Magnetic Resonance Imaging of Flow Dynamics in the Circle of Willis

Robert R. Edelman, MD, Heinrich P. Mattle, MD, Gerald V. O'Reilly, MD, Klaus U. Wentz, MD, Cheng Liu, MD, and Bin Zhao, MD

Magnetic resonance angiography was applied to the study of blood flow dynamics in the circle of Willis in nine patients with cerebrovascular disease and two normal volunteers. In conjunction with two-dimensional or three-dimensional gradient-echo acquisitions, selective presaturation of individual vessels was used to determine the direction of blood flow and the origin of the vascular supply. Presaturation causes signal loss within the territory supplied by the presaturated artery, without affecting vessels not crossing the presaturation slab. The results were correlated with those from transcranial Doppler sonography and conventional angiography. Magnetic resonance angiography was able to demonstrate the direction of blood flow, the presence or absence of collateral blood flow, and the blood supply to the pericallosal arteries, as well as the presence of a fetal posterior circulation. Magnetic resonance angiography is a noninvasive means for imaging the blood supply of the major intracranial arteries. (Stroke 1990;21:56-65)

Since Thomas Willis's original description of the arterial circle at the base of the brain in 1664 and its rendering by Sir Christopher Wren, many studies have shown the role of the circle of Willis as a collateral channel to compensate for occlusions and tight stenoses of the extracranial arteries.1-5 Collateral blood flow at the level of the circle of Willis can be assessed noninvasively by transcranial Doppler sonography (TCD).6,7 Recently, magnetic resonance (MR) angiographic techniques have been developed that permit a three-dimensional (3D) display of vessel anatomy without the administration of a contrast agent.8-10 However, to be competitive with conventional angiography, MR angiography should show not only vessel morphology but should also provide functional information, such as delineate specific vascular territories. We describe the application of a novel approach using MR angiography that provides functional information similar to that obtained by conventional angiography. The method, which we call "selective" MR angiography, was applied to normal subjects and patients with cerebrovascular disease to image the collateral circulation across the circle of Willis.

Subjects and Methods

Table 1 summarizes the clinical information of the patients and the two volunteers with normal cerebral circulations. One volunteer was examined to test occlusions of the common carotid artery (CCA). During MR angiography, this volunteer performed autocompression of the CCA with his contralateral hand during the 4 seconds required to obtain each image.

Eight of the nine patients underwent conventional cerebral angiography (seven by selective angiography with cut films and one by intra-arterial digital subtraction angiography). In addition, the seven patients with ischemic cerebral symptoms were examined by TCD (TC 2-64B, EME, Ueberlingen, FRG). The examination technique has been described.6,11 TCD failed in one of the seven patients since the temporal bone was too thick to permit sufficient ultrasound penetration.

Figure 1 illustrates the basic MR angiographic technique used to determine blood flow dynamics. In standard MR imaging, radiofrequency (RF) pulses are used to excite tissue protons within thin slices for two-dimensional (2D) imaging or within thick slabs for 3D imaging. The signal intensity produced by the tissue protons is proportional to their steady-state alignment with the main magnetic field that existed at the moment before application of the RF pulse. The application of multiple RF pulses for imaging per-
TABLE 1. Clinical Information for Subjects

<table>
<thead>
<tr>
<th>Case</th>
<th>Age</th>
<th>Sex</th>
<th>Clinical presentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>70</td>
<td>M</td>
<td>Minor stroke ipsilateral to occlusion, visual field defect</td>
</tr>
<tr>
<td>2</td>
<td>49</td>
<td>F</td>
<td>Minor stroke ipsilateral to occlusion, aphasia</td>
</tr>
<tr>
<td>3</td>
<td>82</td>
<td>M</td>
<td>Transient blindness</td>
</tr>
<tr>
<td>4</td>
<td>76</td>
<td>M</td>
<td>Asymptomatic; carotid bruit</td>
</tr>
<tr>
<td>5</td>
<td>41</td>
<td>F</td>
<td>Recurrent transient left monocular blindness</td>
</tr>
<tr>
<td>6</td>
<td>68</td>
<td>F</td>
<td>Recurrent asymptomatic internal carotid artery stenosis after endarterectomy</td>
</tr>
<tr>
<td>7</td>
<td>62</td>
<td>M</td>
<td>Permanent right monocular blindness</td>
</tr>
<tr>
<td>8</td>
<td>21</td>
<td>F</td>
<td>Left parietal hemorrhage 1 year prior to examination; full recovery</td>
</tr>
<tr>
<td>9</td>
<td>30</td>
<td>M</td>
<td>Three subarachnoid and ventricular hemorrhages; full recovery</td>
</tr>
<tr>
<td>Volunteers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>37</td>
<td>M</td>
<td>Normal volunteer</td>
</tr>
<tr>
<td>11</td>
<td>47</td>
<td>M</td>
<td>Normal volunteer</td>
</tr>
</tbody>
</table>

Age in years. M, male; F, female.

Turbs the steady-state alignments so that the tissue protons produce a lower signal and are said to be partially saturated. The amount of saturation depends on a balance of the time between excitations (repetition time [TR]) and the T1 relaxation time of the tissue. For gradient-echo pulse sequences, in which only a single RF pulse is applied (as opposed to the two-pulse spin-echo sequence), flowing blood appears brighter than stationary tissues. This is because fully aligned, fresh blood protons that have not been exposed previously to RF pulses continuously flow into and out of the slice. These fully aligned protons produce an intense signal, which contrasts with the lower signals from partially saturated stationary tissues. To further enhance the signal intensity of flowing blood, an additional gradient pulse is incorporated into the pulse sequence to eliminate signal loss due to phase shifts induced by constant-velocity flow; this technique is called flow-compensation.

It is possible to modify the appearance of flowing protons by applying an extra RF pulse to them before they flow into the imaging slice. This method is called presaturation.12–14 If the time between application of the presaturation pulse and the RF excitation used for imaging is short compared with the T1 of blood, then flowing blood will be saturated and will appear dark, even if the presaturation pulse is applied to a region that is moderately distant from the imaging slice.

We performed MR angiographic studies using a 1.5-T whole-body scanner (Siemens Medical Systems, Inc., Erlangen, FRG). A linear-mode resonator coil was used for head studies. The gradient-echo technique was a fast low-angle shot (FLASH) sequence with first-order (velocity) compensation.15,16 Individual 2D FLASH images are acquired in just a few seconds; alternatively, a series of contiguous slices are acquired during a few minutes using 3D
acquisition. The 2D FLASH images were acquired in 4 or 8 seconds with a 256×128 or a 256×256 matrix, respectively, and a 25-cm field of view. Scan parameters were TR/echo time (TE)/flip angle 30 msec/10 msec/30°, slice thickness 5 mm, and a single excitation. The 3D images were acquired in 5 minutes using a 3D flow-compensated FLASH sequence. Scan parameters were TR/TE/flip angle 40 msec/8 msec/15°, slab thickness 80 mm, 64 partitions 1.25 mm thick, and a single excitation. Images from the 3D acquisition were postprocessed using a maximum-intensity projection algorithm to create an angiogram-like image (projection angiogram). This method extracts the pixels with the highest intensities from the set of images as viewed along a user-selected angle and assigns the signal intensities to pixels in a projection image. With proper selection of the scan parameters and the pulse sequence, flow-related enhancement makes blood vessels the brightest structures in an image. Therefore, only blood vessels are shown in the final projection image.

Depending on the required degree of vessel selectivity, presaturation regions (slabs) were 1–5 cm thick and could be applied in an arbitrary user-defined orientation. Presaturation causes a loss of signal within the vascular territory supplied by that vessel, including collateral blood flow, without affecting territories supplied by other vessels not coursing through the presaturation slab. However, it is critical to orient the presaturation slab to avoid affecting vessels other than the one of interest.

Results

Results are summarized in Table 2. The following are illustrative cases.

Case 2. Conventional selective arteriography showed occlusion of the left internal carotid artery (ICA). The right ICA appeared normal and also filled the left anterior cerebral artery (ACA) and the middle cerebral artery (MCA) (Figure 2, top left). TCD corroborated collateral blood flow across the anterior part of the circle of Willis from right to left. The MR angiograms showed blood flow in both MCAs (Figure 2, middle left). Presaturating the open right ICA eliminated the signal in the vascular bed of the left MCA (Figure 2, bottom left), while presaturating the left ICA did not affect the appearance of the right MCA signal (Figure 2, right).

Case 3. Conventional angiography revealed 75% stenosis of both ICAs but no collateral circulation. TCD was normal. Selective presaturation of the ICAs did not change the signal in the arteries of the opposite hemisphere, indicating blood supply from the ipsilateral side. Presaturation of the vertebral arteries did not change the signal in the MCAs, implying no blood supply from the vertebobasilar system to the territory of the stenosed carotid arteries.

Case 5. Conventional angiography revealed a high-grade (90%) stenosis of the left ICA; the right ICA was normal. Conventional angiography also revealed slight collateral blood flow from the right to the left ICA territories across the anterior part of the circle of Willis. In this case, there was discordance of conventional angiography compared with TCD and MR angiography. TCD did not demonstrate the collateral blood flow seen on conventional angiography. The blood flow in both ACAs was antegrade but asymmetric. Mean maximal velocity in the right ACA was 58 cm/sec while that in the left ACA was only 24 cm/sec; this velocity difference is abnormal. TCD did not identify blood flow across the posterior communicating artery. MR angiography showed antegrade blood flow in both ACAs. Presaturating the ICAs did not affect the signal in the contralateral ACAs or MCAs. Presaturation of the posterior circulation had no effect on the anterior circulation.

Case 6. Conventional angiography demonstrated a high-grade (90%) stenosis of the right ICA. There was slight collateral blood flow across the anterior part of the circle of Willis to the right MCA after injection of contrast into the left ICA. The first segment of the pericallosal arteries was unpaired (so-called azygos type), and the right ACA appeared hypoplastic. The pericallosal arteries filled from the left side (Figure 3, top). The 3D MR angiogram in a coronal plane demonstrated a single vessel in the midline, corresponding to the unpaired segment of the pericallosal arteries (Figure 3, upper middle). Presaturating the right carotid system did not alter the signal of the azygos ACA or that of the left MCA (Figure 3, lower middle). Presaturating the left carotid artery eliminated the signal in the azygos ACA (Figure 3, bottom). However, the signal in the right MCA was not changed. The right MCA was thus, in contrast to the ACA, not supplied from the left ICA.

Case 8. Conventional angiography demonstrated a large left parietal arteriovenous malformation that was primarily supplied from the left MCA and to a minor extent from a peripheral branch of the left posterior cerebral artery (PCA). The left PCA originated from the basilar artery (BA) (Figure 4, top left). The origin of the right PCA from the BA was markedly hypoplastic. The right PCA was fed mainly from the right ICA via the right posterior communicating artery (Figure 4, bottom left). Presaturating the carotid arteries while performing 3D MR angiography eliminated the signal of the right PCA (Figure 4, bottom right) while the signal in the left PCA was unchanged compared with 3D MR angiography without presaturation (Figure 4, top right).

Case 10. This normal volunteer was examined to demonstrate the collateral capacity of the circle of Willis. Results of extracranial Doppler and TCD were normal. Upon compression of the left or right CCA, TCD showed immediate collateral blood flow across the anterior part of the circle of Willis. MR angiography without compression demonstrated symmetric signals in both ACAs and MCAs (Figure 5, top). Presaturating the left ICA did not affect the signal of the right MCA (Figure 5, middle). When the volunteer compressed the right CCA with his left hand, the signals of the right MCA and ACA disap-
<table>
<thead>
<tr>
<th>Case</th>
<th>Patients</th>
<th>Conventional angiography</th>
<th>Transcranial Doppler sonography</th>
<th>Magnetic resonance angiography</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>R ICA occlusion, L ICA supplies, R ACA and MCA</td>
<td>Collateral blood flow from L to R</td>
<td>Collateral blood flow from L to R</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>L ICA occlusion, R ICA supplies L ACA and MCA</td>
<td>Collateral blood flow from R to L</td>
<td>Collateral blood flow from R to L</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Bilateral 75% stenosis of ICA</td>
<td>No collateral circulation</td>
<td>No collateral circulation</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>65% stenosis of R ICA, 50% stenosis of L ICA, no collateral circulation</td>
<td>No collateral circulation</td>
<td>No collateral circulation</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>90% stenosis of L ICA, probable fibromuscular dysplasia, collateral circulation from R ICA to L ACA and MCA</td>
<td>Asymmetric velocities in ACAs, no collateral blood flow</td>
<td>No collateral circulation</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>90% stenosis of R ICA. Faint cross-flow from L ICA to MCA. Azygos-type pericallosal artery filled from L</td>
<td>No signal obtained because temporal bone too thick</td>
<td>Filling of pericallosal arteries from L</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Not performed</td>
<td>Collateral blood flow from L ACA to R ACA and MCA</td>
<td>Collateral supply of R ACA and MCA from L ICA</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>L parietal AVM fed from L MCA and PCA branch. L PCA originates from BA, R PCA from R ICA and PCoA, respectively</td>
<td>Not performed</td>
<td>Supply of R PCA from carotid and L PCA from BA system</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>L parieto-occipital AVM fed from MCA and anterior and posterior choroidal arteries. L PCA originates from BA, R PCA from R ICA and PCoA, respectively</td>
<td>Not performed</td>
<td>Supply of R PCA from carotid artery, L PCA from BA</td>
<td></td>
</tr>
</tbody>
</table>

**Volunteers**

<table>
<thead>
<tr>
<th>Case</th>
<th>Patients</th>
<th>Conventional angiography</th>
<th>Transcranial Doppler sonography</th>
<th>Magnetic resonance angiography</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Not performed</td>
<td>Collateral blood flow during test compressions</td>
<td>Collateral blood flow during test compressions</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Not performed</td>
<td>Normal</td>
<td>Presaturation of vertebral arteries at atlas loop eliminates BA and PCA signals</td>
<td></td>
</tr>
</tbody>
</table>

R, right; L, left; ICA, internal carotid artery; ACA, anterior cerebral artery; MCA, middle cerebral artery; AVM, arteriovenous malformation; PCA, posterior cerebral artery; BA, basilar artery; PCoA, posterior communicating artery.

Peared, indicating crossflow from the open ICA to territory of the compressed right ICA (Figure 5, bottom).

**Case 11.** This volunteer was examined to localize the best position of the presaturation slab to eliminate the signal in the vertebrobasilar circulation without disturbing the signal in the carotid system. The signal in the vertebrobasilar arteries can be selectively eliminated by presaturation of the vertebral arteries at the level of the atlas loop, where they
FIGURE 2. Case 2; left internal carotid artery (ICA) occlusion. Right side of body appears on left side of figure. Top left: Selective right ICA angiogram demonstrates collateral right-to-left blood flow through anterior communicating artery. Middle left: Axial fast, low-angle shot (FLASH) magnetic resonance image shows blood flow in both middle cerebral arteries (MCAs). Bottom left: Presaturation of right ICA (dark bar) eliminates signal from left MCA. Remaining signal (arrow) is from middle cerebral vein sinus, flowing to cavernous sinus. Right: Presaturation of left ICA (dark bar) does not eliminate signal in right MCA.

are farthest from the carotid arteries. First, the position at which the vertebral arteries loop posteriorly around the atlas was localized with an axial FLASH image (Figure 6, top). Based on this image, the presaturation slab was positioned posterior to the carotid arteries. The 3D MR angiogram at the level of the circle of Willis demonstrated that there was no signal from the BA and PCAs (Figure 6, middle). For comparison, the same 3D MR angiogram without presaturation was performed; the BA and PCAs were clearly seen (Figure 6, bottom).

Discussion

We have demonstrated the application of newly developed MR techniques to study blood flow direction in the basal cerebral arteries and collateral blood flow at the level of the circle of Willis. These methods use the combination of 2D or 3D MR angiography
FIGURE 3. Case 6; high-grade stenosis of right internal carotid artery (ICA). Right side of body appears on left side of figures. Top: Left ICA angiogram, frontal view. Azygos anterior cerebral artery (ACA) filled from left ACA. Right ACA is hypoplastic and there is faint filling of right middle cerebral artery (MCA) due to left-to-right collateral blood flow. Upper middle: Coronal three-dimensional magnetic resonance angiogram shows single vessel in midline, corresponding to azygos ACA (arrow). Lower middle: Presaturation of right ICA (dark bar) does not affect signal of vessel in midline or left MCA. Bottom: Presaturation of left ICA (dark bar) demonstrates that right MCA is not supplied from left ICA. However, signal of azygos ACA is eliminated, indicating its supply from left ICA.
FIGURE 4. Case 8; fetal posterior circulation. Right side of body appears on left side of figures. Top left: Left vertebral angiogram, frontal view. Marked asymmetric filling of posterior cerebral arteries (PCAs). Origin of right PCA from basilar artery (BA) is hypoplastic. Bottom left: Right internal carotid artery (ICA) angiogram, frontal view, demonstrates good filling of right PCA. Top right: Axial three-dimensional magnetic resonance (3D MR) angiogram. Symmetric filling of PCAs and posterior communicating arteries. Bottom right: Axial 3D MR angiogram combined with coronal presaturation of ICAs (dark bar). Signal in right PCA disappears, indicating its blood supply is primarily from right ICA.

with RF presaturation pulses to determine blood flow dynamics. The selective MR angiography technique is rapid and lengthens the study time for a routine MR examination by only a few minutes.

MR accurately demonstrated the direction of blood flow, the presence or absence of collateral blood flow, and the blood supply to the pericallosal arteries and to the PCAs. In one patient, there was a discrepancy between the findings by conventional angiography and those of TCD and MR angiography. The significance of this discrepancy is uncertain. Conventional angiography showed collateral blood flow while the other two techniques did not. It is possible that TCD and MR angiography provide more accurate definition of the patterns of collateral blood flow under existing physiologic conditions than conventional angiography, which may not always be completely accurate since contrast injection might transiently produce a nonphysiologic state by increasing pressure in the injected vessel. Alternatively, different physiologic conditions may have existed at the time of conventional angiography compared with TCD and MR angiography (e.g., different blood pressure), so that the examinations may not be directly comparable.

Collateral blood flow patterns may have significant clinical implications in patients at risk for stroke. The presence or absence of collateral blood flow, in association with cerebrovascular occlusive disease, may affect the clinical presentation and area of ischemic damage. The combination of 3D MR angiography with the assessment of collateral blood flow by MR may prove useful in acute stroke patients. It can be used to show occlusion of portions of the
circle of Willis due to an embolus or extension of a thrombus from the ICA and the presence of surviving collateral pathways. This information might be helpful in the classification of acute stroke patients and might more accurately predict their prognosis. It might also be useful in designing and evaluating medical treatment studies or in planning aggressive therapeutic strategies, such as local intra-arterial fibrinolysis\textsuperscript{25,26} or emergency embolectomy.\textsuperscript{27}

TCD is an excellent method for demonstrating collateral blood flow through the anterior communicating artery. Moreover, TCD is a bedside tool and can be applied in unstable patients, which is not the case with MR angiography. However, MR angiography does have significant advantages over TCD. First, MR angiography produces images with high spatial resolution and can directly demonstrate vascular lesions. This is not currently feasible with TCD.

FIGURE 5. Case 10; volunteer examined to demonstrate collateral capacity of circle of Willis. Right side of body appears on left side of figures. Top: Axial fast, low-angle shot (FLASH) magnetic resonance image shows symmetric signal from both anterior cerebral arteries (ACAs) and middle cerebral arteries (MCAs). Arrows indicate sphenoparietal sinus. Middle: Presaturation of left internal carotid artery (ICA) (dark bar) does not affect signal of right MCA. Bottom: Presaturation of left ICA (dark bar) while right common carotid artery compressed eliminates signal from right ACA and MCA.
Second, the field of view is not restricted with MR angiography. Therefore, it can visualize collateral pathways that cannot be shown by TCD. For instance, we showed blood flow through a fetal posterior circulation, which cannot be demonstrated reliably by TCD. This finding can have important clinical implications. This condition, in which an embryonic circulation persists and the PCA remains a branch of the ICA, is present unilaterally in 10% and bilaterally in 7.7% of adults. Thrombosis or embolism of the ICA
blood flow across the circle of Willis and thereby may cause ischemic symptoms or infarction of the occipital pole.23-29 Conversely, such an anatomic configuration prevents occipital pole infarction in BA territory in a patient with fetal posterior circulation.23-29 To date, only conventional angiography has been capable of demonstrating the origin of the PCA. In our study, MR angiography demonstrated a fetal posterior circulation in two angiographically verified cases (Figure 4). If the PCA originates from the BA, carotid artery disease would be considered irrelevant to symptoms in the posterior circulation. If a fetal posterior circulation is present, then carotid artery disease could be the source of the symptoms and a carotid endarterectomy would be a therapeutic consideration. Thus, in addition to its general utility in assessing collateral blood flow pathways in the cerebrovascular system, MR angiography may prove particularly useful in patients with occipital lobe ischemia.

A final application of MR angiography may be in the planning of therapy for patients who are candidates for carotid ligation or balloon occlusion for a cavernous carotid aneurysm or fistula or neck tumors involving the carotid sheath. In these patients, autocompression may be performed to assess collateral blood flow across the circle of Willis and thereby evaluate the risk of stroke from such potential arterial occlusive procedures.

In conclusion, we have shown that MR angiography demonstrates collateral blood flow across the circle of Willis and shows detailed 3D anatomy of the cerebrovascular system. This method may improve our understanding of the pathogenesis of stroke and ensure that the most appropriate treatment is instigated.

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References

Key Words • cerebral blood flow • circle of Willis • magnetic resonance imaging • ultrasonics
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