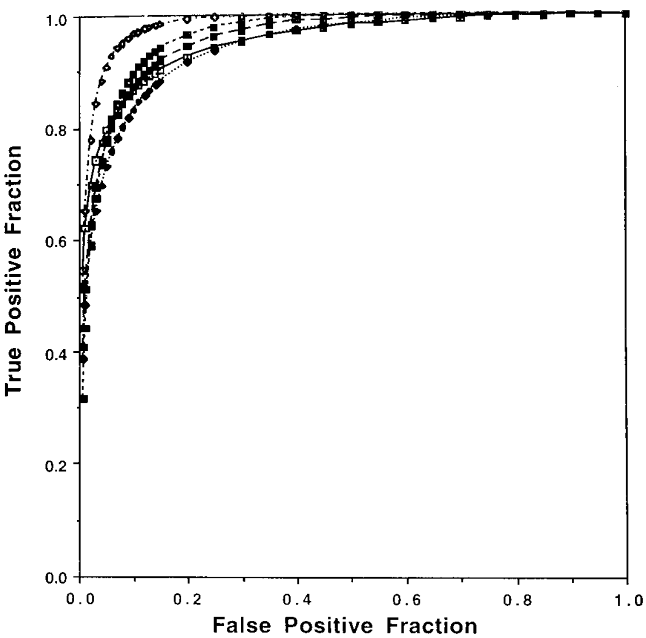
TABLE 4: A_z indexes for detection of stenosis and occlusion

Technique of Examination	Observer 1	2	3	4	5	Mean*
MIP images	0.95	0.96	0.94	0.96	0.98	0.959 ± 0.015
MIP plus source images	0.95	0.96	0.97	0.96	0.99	0.963 ± 0.095

* Values given are mean ± standard deviation.

an artifact simulating stenosis. This may account for the tendency on the part of all our observers to have underestimated the degree of stenosis on the MR angiograms. An understanding of the limitations of MR angiography as well as of the tendency by observers to underestimate the degree of stenosis is important for educating colleagues about these liabilities.

There are some limitations of this study. First, a much larger percentage of angiographically normal subjects would have been included in a random screening population, although a relatively large percentage of angiographically normal subjects were included in our study. Sensitivity and specificity may vary with a change in the ratio between patients with and without stenoocclusive disease (8). Second, only the axial source images were evaluated together with the MIP images. It was often necessary to measure the stenosis on one axial section and the more distal vessels on another. Since the vessel ge-



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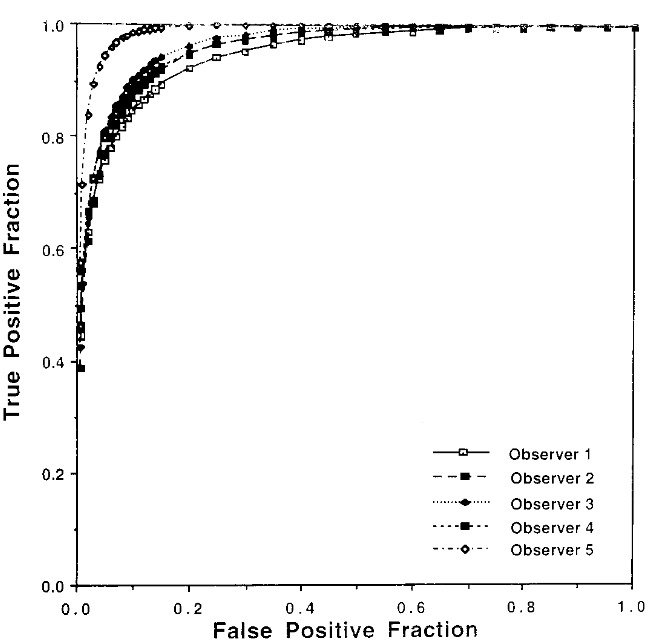

B

Fig 5. Observed ROC curves for MR angiography. *A*, MIP images; *B*, MIP plus source images.

TABLE 5: κ values for interrater variability

Observers	MIP Images	MIP Images plus Source Images
Interrater agreement		
1 versus 2	0.39	0.30
1 versus 3	0.42	0.41
1 versus 4	0.40	0.33
1 versus 5	0.33	0.32
2 versus 3	0.31	0.30
2 versus 4	0.45	0.55
2 versus 5	0.57	0.51
3 versus 4	0.35	0.44
3 versus 5	0.29	0.48
4 versus 5	0.46	0.60
Multiple rater agreement*	0.40 ± 0.08	0.42 ± 0.11

* Mean ± standard deviation.

ometry of the intracranial internal carotid and middle cerebral arteries is complicated, multiplanar reconstruction images that are parallel or perpendicular to vessels may be needed for more exact evaluation of the stenosis. However, in this study, overestimation and underestimation of stenosis were markedly reduced when interpretations were made on axial source images. Multiplanar reconstruction images usually require much more effort and time to reconstruct. Therefore, the axial source images may be enough for routine clinical evaluation. Third, since the diameter of intracranial vessels is smaller than that of the extracranial vessels, exact measurement of stenosis was difficult. Therefore, we used the five-level grading system instead of actual measurement data. Fourth, the intrinsic resolution of MR angiography might have been a limiting factor in measurement accuracy (7). Vessel diameters on MR angiograms could be measured with a precision of 0.16 mm by using the magnifying loupe; however, the actual acquired voxel size of the MR angiograms was only 1.09 × 0.55 mm. Pixel-related artifacts of the vessel margin were apparent on source images. It is likely that substantial improvements in measurement accuracy will necessitate higher-resolution data acquisition (7). Fifth, the nonselective MIP technique was used in this study. Selective MIP images reduce some of the artifacts of MIP images as well as eliminate the problem of overlapping vascular structures. In this study, however, all MIP images were arranged so as to be viewed stereoscopically. Although we know of no study that has objectively measured the added value of stereoscopic projections of MR angiographic images, we suspect that stereoscopic viewing can increase both sensitivity and specificity as compared with viewing standard collapsed and projection images alone. With the added advantage of stereoscopic views, the handicap of the nonselective MIP technique might be reduced. Finally, although MR angiography used in this study covered the circle of Willis, stenoocclusive disease involving more peripheral branches or cerebellar arteries may have been missed. Multiple overlapping slabs may be required to cover the whole cranium (19).

In conclusion, interpretation of source images rather than MIP images alone reduced reviewers' tendency to overestimate stenosis on MR angiograms and improved the sensitivity for detecting stenosis of 50% or greater in the quantitative study. However, there was a discrepancy between the quantitative study and visual inspection by experienced observers, who tended to interpret signal loss in the vessels as an artifact simulating stenosis and to underestimate intracranial vascular stenosis.

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References

1. Masaryk AM, Ross JS, Dicello MC, Modic MT, Paranandi L, Masaryk TJ. 3DFT MR angiography of the carotid bifurcation: potential and limitations as a screening examination. *Radiology* 1991;179:797–804
2. Litt AW, Eidelman EM, Pinto RS, et al. Diagnosis of carotid artery stenosis: comparison of 2DFT time-of-flight MR angiography with contrast angiography in 50 patients. *AJNR Am J Neuroradiol* 1991;12:149–154
3. Polak JF, Bajakian RL, O'Leary DH, Anderson MR, Donaldson MC, Jolesz FA. Detection of internal carotid artery stenosis: comparison of MR angiography, color Doppler sonography, and arteriography. *Radiology* 1992;182:35–40
4. Heiserman JE, Drayer BP, Fram EK, et al. Carotid artery stenosis: clinical efficacy of two-dimensional time-of-flight MR angiography. *Radiology* 1992;182:761–768
5. Huston J III, Lewis BD, Wiebes DO, Meyer FB, Riederer SJ, Weaver AL. Carotid artery: prospective blinded comparison of two-dimensional time-of-flight MR angiography with conventional angiography and duplex US. *Radiology* 1993;186:339–344
6. De Marco JK, Nesbit GM, Wesbey GE, Richardson D. Prospective evaluation of extracranial carotid stenosis: MR angiography with maximum-intensity projections and multiplanar reformation compared with conventional angiography. *AJR Am J Roentgenol* 1994;163:1205–1212
7. Anderson CM, Lee RE, Levin DL, et al. Measurement of internal carotid artery stenosis from source MR angiograms. *Radiology* 1994;193:219–226
8. Korogi Y, Takahashi M, Mabuchi N, et al. Intracranial vascular stenosis and occlusion: diagnostic accuracy of three-dimensional, Fourier transform, time-of-flight MR angiography. *Radiology* 1994;193:187–193
9. Johnson BA, Heiserman JE, Drayer BP, Keller PJ. Intracranial MR angiography: its role in the integrated approach to brain infarction. *AJNR Am J Neuroradiol* 1994;15:901–908
10. Stock KW, Radue EW, Jacob AL, Bao X-S, Steinbrich W. Intracranial arteries: prospective blinded comparative study of MR angiography and DSA in 50 patients. *Radiology* 1995;195:451–456
11. Katz DA, Marks MP, Napel SA, Bracci PM, Roberts SL. Circle of Willis: evaluation with spiral CT angiography, MR angiography, and conventional angiography. *Radiology* 1995;195:445–449
12. Metz CE. ROC methodology in radiographic imaging. *Invest Radiol* 1986;21:720–733
13. Metz CE. Some practical issues of experimental design and data analysis in radiological ROC studies. *Invest Radiol* 1989;24:234–245
14. Hanley JA, McNeil BJ. The meaning and use of the area under a receiver operating characteristic (ROC) curve. *Radiology* 1982;143:29–36
15. Fleiss JL, ed. *Statistical Methods for Rates and Proportions.* 2nd ed. New York, NY: Wiley; 1981:212
16. Urchuk SN, Plewes DB. Mechanisms of flow-induced signal loss in MR angiography. *J Magn Reson Imaging* 1992;2:453–462
17. Anderson CM, Saloner D, Tsuruda JS, et al. Artifacts in maximum intensity projection display of MR angiograms. *AJR Am J Roentgenol* 1990;154:623–629
18. Heiserman JE, Drayer BP, Keller PJ, Fram EK. Intracranial vascular stenosis and occlusion: evaluation with three-dimensional time-of-flight MR angiography. *Radiology* 1992;185:667–673
19. Blatter DD, Parker DL, Robison RO. Cerebral MR angiography with multiple overlapping thin slab acquisition. Part I. Quantitative analysis of vessel visibility. *Radiology* 1991;179:805–811 Moderate stenosis of the internal carotid artery.