Comparison of Magnetic Resonance Volume Flow Rates, Angiography, and Carotid Dopplers

Preliminary Results

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Background and Purpose
We compared the results of conventional angiography, carotid Doppler, and magnetic resonance angiography volume flow rates to determine the clinical utility of volume flow rate assessment of blood flow to the anterior circulation in patients with carotid occlusive disease.

Methods
From 11 symptomatic patients, a total of 22 extracranial carotid arteries were studied with all three techniques. The studies were independently read, and regression analysis was used to compare the measurements.

Results
Carotid Doppler measurements of the distal extracranial carotid arteries were proportional to the inverse of the extracranial carotid volume flow rate ($r = 0.53, R^2 = 29\%, P < 0.01$), volume flow rates were proportional to the inverse of measured percent stenosis on angiography ($r = 0.84, R^2 = 71\%, P < 0.01$), and Dopplers were proportional to angiography ($r = 0.94, R^2 = 90\%, P < 0.01$). Symptomatic Doppler systolic velocity was significantly higher ($P < 0.002$), symptomatic measured stenosis was significantly higher ($P < 0.002$), and symptomatic volume flow rate was significantly lower ($P < 0.01$) than their respective asymptomatic-side values. These preliminary observations, however, may well change once a large data set, especially one in which more patients with high-grade carotid stenosis are included, is studied.

Conclusions
Assessment of carotid volume flow rates by magnetic resonance angiography quantifies flow reduction secondary to atherosclerotic occlusive disease. The easily obtained flow data add both documentation of arterial flow characteristics related to internal carotid stenosis and information regarding the adequacy of collateral pathways. (Stroke. 1994;25:413-417.)

Key Words
- angiography, magnetic resonance
- carotid arteries
- magnetic resonance imaging
- ultrasonics

Magnetic resonance imaging and magnetic resonance angiography are fast becoming valuable tools in the noninvasive delineation of cerebrovascular abnormalities and are beginning to replace the use of catheter-generated invasive x-ray angiography (XRA). Magnetic resonance angiographic (MRA) images can be obtained without contrast medium by exploiting the physical properties of moving blood. MRA methods have been used to produce clinically relevant angiographic images of the cerebral vasculature. MRA techniques have also been used to measure blood flow by using time-of-flight phenomena or phase-contrast effects.

Phase-contrast MRA is based on the principle that blood flowing at a constant velocity through a magnetic field gradient will experience a predictable change in spin phase relative to the surrounding stationary tissue. Cine phase-contrast angiography is an MRA acquisition technique that can provide flow velocity, volume flow rate, and flow characteristics.

We report a prospective study on a group of patients with symptomatic carotid occlusive disease to compare cardiac-triggered cine two-dimensional phase-contrast angiographic measurement of extracranial internal carotid artery volume flow rates (PCVFRs) to carotid Doppler examinations and XRA.

Subjects and Methods
Eleven patients were evaluated by carotid Doppler, XRA, magnetic resonance imaging, MRA, and PCVFR determinations at our institution. These patients had been referred for consideration for entrance into the North American Symptomatic Carotid Endarterectomy Trial (NASCET), and all had unilateral carotid territory minor stroke or transient ischemic attack.

The carotid Doppler examinations were performed by an experienced technician with a pulsed-wave Doppler with a 7.5-MHz probe (Acuson, Inc). Degree of stenosis was determined by measuring the peak systolic velocity, the diastolic velocity, and the degree of spectral broadening. For this study the highest systolic velocity (in centimeters per second) of the extracranial internal carotid artery was used for comparisons.

Conventional XRA was performed through femoral artery catheterization with selective carotid artery injections in all 11 patients. Biplane views of the carotid bifurcation were obtained using digital subtraction technique. Angiographic percent stenosis was according to NASCET criteria and was represented by the formula $1 - ([diameter of the narrowest lesion/diameter of the distal internal carotid artery]) \times 100$. Measured stenoses according to XRA and according to MRA were not otherwise directly compared for the present study. The MRA examinations were obtained by our usual protocol that combines time-of-flight and phase-contrast techniques.

A cardiac-triggered cine two-dimensional phase-contrast angiographic acquisition was obtained to measure distal extracranial internal carotid artery PCVFRs. The examinations were performed on a 1.5-T General Electric Signa Scanner operating at software level 4.8. In this method, introduced by O'Donnell, implemented for clinical studies by Evans et al, the...
TABLE 1. Comparison of Doppler, Angiography, and Volume Flow Rates

<table>
<thead>
<tr>
<th>Patient</th>
<th>Doppler Velocity, cm/s</th>
<th>% Stenosis on Angiography</th>
<th>PCVFR, mL/min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Symptomatic</td>
<td>Asymptomatic</td>
<td>Symptomatic</td>
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<tr>
<td>1</td>
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<td>9</td>
<td>265</td>
<td>91</td>
<td>80</td>
</tr>
<tr>
<td>10</td>
<td>NINT</td>
<td>238</td>
<td>82</td>
</tr>
<tr>
<td>11</td>
<td>NINT</td>
<td>88</td>
<td>100</td>
</tr>
</tbody>
</table>

Mean±SD 188±65* | 96±52 | 55±20* | 15±22 | 147±78† | 256±95

Doppler velocity indicates highest systolic velocity on Doppler; PCVFR, phase-contrast volume flow rate; pl, plaque; nl, normal; and NINT, noninterpretable.

*P<.002, Wilcoxon two-sample rank test, symptomatic-side higher values.
†P<.01, Wilcoxon two-sample rank test, symptomatic-side lower values.

and validated by Tang et al12 and Sondergaard et al,13 velocity of flow was measured by acquiring two interleaved acquisitions with opposite polarity of the bipolar phase encoding gradients. The phase difference between the two acquisitions was proportional to the first gradient moment, a constant called the gyromagnetic ratio, and flow velocity. The first gradient moment was calculated based on amplitude and duration of the bipolar flow-encoding gradient. Thus, the phase difference between the two acquisitions was directly proportional to the velocity of flow along the applied axis of the bipolar gradient pulse.

The main advantage of this approach was that adverse effects of magnetic field inhomogeneity, eddy currents, and radiofrequency penetration were minimized.11 In the present study the scans were acquired in the axial plane, resulting in the assessment of flow in the superior/inferior direction. To encode for the correct range of velocities, the bipolar flow-encoding gradient amplitude and change in the first gradient moment were selected.

TABLE 2. Phase Cardiac Cycle Plot Data*

<table>
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<tr>
<th>Frame</th>
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<th>Left ICA</th>
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</thead>
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<tr>
<td>16</td>
<td>17.4505</td>
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</table>

Average 38.6 | 238.7

*Patient 9, Table 1, right internal carotid artery (ICA), symptomatic. PCVFR indicates phase-contrast volume flow rate.
FIG 2. Showing that laminar flow is reestablished quickly distal to a stenosis, thus allowing measurement of phase-contrast volume flow rate, note that the poststenotic internal carotid artery in this two-dimensional time-of-flight magnetic resonance angiogram (patient 9 in Tables 1 and 2) has excellent signal quality at the second cervical vertebral level (arrow). TR indicates repetition time; TE, echo time; R, right; and L, left.

moment was selected so that the phase shift varied from $-180^\circ$ to $+180^\circ$. This produced a linear phase shift over the range of desired velocities. The phase difference, which is proportional to velocity, was displayed as variations in pixel intensity on the phase image. Motion in the positive direction along the flow-encoding axis appeared as bright pixels, flow in the opposite direction appeared as dark pixels, and stationary tissue appeared gray. The PCVFR technique was also used because of its ability to integrate blood flow across the entire lumen of a particular vessel. A region of interest outlining the vessel was summed, thereby deriving the total flow across the slice. A region of interest was drawn around the edge of the vessel under study to exclude as much background as possible and reduce the amount of background noise in the calculations. Either "magnitude" images or "magnitude-weighted" velocity images were available for defining the region of interest. The region of interest was then superimposed in the subsequent images throughout the cardiac cycle, typically 16 images total, to determine whether the vessel changed in size or location during the cardiac cycle. If the vessel was in a different configuration, new regions of interest had to be defined. The background stationary tissue was then sampled adjacent to the vessel. A phase correction was performed from local background points. The value in each pixel of each frame of the velocity-encoded image represented the average velocity of flow in that pixel (in centimeters per second). When each pixel (in centimeters per second) was multiplied by the pixel area (in square centimeters), the PCVFR (in milliliters per second) through that pixel in that frame was obtained. Summation of such values within a region that contained the blood vessel of interest yielded the total PCVFR (in milliliters per minute) through the vessel at that time.

FIG 3. Plot shows regression of Doppler vs percent stenosis as measured on invasive angiography. With the possibility of reduced Doppler velocity with some high-grade lesions, correlating with increased stenosis, a linear relation will no longer be a sufficient description of these data. ICA indicates internal carotid artery.

FIG 4. Plot shows regression of Doppler vs phase-contrast volume flow rate (PCVFR). Note that one Doppler reading (solid black circle with arrow), with a low PCVFR reading, was uninterpretable. If this point was available, the regression line might shift upward and the $R^2$ value would be higher, or it might shift downward if the high-grade stenosis had a reduced Doppler reading. Again, expansion of the data set to include more patients with high-grade internal carotid artery (ICA) stenosis will remove the linearity of this relation.

\[ y = 0.4x + 17 \]
\[ F = 163, p < 0.01 \]
\[ r^2 = 0.90 \]
\[ Residual error = 9 \]
point in the cardiac cycle, and the average PCVFR throughout the cardiac cycle was then calculated. For vascular measurements, a region of interest was defined for each of the internal carotid arteries at peak systole in the cardiac cycle. Distal extracranial internal carotid arteries were studied so as to avoid undesired loss of signal, which usually occurs five to seven vessel diameters distal to a moderate or high-grade stenosis. Although our measurements are not at a fixed distance, they are uniformly done at the level of the second cervical vertebrae.

Magnetic resonance imaging parameters included repetition time of 54 milliseconds, echo time of 9.7 milliseconds, two excitations, flip angle of 30 degrees, matrix of 256×128 pixels, field of view of 16 to 18 cm, and section thickness of 5 mm.6,7 The PCVFR measurements were made independently and blinded to the results of carotid Doppler and XRA measurements. Linear regressions were employed using all arterial measurements, whether symptomatic or not. Two-tailed Wilcoxon two-sample rank testing was used to study symptomatic versus asymptomatic sides in terms of the measurement of each technique. Bonferroni’s method of correction was applied to multiple comparisons.

Results

Carotid Doppler measurements of systolic velocity were available on 11 asymptomatic and nine symptomatic internal carotid arteries, respectively. Doppler examinations were otherwise uninterpretable in two symptomatic arteries, one of which was completely occluded and the other nearly occluded as viewed on XRA. The mean±SD systolic velocities of the interpretable data were 96±52 and 188±65 cm/s for asymptomatic and symptomatic sides, respectively (P<0.002, Table 1).

The XRA measurements of percent stenosis were available on all 22 internal carotid arteries. The mean±SD percent stenosis was 15±22% and 55±20% for asymptomatic and symptomatic sides, respectively (P<0.002, Table 1).

Magnetic resonance measurements of distal extracranial PCVFRs (Table 2, Figs 1 and 2) were also available on all 22 internal carotid arteries. The mean±SD PCVFRs were 256±95 and 141±78 mL/min for asym-

tomatic and symptomatic sides, respectively (P<0.01, Table 1).

Doppler measurements were directly proportional to measured percent stenosis (P<0.01, Fig 3). Doppler measurements were inversely proportional to PCVFRs (P<0.01, Fig 4), and PCVFRs were inversely proportional to measured percent stenosis (P<0.01, Fig 5).

Discussion

Phase-contrast MRA is a flow analysis technique that accurately measures blood flow to the brain in normal and disease states. Noninvasive measurements of flow velocity and volume flow rates are generated from velocity-induced differences in spin phase. The quantitative accuracy of phase-contrast measurements of velocity and volume flow rates has also been validated.11,17 Bendel et al.18 in a study of two normal volunteers and six patients with cerebrovascular disease, found that MRA measurements yielded values between 250 and 580 mL/min for the PCVFR through each of the common carotid arteries in the two normal volunteers.

Few techniques have evolved as rapidly as MRA. There are a few studies that have compared XRA with MRA of the carotid bifurcation,19-23 but MRA often overestimates the degree of stenosis.23 In the present study we have been able to show preliminary correlations between carotid Doppler systolic velocity, conventional XRA-measured percent stenosis, and PCVFRs of the extracranial internal carotid artery. Our correlations are tempered by our small data sampling and by our limited number (n=2) of internal carotid arteries with high-grade stenosis. As we study more patients with high-grade stenosis in the preocclusive ≥85% range, a reduction in Doppler velocity might well be the expected correlation to a reduced PCVFR value. The impetus of this relation is reflected in the low R2 value of .29 in Fig 4. Figs 4 and 5, realistically, will become bimodal or hyperbolic once we expand our data set to include more preocclusive internal carotid arteries.

Despite a limited number of subjects and a limited number of preocclusive stenoses, we found that Doppler systolic velocities and measured stenoses were significantly higher and PCVFRs were significantly lower for the symptomatic-side extracranial internal carotid artery compared with the asymptomatic side. As our data set expands and we study higher-grade stenoses, we anticipate that linear regressions will no longer suffice as a data analysis technique. We do believe, however, that we have begun to noninvasively demonstrate specific measured flow volume data relative to arterial pathology.

Future advances in these measurement techniques include sophistication of the PCVFR determination at the site of maximal stenosis and more exacting measurements of the percent stenosis on the magnetic resonance vascular anatomic images. A paradigm to compare middle cerebral artery PCVFRs and internal carotid artery PCVFRs will allow direct quantitation of potential collateral flow to the symptomatic hemisphere of patients with vascular disease.

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References

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**Preliminary results.**

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