Diagnosis of Carotid Artery Stenosis: Comparison of 2DFT Time-of-Flight MR Angiography with Contrast Angiography in 50 Patients

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Fifty patients underwent 2DFT time-of-flight MR angiography and intraarterial contrast angiography for evaluation of possible carotid atherosclerotic disease. The MR angiography technique employed contiguous axial flow-sensitive (short TR/TE) slices that were reformatted and postprocessed by using a maximum-intensity projection algorithm to provide 16 angiographic views of the carotid arteries. Both studies were independently reviewed by two observers in a blinded manner. Carotid arteries were categorized as normal, mildly stenotic, moderately stenotic, severely stenotic, or occluded. For the 94 carotid arteries available for review, one observer reported a 70% agreement between the two techniques and the second observer reported a 56% agreement ($p = .0001$). The best correlation was in the severely stenotic category and the worst was in the occluded category. Agreement between observers was 67% for MR angiography and 72% for contrast angiography, which was similar to that between the two techniques. Although not all carotid atherosclerotic disease was visualized equally well, 2DFT time-of-flight MR angiography had a good overall correlation with the “gold standard” of intraarterial contrast angiography, supporting its use as a screening technique. While further improvements are needed, use of MR angiography as the primary diagnostic tool for many patients with suspected carotid stenosis should continue to increase.


Cerebrovascular disease is the third leading cause of death in the United States, and ischemic disease caused by atherosclerotic carotid artery disease is responsible for the vast majority of strokes [1]. Accordingly, much effort has been directed toward developing noninvasive methods for evaluating the carotid bifurcation. For example, several recent reports have described MR techniques that exploit and manipulate either the phase phenomenon [2–5] or the time-of-flight effects [6–9] characteristic of flowing spins in imaging the extracranial carotid arteries.

While initially successful in visualizing the normal carotid bifurcation, phase contrast subtraction techniques could not image stenoses accurately because velocity variation within the imaging voxel caused phase cancellation and thus signal void at and distal to the diseased segment [4]. Using a time-of-flight volumetric (3DFT) gradient-echo technique, Masaryk et al. [7] compared MR angiograms with intraarterial digital subtraction angiography (DSA) in 12 patients with good correlation between the two methods (Masaryk et al. Paper presented at the annual meeting of the Radiological Society of North America, Chicago, November 1989). However, in three-dimensional imaging techniques, because the entire volume is being excited with each TR, signal loss due to saturation occurs as blood flows deeper into the volume being scanned. This may create problems in evaluating the distal internal carotid artery. Moreover, in vessels with very slow flow, such as the carotid dissection, the spins within the vessel will become saturated, reducing their signal and possibly making detection of this condition more difficult.

In two-dimensional (2DFT) time-of-flight sequences the relative contrast between the flowing blood and stationary tissues is increased by the high signal of the
maximally magnetized spins as they flow into the slice. These 2DFT sequences have also been used to obtain images of the carotid arteries [6, 8], although the applicability of this technique to depicting the diseased carotid artery has not previously been explored. We used a 2DFT time-of-flight technique to study patients with suspected carotid artery disease and compared the results with those obtained by using intraarterial contrast angiography to evaluate the accuracy of MR angiography in imaging carotid artery stenosis.

Materials and Methods

Between March 1989 and March 1990, 50 patients were referred for MR angiography of the carotid arteries. All patients were being evaluated for suspected atherosclerotic extracranial carotid artery disease and had previously undergone contrast angiography. The MR was performed within 24 hr of the contrast angiogram in 32 patients, within 7 days in six patients, and within 4 months in 12 patients. The patients (28 men and 22 women) ranged in age from 31 to 87 years (mean, 65.8 years).

All patients were studied on a standard 1.5-T MR system (Philips Gyroscan S15) with 10 mT/m gradients using the routine head/neck coil. MR angiograms of the carotid arteries were acquired by using a 2DFT time-of-flight technique (Groen et al., paper presented at the annual meeting of the Society of Magnetic Resonance in Medicine, San Francisco, August 1988) involving the acquisition of 50–60 thin (2–3 mm), contiguous or overcontiguous, axial slices, using a spoiled gradient-echo sequence that was first-order flow compensated in read- and slice-selection directions. The MR signal from stationary tissue was suppressed owing to the short repetition times, typically 40–60 msec, and the use of large flip angles, 60–90°, while high signal was obtained from unsaturated blood flowing into the slice. Other scan parameters were TE = 14–22, field of view = 250 mm, matrix size = 180 x 256, and two excitations. The axial slices typically required 14 min for acquisition.

To suppress the venous flow, a presaturation slab, 50 mm thick, was applied at a 2.5-mm offset cephalad to the slice being imaged. The presaturation slab tracked with the slice to ensure consistent venous saturation. Relaxation of the slice-refocusing gradient allowed for a small amount of slice dephasing that provided additional suppression of the stationary tissue.

Projection MR angiograms were created from the stack of 2D slices by the use of a maximum-intensity projection algorithm. Sixteen projections were obtained at 8° intervals starting from the straight anteroposterior view. They were then displayed as a cine movie loop or filmed as individual hard-copy images. The projection processing was carried out as a background batch job on the Gyroscan VAX 11/750 (Digital Equipment Corp., Maynard, MA) or in the array processor (AP500, Analogic Corp., Wakefield, MA). Typical processing time in VAX background mode for a full image projection is about 90 sec/projection while the corresponding time in the AP500 is 10 sec. To better visualize the anatomy, a user-defined region-of-interest was drawn around each carotid artery on one of the axial slices and was used to confine the 3D projection to a limited area (Simon et al. Paper presented at the annual meeting of the Radiological Society of North America, Chicago, November 1989). This minimized interference from other anatomy and significantly decreased the processing time.

Contrast arteriography was performed via femoral artery catheterization using either film-screen (37 patients) or digital subtraction (13 patients) technique. In three patients, only the right carotid artery was examined, using retrograde right brachial injections with film-screen technique; in one case, only the left carotid artery was studied for clinical reasons.

Both MR and contrast angiograms were reviewed retrospectively. Each study was independently read by two trained neuroradiologists blinded to the patient’s name and clinical history, the results of the other study, and the interpretation of the other observer. A “forced-choice” evaluation of the internal carotid artery at and just above the carotid bifurcation was made on the basis of an estimate of carotid artery narrowing, with the studies reported as normal (0–15% stenosis), mild (16–49% stenosis), moderate (50–79% stenosis), severe...
(80–99% stenosis), or occluded. The original 2D axial slices were not used in evaluation of the MR angiograms. Correlation of results between techniques and between observers was calculated using the Spearman rank correlation test. This examines the nonrandomness of ranked (nonordinal) data in which no statement about the parameter mean can be made in advance.

**Results**

Among the 50 patients studied, three left carotid arteries and one right carotid artery were excluded because they were not studied by contrast angiography. Despite the overall high quality of the MR angiographic images (Figs. 1–6), two other vessels were excluded because the MR angiogram of those vessels were thought to be indeterminate by at least one observer. This left 94 carotid arteries available for review.

Interpretations by the first observer (Table 1) showed MR and contrast angiography in agreement in 66 of 94 vessels for an overall correlation of 70% ($r = .84$, $p = .0001$). The highest level of correlation was in the severe category, with 95% of the vessels correctly diagnosed by MR. The greatest discrepancy between the techniques was in the occluded category, with only 29% correctly interpreted. Of those 28 vessels in which MR angiography did not match contrast angiography, the studies were only one category apart for all but four vessels.

The MR and contrast angiography readings of the second observer (Table 2) were identical in 53 of 94 vessels for a correlation of 56% ($r = .74$, $p = .0001$). Correlation was again best in the severe angiographic category (69%) and worst in the occluded category (25%). Of the 41 cases in which MR and angiography were not in agreement, only 10 were different by more than one category.

Correlation between observers 1 and 2 in interpreting the contrast angiograms was 68 of 94 vessels, or 72% ($r = .87$, $p = .0001$), with the best agreement in the severe category (Table 3). Agreement between observers 1 and 2 in interpreting the MR angiograms was 63 of 94, or 67% ($r = .83$, $p = .0001$), with the highest correlation again in the severe category (Table 4).

**Discussion**

The purpose of this study was to compare intraarterial contrast angiography with MR angiography using a 2D time-
Fig. 5.—A and B, Contrast (A) and MR (B) angiograms in a case of severe stenosis. Although a branch of the external carotid is seen on the MR image (straight arrow), the area of stenosis is not visualized, presumably because of turbulence (curved arrow).

Fig. 6.—A and B, Views of contrast (A) and MR (B) angiography in a case of internal carotid occlusion. The common carotid artery (open arrows) is seen well, as are the main trunk of the external carotid artery (small straight arrows) and the vertebral artery (arrowheads). The proximal internal carotid artery (curved arrow) is seen just above the bifurcation. Note the faint vascular-appearing structure distal to the area of discontinuity on the MR image (larger straight arrows). It is difficult to determine whether this represents continuation of the internal carotid, a branch of the external carotid, or an artifact.
TABLE 1: MR vs Contrast Angiography: Findings by Observer 1

<table>
<thead>
<tr>
<th>MR Angiography</th>
<th>Normal (%)</th>
<th>Mild (%)</th>
<th>Moderate (%)</th>
<th>Severe (%)</th>
<th>Occluded (%)</th>
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<tr>
<td>Normal (%)</td>
<td>5 (63)</td>
<td>2 (9.5)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mild (%)</td>
<td>2 (25)</td>
<td>14 (67)</td>
<td>0</td>
<td>1 (2.5)</td>
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<td>Moderate (%)</td>
<td>1 (12)</td>
<td>3 (14)</td>
<td>8 (42)</td>
<td>1 (2.5)</td>
<td>0</td>
</tr>
<tr>
<td>Severe (%)</td>
<td>0</td>
<td>0</td>
<td>11 (58)</td>
<td>37 (95)</td>
<td>5 (71)</td>
</tr>
<tr>
<td>Occluded (%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2 (29)</td>
</tr>
</tbody>
</table>

Note.—Percentages are relative to total number of cases in each contrast angiography category. Overall agreement for observer 1 was 70%.

TABLE 2: MR vs Contrast Angiography: Findings by Observer 2

<table>
<thead>
<tr>
<th>MR Angiography</th>
<th>Normal (%)</th>
<th>Mild (%)</th>
<th>Moderate (%)</th>
<th>Severe (%)</th>
<th>Occluded (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal (%)</td>
<td>1 (11)</td>
<td>1 (4)</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Mild (%)</td>
<td>4 (44)</td>
<td>5 (23)</td>
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<td>0</td>
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<tr>
<td>Moderate (%)</td>
<td>1 (11)</td>
<td>10 (45)</td>
<td>3 (37)</td>
<td>2 (4)</td>
<td>0</td>
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<tr>
<td>Severe (%)</td>
<td>3 (33)</td>
<td>6 (27)</td>
<td>5 (63)</td>
<td>42 (89)</td>
<td>6 (75)</td>
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<tr>
<td>Occluded (%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3 (6)</td>
<td>2 (25)</td>
</tr>
</tbody>
</table>

Note.—Percentages are relative to total number of cases in each contrast angiography category. Overall agreement for observer 2 was 56%.

TABLE 3: Contrast Angiography: Comparison of Interpretations by Observers 1 and 2

<table>
<thead>
<tr>
<th>Observer 1</th>
<th>Normal</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Occluded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>6</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mild</td>
<td>3</td>
<td>15</td>
<td>3</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Moderate</td>
<td>0</td>
<td>3</td>
<td>4</td>
<td>11</td>
<td>1</td>
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<tr>
<td>Severe</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>36</td>
<td>0</td>
</tr>
<tr>
<td>Occluded</td>
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<td>0</td>
<td>0</td>
<td>7</td>
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</table>

Note.—Overall agreement between observers was 72%.

TABLE 4: MR Angiography: Comparison of Findings by Observers 1 and 2

<table>
<thead>
<tr>
<th>Observer 1</th>
<th>Normal</th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
<th>Occluded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Mild</td>
<td>0</td>
<td>5</td>
<td>9</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Moderate</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Severe</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>50</td>
<td>4</td>
</tr>
<tr>
<td>Occluded</td>
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<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Note.—Overall agreement between observers was 67%.

as is usually done with routine clinical examinations in most institutions. However, the use of a "forced-choice" ranking system caused the observers to have to make difficult decisions when a study, whether an MR or contrast angiogram, was on the borderline between two categories. For example, the difference between 49% stenosis (mild category) and 50% stenosis (moderate category) is difficult to ascertain visually. This problem with the "forced-choice" analysis is demonstrated by the 67% and 72% interobserver correlations for each of the two techniques. If only differences of more than one category are considered, the overall correlation between MR and contrast angiography for each observer is 96% and 89%, respectively, and the interobserver correlation is 97% for contrast angiography and 95% for MR angiography.

The best correlation between techniques and, in fact, between observers in the same technique was in the severe category. Although the severely narrowed vessel lumen was occasionally seen on the MR examination (Fig. 4), MR angiograms in the severely stenotic cases often did not show the region of stenosis well. Conversely, an apparent discontinuity in the vessel on the MR angiogram with a clearly defined proximal and distal portion of adjacent vessel always correlated with a severe stenosis on contrast angiography (Fig. 5). This discontinuity results from intravoxel spin dephasing, which occurs because in laminar flow there is a range of velocities across the vessel diameter. Spins moving at varying velocity acquire different amounts of phase and may appear to cancel each other in the image. In addition, the flow void caused by the rapid acceleration of spins through the area of stenosis will also contribute to the discontinuity. Whereas the dephasing problem may be ameliorated with thinner slices and shorter echo times, the phase changes resulting from acceleration are more difficult to correct. In fact, the use of additional flow-compensating gradients to achieve this cor-
rection may have the deleterious side effect of increasing the echo time and hence the dephasing.

Other potential causes for signal loss in the region of stenosis that could lead to overestimation of the degree of narrowing are calcium or old hemorrhage within the atheroma. These would cause local field inhomogeneities that would result in spin dephasing, but again shorter echo times and thinner slices should reduce this problem.

This apparent discontinuity seen in the severely stenotic vessels is partially responsible for the poor correlation of MR and contrast angiography in the occluded cases. The occluded internal carotid arteries were often misinterpreted on the MR images as patent, because a small external carotid vessel or an artifact seen cephalad to the area of discontinuity was thought to be the continuation of the internal carotid artery (Fig. 6). While some of these cases were correctly interpreted because of the availability of multiple projections, in most it was difficult to correctly diagnose an occluded vessel, and these misdiagnoses were all interpreted as severe stenosis. The other factor in producing this error was the limitation of the study to the extracranial carotid circulation. Presumably, had additional cephalad slices been obtained and the vascular anatomy in the petrous and cavernous portions of the carotid arteries been defined, it would have been easier to distinguish between branches of the external carotid artery and continuation of the internal carotid artery itself. In addition, evaluation of the siphon is important in patients with carotid bifurcation stenosis to exclude tandem lesions prior to surgery.

Flow-related phase effects also caused some problems in the interpretation of normal carotid arteries. Although the carotid bulb was often seen (Fig. 1), in many cases there was some apparent “flattening” of the bulb, probably caused by the reversal of flow known to occur at this location [9]. If interpreted by strict contrast angiographic criteria, this flattening would be considered as evidence of mild stenosis, which could be misleading in some cases.

The most significant overall limitations of the 2DFT technique were an occasional “step-ladder” artifact seen in the projections and rare cases of poor signal to noise in the vessel. The artifact was most likely caused by minimal patient motion between axial slices. The overall poor signal is not as clearly understood but may result from poor cardiac output, which reduces the amount of spin refreshment in the vessel at each TR.

The maximum-intensity projection algorithm is also known to create some artifacts in patients with stenosis [9]. In general, it causes an apparent decrease in vessel diameter as well as an artificial lengthening of the stenotic portion (Fig. 3). This accounts for the tendency of both observers to have overestimated the degree of stenosis on the MR angiograms. The first problem is correctable by adjusting one’s interpretation of the stenosis to account for the slightly underestimated diameter on the MR study. Observer 1 had more MR angiographic experience than observer 2, which may account for his better overall rate of correlation. The problem of overestimating the length of stenosis was noted by both observers and is not easily correctable.

Intraarterial contrast angiography remains the “gold standard” for the complete evaluation of atherosclerotic carotid artery disease. However, the small but measurable complication rate related to this procedure as well as its invasive nature argue strongly for the development and implementation of alternative diagnostic methods. The good correlation shown in this study between 2DFT time-of-flight MR angiography and contrast angiography suggests that the MR technique is sufficient as a screening method to separate those patients with a potentially correctable stenosis from those in whom surgery is not indicated. For many of the patients with a nonsurgical stenosis or a normal carotid bifurcation, MR angiography will probably be the only examination performed. Continued improvement of this technique as well as its extension to include visualization of the petrous and cavernous portions of the internal carotid artery should reduce the number of individuals requiring contrast angiography in the future. Finally, correlation of other diagnostic techniques, such as duplex sonography, with MR angiography may provide additional diagnostic certainty and further reduce the indications for contrast angiography.

ACKNOWLEDGMENTS

We acknowledge Mary Sue Shields for her help in coordinating the patients for this study and the MR Advanced Clinical Development Group of Philips Medical Systems North America for providing and supporting the prototype MR angiographic software used.

REFERENCES