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Qualitative Phase Contrast MRA in the Normal and Abnormal Circle of Willis

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PURPOSE: To determine the direction of blood flow in the circle of Willis using a 3-D phase contrast MR angiographic (MRA) technique with high spatial resolution. **SUBJECTS:** Fifty healthy subjects and 15 patients with occlusive disease were studied using 3-D phase contrast MRA. **RESULTS:** In the 50 normal subjects, 39 (78%) had detectable flow in one or both posterior communicating arteries. In 24 (48%) of these subjects, flow was detected in both posterior communicating arteries, whereas unilateral flow was detected in 15 (30%). In 36 (92%) of the 39 normal subjects, flow in the posterior communicating artery was from anterior to posterior with only 3 (8%) showing reverse flow from posterior to anterior. The A1 segment of both anterior cerebral arteries was identified in 100% of normal subjects with flow in the expected direction from carotid to the A2 segment. In patients with carotid occlusion, the pattern of flow in the circle of Willis was altered with reversed flow in the ipsilateral posterior communicating artery and sometimes in the ipsilateral A1 segment. An ipsilateral posterior communicating artery was present in 10 of 17 occluded carotid arteries, all showing reversed flow. **CONCLUSION:** 3-D phase contrast MRA provides useful information about the hemodynamics of normal and abnormal blood flow in the circle of Willis.

Index terms: Magnetic resonance angiography (MRA); Cerebral blood, flow; Arteries, cerebral; Arteries, carotid

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Although the anatomy of the circle of Willis is well known, the physiologic flow of blood in the adult under normal circumstances has not been studied to our knowledge. While conventional angiography provides some information, it is not performed under normal physiologic conditions. In neonates, color Doppler imaging has permitted characterization of flow in the circle of Willis of full-term infants (1). Phase contrast magnetic resonance angiographic (MRA) techniques use signals derived from phase shifts caused by flowing blood (2–6). In contradistinction to time-of-flight techniques, the phase contrast sequence measures a vector quantity that contains information about blood flow direction and velocity. This information can be used to produce qualitative analyses of blood flow in normal and abnormal vessels. We have adapted this technique to identify the normal direction of blood flow in the vessels of the circle of Willis and have applied this method to identifying abnormal flow secondary to vessel occlusion.

Materials and Methods

Patients were selected for inclusion in this study group based on the following criteria: nonspecific, nonlateralizing neurologic complaints (ie, headache), no history of cerebrovascular disease, and normal, conventional T1-weighted, 800/20/1 (T1W) and T2-weighted 2500/30,80/1, (T2W) MR examinations. Fifty consecutive normal subjects who met these criteria were entered in the study group. A second group consisted of 15 patients with known (angiographically proven) carotid occlusive disease. Of these, two patients had bilateral carotid occlusions and the remaining 13 had unilateral carotid occlusions. Thus, 17 hemispheres were at risk.

All patients as well as normal subjects underwent a 3-D phase contrast MRA sequence for evaluation of the circle of Willis. Scans were performed on a 1.5-T system (Signa, GE Medical Systems, Milwaukee, WI) in the axial plane with these parameters: TR 25, TE minimum (<10), flip

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angle 20–25°. To maximize small vessel resolution a 256 × 256 matrix was used. Section thickness was calculated to produce isotropic $.97^3$–1.0^3 mm^3 voxels within the volumetric data set. Imaging volumes consisted of 28–60 sections. A "source" image is an individual section in this 3-D data set. A "collapsed" or "projection" image is the summation of some or all of the sections in the data set in an axial orientation.

A peak-encoded velocity (VENC) of 80 cm/sec was used for this study. This MRA technique allows for flow encoding in all three orthogonal directions and produces three direction-sensitive flow images (right/left, anterior/posterior, superior/inferior) for each section location:

1. Right-to-left image depicts right-to-left flow as white, left-to-right flow as black.
2. Anterior/posterior image depicts anterior-to-posterior flow as white, posterior-to-anterior flow as black.
3. Superior/inferior image depicts superior-to-inferior flow as white, inferior-to-superior flow as black.

Conventional magnitude images that depict static anatomy are also produced.

Thick axial projection (collapsed) images covering the entire circle of Willis are produced from the 3-D data set using an algorithm that is a variant of maximum intensity projection (6). In this method, the pixel value having the largest absolute value along a ray is retained, including its sign. In contrast to maximum intensity projection, the resulting pixel value can be positive or negative and, therefore, direction information is retained.

The axial projection flow images were analyzed for the presence or absence and the direction of blood flow in the posterior communicating (PComm) arteries and in the A1 segment of the anterior cerebral arteries. When these arteries were not detectable on the projection images, the individual source images were analyzed.

Results

Flow in one or both PComm arteries was detected in 39 (78%) of the 50 normal subjects in this study group. In 24 (48%) subjects, flow in PComm arteries was seen bilaterally; in 15 (30%) subjects, flow in a PComm artery was identified unilaterally.

Flow was identified in a total of 63 PComm arteries in these 50 subjects; 57 of these (90%) were identified on the projection (collapsed) images (Fig. 1). The remaining six PComm arteries were small and required examination of individual thin section source images to detect them (Fig. 2). All three direction-specific images were necessary because different orientations of the PComm artery produced flow signal on different images. Therefore, phase images sensitive to flow in a right/left and superior/inferior direction, in addition to the anterior/posterior direction, could be necessary for small PComm identification.

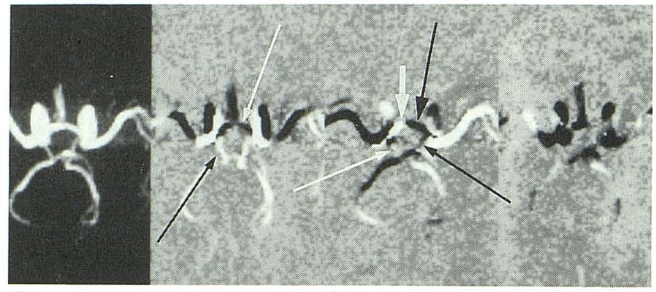


Fig. 1. Normal 3-D phase contrast MR angiogram.

A, Collapsed-speed image shows both posterior communicating (PComm) arteries and both A1 segments of the anterior cerebral artery.

B, Anterior to posterior image: flow from anterior to posterior is *"white"* and posterior to anterior is *"black."* Note normal PComm arteries are *white* (*black arrows*) indicating flow from anterior (carotid) to posterior (posterior cerebral) and normal A1 segments (*white arrows*) are *black* indicating flow from posterior (carotid) to anterior (anterior cerebral).

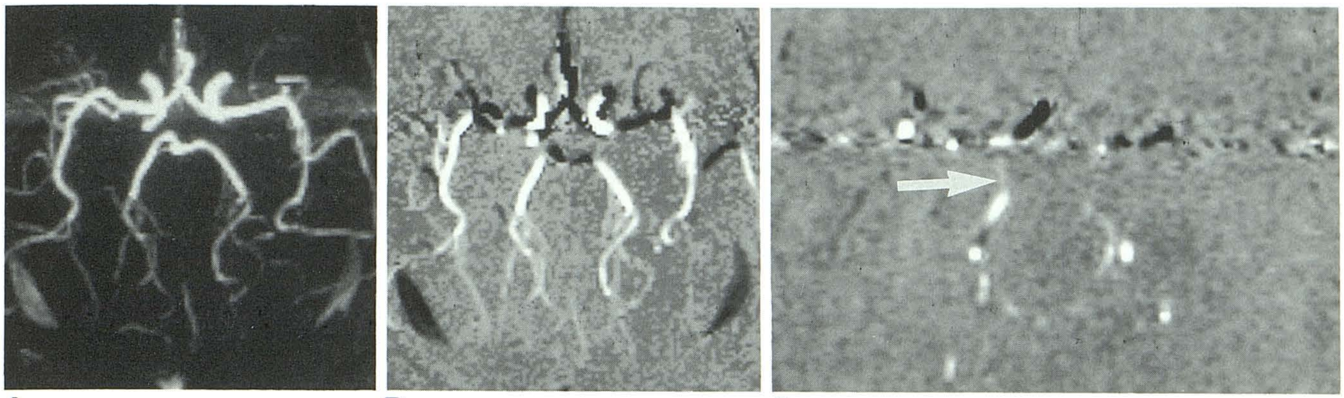
C, Right to left image: flow from right to left is *white* and left to right is *black*. Both PComm arteries and both A1 segments are visualized. Right = *long white arrow*, left PComm artery = *long black arrow*, right A1 = *larger white arrow*, left A1 = *larger black arrow*.

D, Superior to inferior image: flow from superior to inferior is *white* and inferior to superior is *black*. Neither PComm artery nor A1 segments are seen.

The direction of blood flow was from anterior (carotid) to posterior (posterior cerebral artery) in 36 (92%) of these normal patients with identified PComm arteries. Posterior to anterior blood flow was present in three (8%) normal patients. In this latter group, two had unilateral and one had bilateral posterior to anterior flow in the PComm arteries. Two of these three patients were in the pediatric age group, ages 7 and 9.

The A1 segment of the anterior cerebral arteries was identified in all 50 normal subjects bilaterally. In one subject, source image analysis was required to confirm flows in the A1 segment (Fig. 3). In all normal subjects the direction of flow in the A1 segment was from posterior (carotid) to anterior (A2 segment) and from lateral to medial, as expected.

This 3-D phase contrast MRA technique was applied to 15 patients with carotid occlusions, 13 with unilateral occlusions (left = 8, right = 5) (Fig. 4) and two with bilateral carotid occlusions (Fig. 5). A total of 17 hemispheres were at risk. Of these 17 occluded carotid arteries, 10 exhibited flow in the PComm arteries ipsilateral to the occluded carotid, and in each of these retrograde flow (posterior to anterior) was demonstrated (Fig. 6). Of these 10, four had small infarcts in a



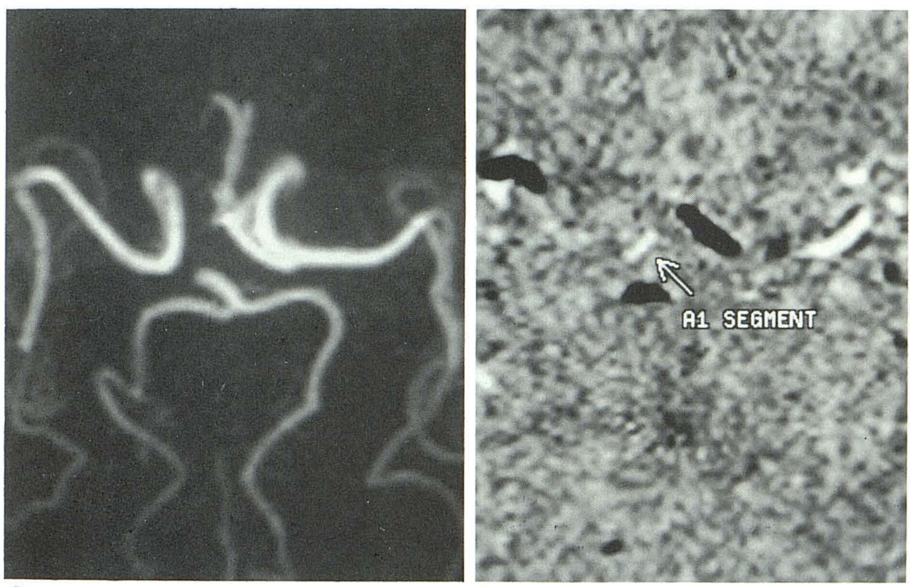
A B C

Fig. 2. Apparent absence of the posterior communicating (PComm) arteries in a normal subject.

A, The collapsed speed image does not demonstrate PComm arteries.

B, The anterior to posterior directional collapsed image also does not demonstrate PComm arteries.

C, The single-source image through the PComm arteries shows the presence of the right PComm artery (*arrow*) that is lost in the collapsed images (*A* and *B*). A smaller left PComm artery is also present.



A B

Fig. 3. Apparent absence of the A1 segment of the anterior communicating artery in a 65-year-old man. No posterior communicating arteries are visualized.

A, The collapsed-speed image shows apparent absence of the right A1 segment of the anterior cerebral artery.

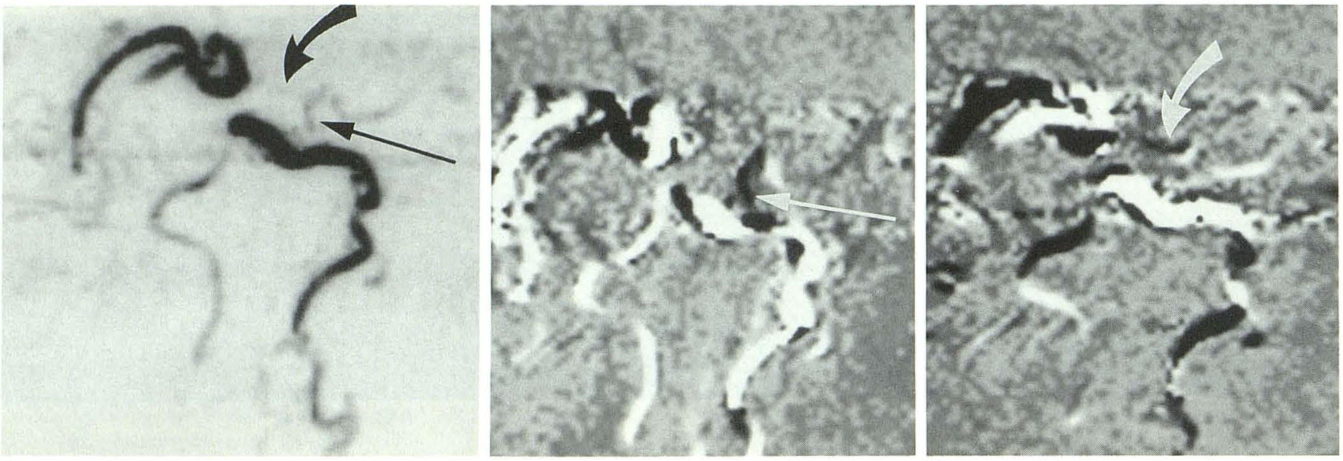
B, A single-source image (right/left axis) through the anterior cerebral arteries demonstrates presence of the right A1 segment (*arrow*) of the anterior communicating artery.

watershed distribution identified on the axial T2W images. Six had no detectable infarct.

In comparison, seven carotid occlusions had no demonstrable ipsilateral PComm artery. Of these seven, six had infarcts demonstrable on T2W images; four were large watershed infarcts and three were large middle cerebral artery infarcts. Only one of these occlusions did not have an infarct, and that patient had ophthalmic artery collateral flow. With carotid occlusion the presence of ipsilateral PComm artery flow appears to confer some protection against infarction, although this connection falls short of significance ($P = .082$, Fisher exact test). The phase contrast images showed the other relevant collateral pathways in carotid occlusion with reverse flow in the ipsilateral ophthalmic arteries (7), reverse flow in the ipsilateral A1 segment (3), and leptomeningeal collaterals (1).

Discussion

PComm arteries are commonly visualized in cerebral arteriography. Pathologic studies have shown a high incidence of their anatomic presence. Their functional presence under normal circumstances, however, is not known. Phase contrast MRA has the ability to detect this vessel if there is significant flow within it, and to determine the direction of blood flow. MRA depiction



A **B** **C**

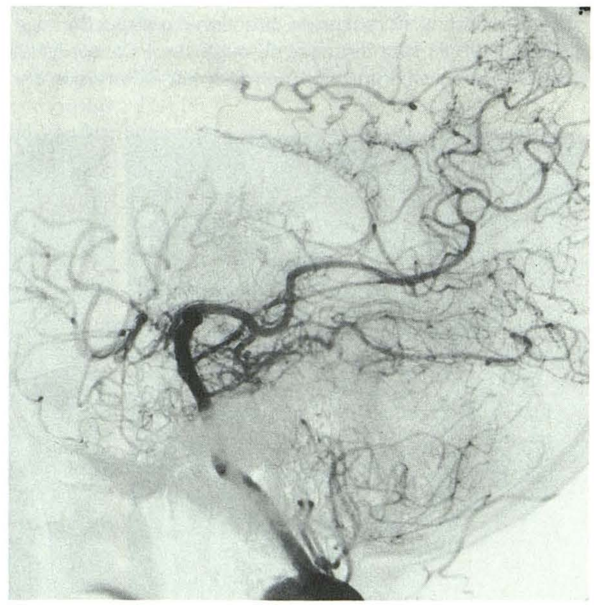
Fig. 4. Unilateral carotid occlusion with retrograde flow in the posterior communicating (PComm) artery and antegrade flow in the A1 segment of the anterior cerebral artery.

A, The collapsed-speed image demonstrates decreased flow in the left anterior and middle cerebral arteries due to the carotid occlusion. Note the presence of the left PComm artery (*arrow*) and a small left A1 segment (*curved arrow*) of the anterior cerebral artery. The large left posterior cerebral artery provides collateral circulation.

B, This collapsed anterior to posterior directional image shows a black PComm artery indicating retrograde collateral flow (*arrow*).

C, This right-to-left collapsed directional image shows a black A1 segment of the anterior cerebral artery (*curved arrow*) indicating antegrade flow as it fills from the retrograde flow from the PComm artery.

D, The vertebral injection demonstrates collateral flow to the anterior circulation via the left PComm posterior pericallosal, and leptomeningeal collaterals from the posterior cerebral arteries.



D

of this vessel depends on blood flow and, therefore, indicates its functional rather than anatomic presence. PComm arteries were identified in 78% of normal subjects with this technique, less than the 90% demonstrated in postmortem and angiographic studies (7). It is not unexpected that the PComm functional presence is lower than its detected anatomic presence, although different technique parameters might increase this fraction somewhat. MRA detection in this study is comparable to that in Doppler studies of newborns (70%) (1). Nevertheless, detectable flow in the PComm arteries was present in a high percentage of normal individuals. It is also not unexpected that anterior to posterior is the predominant flow direction. The 92% anterior to posterior flow in these normal individuals is similar to the high percentage seen in normal neonates, 98.6% (1). The reversed flow in two pediatric patients was unusual and no specific reason is evident, although similar findings have been reported in normal neonates (1). The A1 segments of the anterior cerebral arteries were seen in all normal individuals; flow was in the expected antegrade direction.

The technical parameters used in acquiring MRA images influences the detectability of small vessels with slow flow such as the normal PComm arteries. With phase-sensitive techniques, two major factors are important: 1) spatial resolution and 2) velocity encoding strength. One of these factors is the operator-selected VENC sensitivity to flow. This VENC defines the dynamic range of blood flow to which the sequence is sensitive. A high VENC chosen for major cerebral vessels will result in lower signal from vessels with slower

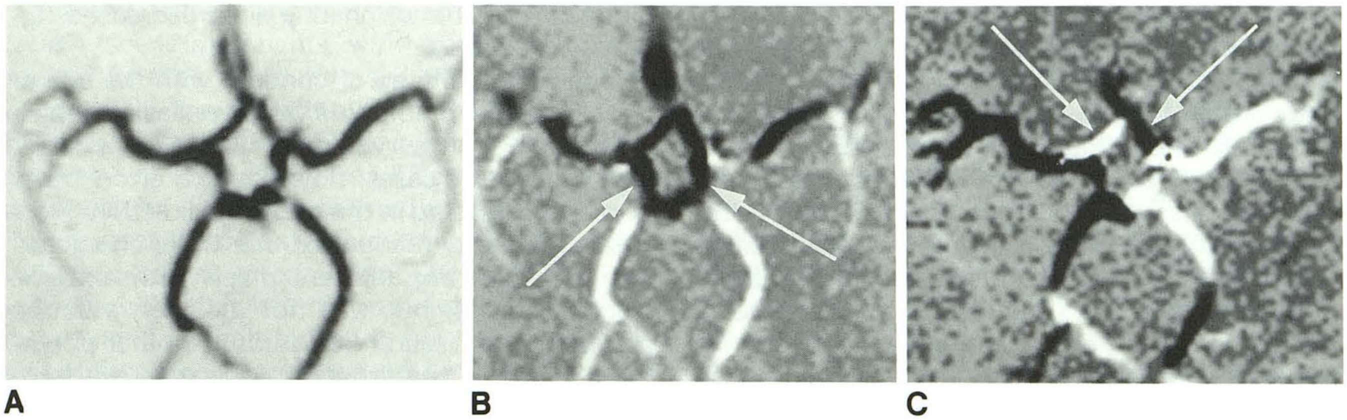


Fig. 5. Bilateral carotid occlusions.

A, The collapsed-speed image of the circle of Willis demonstrates an anatomically normal circle of Willis. Note the large posterior communicating (PComm) arteries.

B, The anterior/posterior directional image demonstrates black PComm arteries (*arrows*) indicating retrograde flow (anterior to posterior).

C, The right-to-left directional image confirms retrograde flow in both PComm arteries. There is antegrade flow in each anterior cerebral artery A1 segment (*arrows*) (right A1 = *white*, left A1 = *black*).

D, The conventional angiogram demonstrates filling of the entire anterior circulation via the PComm arteries.

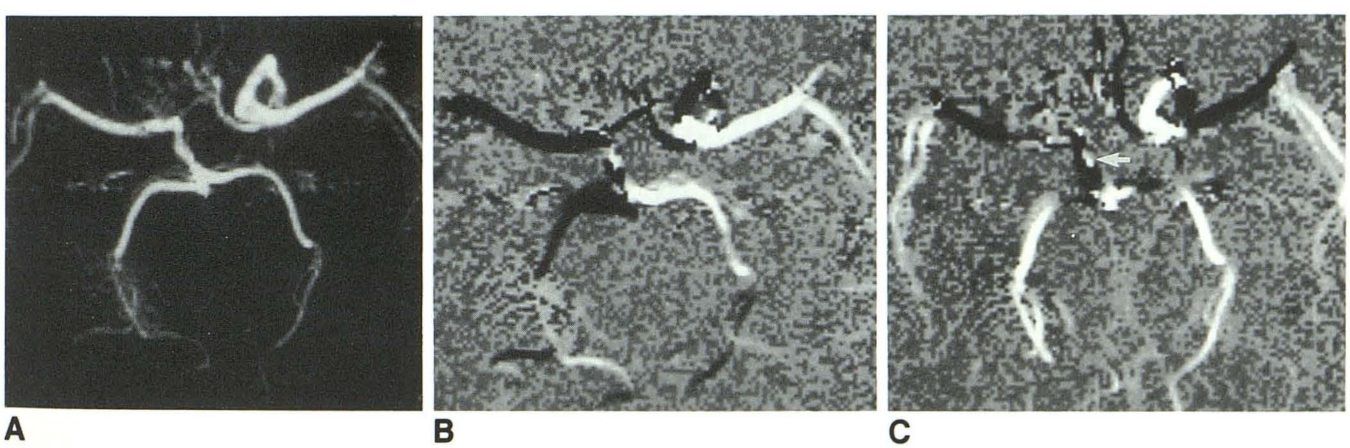


Fig. 6. MR angiogram (*B*) and phase contrast images (*B* and *C*) of a 6-year-old boy with right internal carotid occlusion and no evidence of cerebral infarction.

A, The MR angiogram shows occlusion of the right carotid artery and a large ipsilateral right posterior communicating artery. A small right A1 segment of the anterior cerebral artery is present.

B, The phase contrast image with flow encoding in the right-left direction shows retrograde flow in the ipsilateral A1 segment of the anterior cerebral artery (ie, *black* indicating right-to-left flow). The ipsilateral PComm artery is black with a small area of white. This white region is indicative of aliasing due to high flow.

flow. Because a relatively high VENC was employed in this study, slow flow through the PComm arteries fell at the bottom of the dynamic range making small vessels with slow flow more difficult to detect (Fig. 7). A smaller VENC would be preferred for studies in which evaluation of these vessels is the primary goal. It has been proposed that evaluation of MRA studies should include inspection of the individual source images of the acquired data set, because of reduced contrast in computed projections (8). This step is useful when signal intensity in the vessel is low due to slow velocity, small vessel size, and/or the presence of partial volume averaging. Source image analysis in this study did improve detection of small PComm arteries by 10% over axial projection image. Source image analysis was less critical for anterior cerebral detection.

The other major factor controlling vessel detectability is spatial resolution, which is a function of both section thickness and pixel size. Since the PComm arteries tend to lie in an axial plane, use of thicker axial sections would be deleterious. The PComm artery can have loops oriented in a sagittal plane, which can exacerbate partial volume effects. VENC in all three directions helped detection of arteries with more complex anatomic orientations. We used thin section thicknesses (0.7 mm–1.0 mm) and a 256 × 256 matrix to produce small isotropic voxels to minimize partial volume averaging. Smaller voxel sizes could further increase small vessel detection, but this advantage must be weighed against decreased signal-to-noise ratio.

One potential area of concern with the use of phase contrast methods is velocity aliasing, which occurs when true velocities exceed the peak VENC. In these cases, flows can be erroneously portrayed as being in the opposite direction. Flow aliasing is easily recognized due to its characteristic of producing adjacent pixels with extreme velocity values, but was not a factor with the parameters chosen in this study. Another potential concern is the limited information available with this technique if a voxel contains a small portion of a vessel and a large proportion of static signal. In these cases, direction information can be compromised. This was not a factor in the present study due to the use of small isotropic voxels.

This study was undertaken to determine the normal distribution of blood flow in the circle of Willis. The 3-D phase contrast angiogram allows complete delineation of the direction of blood flow in the circle of Willis. This information is available primarily on the images that are encoded in the right-left and anterior-posterior directions. As would be expected given the higher blood flow in the carotid arteries compared to basilar artery, normal flow in the PComm arteries is from anterior to posterior. Fetal-type PComm arteries could be detected because of their large size in conjunction with a small, ipsilateral P_1 segment.

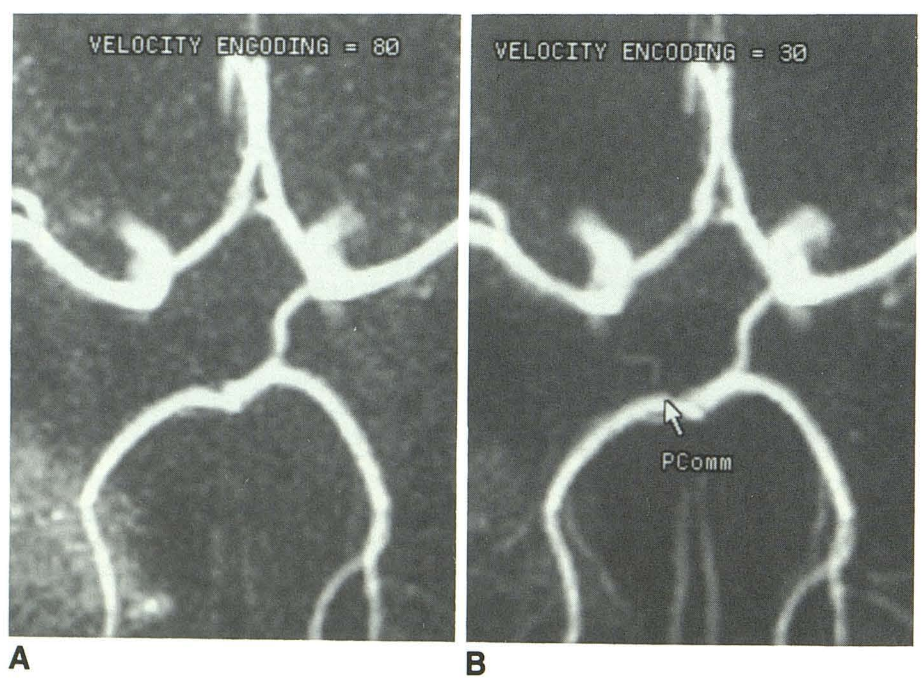


Fig. 7. Normal subject utilizing two different VENCs.

A, At a VENC of 80 cm/sec there is apparent absence of the right posterior communicating (PComm) artery.

B, At a VENC of 30 cm/sec the right PComm artery becomes visible due to lower background noise at lower VENCs.

Reversed flow in the PComm arteries was commonly seen in patients with occlusion of the carotid arteries. This reversed flow consistently occurred in the ipsilateral PComm artery in all patients with carotid occlusion in this study. The presence of a medium-sized PComm artery (approximately, 2–3 mm) seemed to afford protection against significant infarction in the ipsilateral middle cerebral artery distribution. Of the 10 carotid occlusions with an ipsilateral PComm artery, only four had evidence for infarction, and those were small watershed-type infarcts. In contrast, the lack of PComm artery flow, while not definitively predictive of infarction, seems to indicate a higher risk for such patients, since six of seven such occlusions had infarcts. While anterior communicating artery and ophthalmic artery collaterals may prevent infarction (two occlusions), the PComm arteries seemed to confer greater protection. The other major routes of collateral circulation in carotid occlusion, the anterior communicating artery, retrograde flow in the ophthalmic artery, and leptomeningeal collaterals over the hemisphere, were all demonstrable using the phase contrast MRA technique. The anatomic configuration of the circle of Willis can determine the severity of sequellae from carotid occlusion, and the phase contrast MR angiogram may have predictive value, since it shows the collateral pathways available in the circle of Willis. One such demonstration occurred in a neck-tumor patient who was being tested for potential carotid artery sacrifice. The MR angiogram showed an isolated right carotid artery with no flow in the ipsilateral PComm artery or in the right A1 segment. This patient tolerated carotid occlusion for less than 3 seconds. The anatomic constraints of the circle of Willis, therefore, might predict this type of outcome. The lack of visualization of vessels in the circle of Willis suggests that they are not readily recruitable for collateral flow in the acute situation.

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