
AJNR

# Impaired cerebral vasoreactivity after embolization of arteriovenous malformations: assessment with serial acetazolamide challenge xenon CT.

R W Tarr, D W Johnson, J A Horton, H Yonas, S Pentheny, S Durham, C A Jungreis and S T Hecht

This information is current as of April 19, 2024.

*AJNR Am J Neuroradiol* 1991, 12 (3) 417-423
http://www.ajnr.org/content/12/3/417

# Impaired Cerebral Vasoreactivity After Embolization of Arteriovenous Malformations:
## Assessment with Serial Acetazolamide Challenge Xenon CT

Robert W. Tarr[1,2]
David W. Johnson[1]
Joseph A. Horton[1,3]
Howard Yonas[3]
Susan Pentheny[1]
Susan Durham[3]
Charles A. Jungreis[1,3]
Stephen T. Hecht[1,3]

**Embolization of a portion of the nidus of an arteriovenous malformation not only may alter hemodynamics within the nidus, but also may change blood flow dynamics in adjacent normal vessels. Sequential acetazolamide-challenge xenon CT cerebral blood flow studies were performed in eight patients before and after embolization of arteriovenous malformations to assess the hemodynamic effects on the major vascular territories supplying the malformation. Acetazolamide is a potent cerebral vasodilator, and its administration combined with cerebral blood flow studies allows assessment of cerebral vasoreactivity. In seven of the eight patients, one or more parenchymal areas exhibited a normal cerebral blood flow augmentation response to acetazolamide before embolization, but diminished acetazolamide flow augmentation was seen after embolization, indicating abnormal vasoreactivity. We found that the decrease in vasoreactivity peaked 6–10 days after embolization. In one of the eight patients, a temporary delayed neurologic deficit developed during a period of impaired cerebral vasoreactivity following embolization.**

**Our results suggest that embolization of an arteriovenous malformation can induce vasoreactivity changes in adjacent normal vessels. Because these changes appear to be somewhat time-dependent, an appropriate interval should be observed between embolization stages or before surgical resection of an arteriovenous malformation following embolization to allow hemodynamic equilibration to occur. Acetazolamide challenge combined with serial cerebral blood flow studies following embolization enables determination of this hemodynamic equilibration.**

***AJNR* 12:417–423, May/June 1991**

Received June 8, 1990; revision requested September 20, 1990; revision received October 20, 1990; accepted November 10, 1990.

Presented at the annual meeting of the American Society of Neuroradiology, Los Angeles, CA, March 1990.

[1] Department of Radiology, University of Pittsburgh School of Medicine, Presbyterian-University Hospital, DeSota at O'Hara Sts., Pittsburgh, PA 15213.

[2] Present address: Department of Radiology, University Hospitals of Cleveland, Case Western Reserve University, 2074 Abington Rd., Cleveland, OH 44106. Address reprint requests to R. W. Tarr.

[3] Department of Neurosurgery, University of Pittsburgh School of Medicine, Presbyterian-University Hospital, Pittsburgh, PA 15213.

0195–6108/91/1203–0417
© American Society of Neuroradiology

Arteriovenous malformations (AVMs) usually have chronic effects on blood flow to surrounding brain parenchyma. They do this by altering perfusion pressures in normal cerebral vessels secondary to the low resistance of the shunt [1–10]. We have previously used stable xenon CT cerebral blood flow (CBF) studies with acetazolamide challenge to identify parenchymal regions of low vascular reserve associated with AVMs [4]. Acetazolamide administration normally causes a global and symmetric increase in CBF because of temporary cerebral vasodilatation [4, 11–16]. Vascular areas that fail to augment CBF normally in response to acetazolamide challenge are presumed to have diminished vasoreactivity [4, 11].

Abrupt occlusion of the shunt through an AVM following surgical resection or substantial AVM embolization may cause edema or hemorrhage in the adjacent brain [17–23]. This phenomenon, termed normal perfusion pressure breakthrough syndrome, is thought to be due to an abrupt rise in perfusion pressure in arteriolar beds that have abnormal autoregulatory capabilities [24]. To determine changes in CBF and vasoreactivity induced by partial nidus embolization, we studied patients before and after AVM embolization with xenon CT CBF studies combined with acetazolamide challenge.

## Subjects and Methods

We examined eight patients with supratentorial AVMs, five men and three women 16–55 years old. Although four of the eight patients had a history of intracranial hemorrhage, none of the patients had a history of acute or subacute hemorrhage. AVM size was categorized as small (less than 3 cm), medium (3–6 cm), and large (greater than 6 cm in greatest diameter) on the basis of angiography [25]. Each patient was studied with a baseline xenon CT CBF study and an acetazolamide challenge xenon CT CBF study immediately before and at various time intervals (from 1 to 26 days) following partial embolization of the AVM nidus. In two patients, more than one CBF study was performed following embolization. None of the eight patients required sedation for any xenon CT CBF study. However, anxiety attacks precluded completion of CBF studies in two patients not included in this study.

CBF studies were performed by using the stable xenon CT and acetazolamide-challenge method previously described [4, 11, 26–28]. All xenon CT CBF studies were performed by using a GE 9800 CT scanner equipped with a CBF hardware and software package (General Electric Medical Systems, Milwaukee, WI). Each examination consisted of a baseline two-level CBF study and a repeat two-level CBF study performed 20 min after the IV administration of 1 g of acetazolamide. To obtain identical supratentorial scanning levels, patients were not moved between the baseline and acetazolamide-challenge studies. Scanning levels identical to those used for preembolization CBF studies were chosen for postembolization CBF studies by matching postembolization unenhanced axial scout CT levels with unenhanced axial scout CT levels that accompanied the preembolization CBF studies. The basal ganglia/lateral ventricle configuration was used as a reference for choosing the first level of the CBF study. The second level was automatically chosen 3 cm superior to the first level. Scan angulation was kept constant for individual patients.

Preembolization angiographic data were used to determine which major vascular territories (anterior cerebral, middle cerebral, and/or posterior cerebral) had vascular pedicles that supplied the AVM. The vascular territories that had feeding pedicles to the AVM were defined as near-site regions on the CBF studies. Near-site CBF data at each level were analyzed by using multiple contiguous 2.0-cm-diameter region-of-interest (ROI) circles aligned along the cerebral cortex [4]. The ROI diameter of 2.0 cm was chosen to maximize gray matter and minimize white matter inclusion with the individual ROIs. ROIs including the AVM nidus or draining veins were excluded from quantitative analysis. Individual ROIs encompassing identical near-site parenchymal areas were analyzed from baseline CBF and flow augmentation after acetazolamide challenge before and after embolization. Blood flow values for consecutive studies were adjusted for changes in carbon dioxide tension by assuming a change of 3% increase in CBF per 1 mm Hg increase in carbon dioxide tension [29, 30]. The preembolization study was used as the reference for this adjustment. Baseline CBF for each parenchymal area encompassed by an ROI was categorized as low (less than 35 $ml \cdot 100\ g^{-1} \cdot min^{-1}$), normal (35–75 $ml \cdot 100\ g^{-1} \cdot min^{-1}$), or high (greater than 75 $ml \cdot 100\ g^{-1} \cdot min^{-1}$) [31]. Flow augmentation after acetazolamide challenge was categorized as normal (10% or more increase in CBF) or decreased (<10%). Comparable ROIs for each level were analyzed for flow characteristics on pre- and postembolization studies.

Superselective partial nidus embolization was performed with a 2.4-French Tracker catheter and 0.016-in. (0.41-cm) steerable guidewire system (Target Therapeutics, Inc., Los Angeles, CA), introduced coaxially through a diagnostic angiographic catheter. Real-time digital fluoroscopic road-mapping was used for catheter guidance. Digital subtraction microangiography and provocative sodium amytal testing were used to ensure safe catheter position in feeding pedicles. Provocative sodium amytal testing was evaluated with detailed neurologic examination. Pedicle embolization was performed under continuous real-time subtracted fluoroscopic monitoring, using either polyvinyl alcohol (PVA) or a combination of PVA, silk suture material, and coils. Embolization of a pedicle was terminated when flow to the AVM was reduced significantly or became stagnant. The number of pedicles embolized in each patient varied from one to three. Patients were maintained on steroids for 24 hr prior to and 72 hr after embolization procedures.

## Results

Table 1 summarizes patient, AVM, and flow data. We analyzed a total of 169 pre- and postacetazolamide near-site parenchymal areas (individual ROIs) before and after embolization. The mean standard deviation of blood flow measurements within individual ROIs was 19.1 $ml \cdot 100\ g^{-1} \cdot min^{-1}$. Before embolization, the mean near-site baseline CBF for the eight patients was 49.9 $ml \cdot 100\ g^{-1} \cdot min^{-1}$ with an interpatient standard deviation 5.5 $ml \cdot 100\ g^{-1} \cdot min^{-1}$. Following embolization, the mean near-site baseline CBF was 56.8 $ml \cdot 100\ g^{-1} \cdot min^{-1}$ with an interpatient standard deviation of 16.1 $ml \cdot 100\ g^{-1} \cdot min^{-1}$.

Acetazolamide-induced flow augmentation of ≥10% was categorized as normal. The mean flow augmentation in those parenchymal areas categorized as normal was 49.1 ± 28.6%. Before embolization, the mean acetazolamide-induced flow augmentation in all near-site parenchymal areas was 36.1 ± 20.9%. After embolization, the mean acetazolamide-induced flow augmentation of 15.8 ± 24.9% was significantly diminished (t test, $p < .001$).

The results of analyzing individual ROI parenchymal areas of acetazolamide-induced flow augmentation are presented in Table 2. Before embolization, 78% (132/169) of near-site parenchymal areas demonstrated normal (≥10%) acetazolamide-induced flow augmentation, whereas following embolization 58% (98/169) demonstrated normal acetazolamide-induced flow augmentation. Forty percent (53/132) of parenchymal areas that had had normal acetazolamide-induced flow augmentation prior to embolization exhibited diminished (<10%) augmentation after embolization. The proportion of parenchymal areas showing diminished augmentation after

**TABLE 1: Summary of Patients with Supratentorial Arteriovenous Malformations (AVMs) Who Underwent Xenon CT Cerebral Blood Flow Imaging Before and After Embolization**

| AVM Size/ Case No. | Presenting Symptom | No. of Vascular Territories Supplying AVM | No. of Pedicles Embolized | Time of CBF Study (No. of Days Postembolization) |
|---|---|---|---|---|
| Small (<3 cm) | | | | |
| 1 | Headache | 2 | 2 | 4 |
| Medium (3–6 cm) | | | | |
| 2 | Seizures | 2 | 1 | 26 |
| 3 | Hemorrhage | 2 | 1 | 19 |
| 4 | Headache | 1 | 1 | 2 |
| 5 | Hemorrhage | 2 | 2 | 4 |
| 6 | Seizures | 2 | 3 | 1, 5, 12 |
| Large (>6 cm) | | | | |
| 7 | Hemorrhage | 3 | 1 | 2 |
| 8 | Hemorrhage | 3 | 1 | 6, 9 |

**TABLE 2: Two-by-Two Region-of-Interest (ROI) Analysis of Acetazolamide Challenge Cerebral Blood Flow (CBF) Augmentation Before and After Embolization**

| CBF Augmentation After Embolization | CBF Augmentation Before Embolization (No. of ROIs) | | |
|---|---|---|---|
| | Normal (≥10%) | Decreased (<10%) | Total |
| Normal (≥10%) | 79 | 19 | 98 |
| Decreased (<10%) | 53 | 18 | 71 |
| Total | 132 | 37 | 169 |

embolization (42%) was significantly greater than the proportion prior to embolization (22%) (chi-square, $p < .001$).

In seven of the eight patients, one or more parenchymal areas had normal acetazolamide-induced flow augmentation prior to embolization, but exhibited diminished acetazolamide-induced flow augmentation after embolization. Delayed onset of a temporary left upper extremity paresis developed in one patient (case 6) following embolization (Fig. 1). This patient underwent embolization of three pedicles supplying a right parietal AVM. The deficit developed 24 hr after embolization, at which time a CBF study demonstrated increased baseline CBF and diminished acetazolamide flow augmentation in the near-site right middle cerebral artery distribution. The deficit gradually improved and was completely resolved by 12 days after embolization. Interval CBF studies were performed on days 5 and 12 following embolization. On day 5 the CBF study demonstrated decreased acetazolamide flow augmentation in the near-site right middle and anterior cerebral arterial distributions. Baseline flows remained slightly elevated in these distributions compared with the preembolization study. By 12 days after embolization the symptoms had resolved and a CBF study demonstrated normal baseline flows and acetazolamide flow augmentation in the right middle and anterior cerebral arterial distributions.

Figure 2 presents postembolization data regarding the percentage of parenchymal areas that had a normal response to acetazolamide challenge before embolization but developed a diminished acetazolamide response after embolization. The percentages of areas developing diminished acetazolamide responses are plotted relative to the timing of the CBF study following embolization, AVM size, and extent of embolization. There was a significant difference between the number of days after embolization and the percentage of ROI areas with diminished acetazolamide response (chi-square, $P < .001$). Diminished vasoreactivity developed in 33% of parenchymal areas 1–5 days after embolization. This rose to 50% from days 6 through 10 and fell to 0% between days 11 and 26 after embolization. The percentage of parenchymal areas that developed an abnormal response to acetazolamide challenge after embolization did not vary significantly with AVM size or number of pedicles embolized (chi-square, $p > .1$).

Four patients had a history of remote hemorrhage. The percentages of parenchymal areas with a diminished response to acetazolamide challenge before embolization was 13% in patients with a history of prior hemorrhage and 18% in patients without a history of hemorrhage. Following embolization, 38% of parenchymal areas in patients with a history of hemorrhage demonstrated diminished acetazolamide CBF augmentation compared with 48% in patients with no history of hemorrhage. The difference in acetazolamide augmentation responses between those patients with a history of hemorrhage and those without such history was not significant (chi-square, $p > .10$).

Figure 3 shows postembolization data on the percentage of parenchymal areas with diminished acetazolamide flow augmentation responses before embolization and normalization of acetazolamide responses after embolization. The percentage of areas showing normalization of acetazolamide response was significantly greater on days 11–26 (66%) than on days 1–5 (7%) or days 6–10 (0%) after embolization (chi-square, $p < .001$). The percentage of areas demonstrating normalization of acetazolamide response did not vary significantly with AVM size or number of pedicles embolized (chi-square, $p > .05$).

## Discussion

Previous studies have shown that untreated AVMs may have marked effects on parenchymal hemodynamics, both at sites near the AVM and at sites far removed from the lesion [4]. These flow effects of untreated AVMs are often complex within individual patients [4]. One of these effects is an inability of the cerebral vasculature in some regions to respond appropriately to acetazolamide. Acetazolamide is a potent cerebral vasodilator that normally increases global CBF by 5–90% [4, 11–13]. In some untreated AVM patients, the failure to augment CBF appropriately in response to acetazolamide may be due to chronic arteriolar dilatation from lowered perfusion pressures in normal arterial beds [4, 32, 33]. This diminished capacity for CBF augmentation, though evident on acetazolamide CBF studies, may be subclinical [4]. Although clinically silent, the inability to respond appropriately to a vasodilatory challenge suggests impaired vasoreactivity in a vascular bed.

Particle embolization of a portion of an AVM nidus progressively decreases flow through the pedicle being embolized. This progressive alteration in flow is accompanied by an increase in feeder pedicle arterial pressure [34–36]. In addition, nidus embolization may be accompanied by a marked redistribution of regional CBF [37]. These abrupt changes occur in arterial beds that are chronically adjusted to a parallel low-pressure shunt.

In this study, we observed changes in cerebral vasoreactivity that occurred after embolization. These changes were complex and varied among individual patients. In selected near-site parenchymal areas there was a diminished ability of the cerebral vasculature to dilate normally in response to acetazolamide. Although none of the patients in our series received pedicle pressure monitoring during embolization, it is reasonable to hypothesize that the diminished vasodilatory response following embolization resulted from perfusion pressure changes and flow redistribution. These abrupt changes may alter the normal vasomotor responsiveness to vasodila-

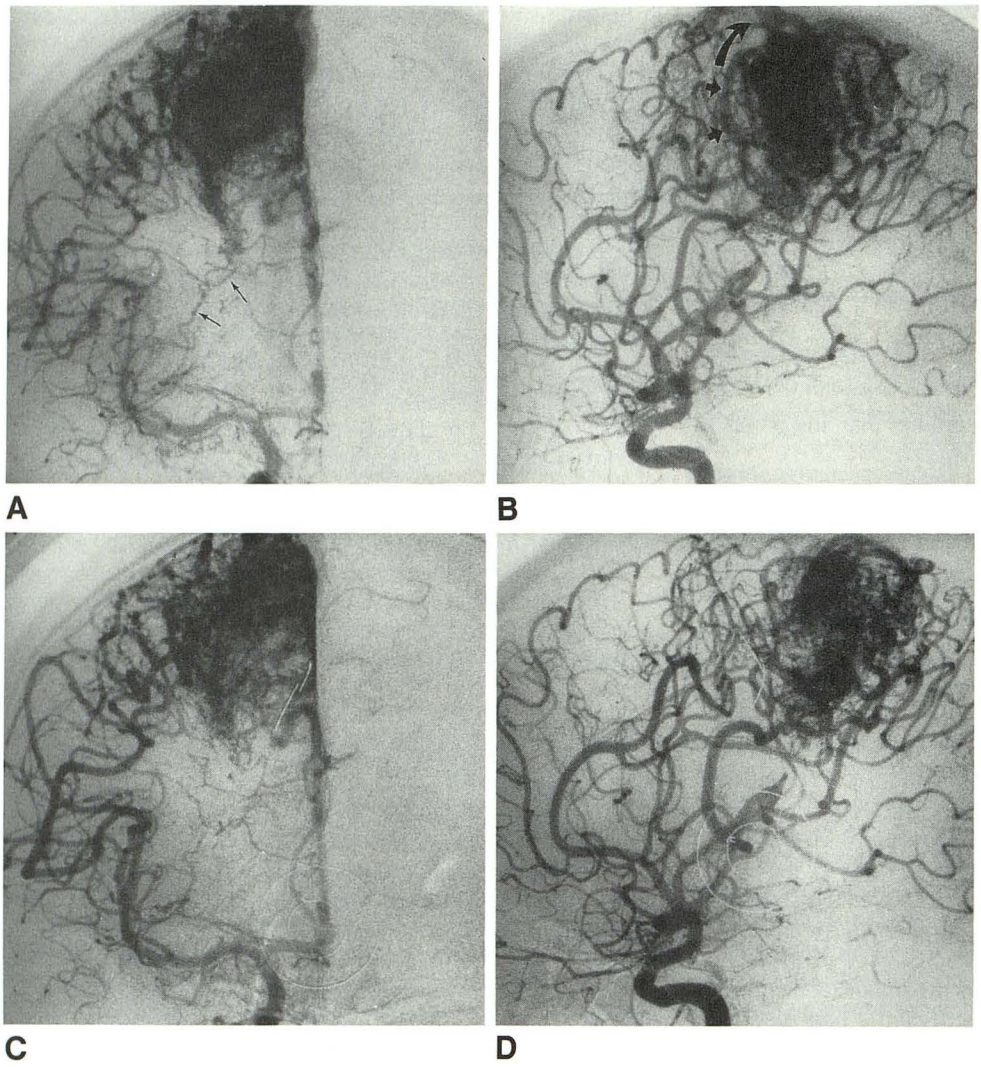



**Fig. 1.—Case 6.**

***A* and *B*, Anteroposterior (*A*) and lateral (*B*) right internal carotid artery angiograms before embolization show a right parietal arteriovenous malformation (AVM) supplied by right anterior cerebral (R ACA), right middle cerebral (R MCA), as well as right lenticulostriate (R LS) arteries. *Arrows* indicate vessels not filled after embolization.**

***C* and *D*, Anteroposterior (*C*) and lateral (*D*) right internal carotid artery angiograms after embolization of two R ACA and one R LS pedicles show smaller size and slower venous filling. Anterior vein filled on *B* (*curved arrow*) is unfilled, even though there is more distal arterial filling.**

**(Fig. 1 continues on the next page.)**

tory challenges. Possibly, the increased intravascular pressure that occurs in selected vascular pedicles following embolization induces a protective increased vasoconstrictive response. Vessels that experience this increased vasomotor tone may initially be incapable of dilating normally in response to acetazolamide. In this series, we found that diminished vasoreactivity was more prominent in the first 10-day period after embolization. The vasoreactivity changes observed after embolization did not vary significantly with preembolization AVM size or number of pedicles embolized. Previous authors have noted that flow redistribution and abnormal vasoreactivity after AVM embolization or resection may predispose to parenchymal edema or hemorrhagic complications [17, 20, 33, 37].

The diminished vasodilatory capacity after embolization was subclinical in the majority (seven of eight) of our patients. However, in one of our patients (case 6), a delayed neurologic deficit developed in a time course related to elevated baseline CBF and abnormal acetazolamide response (Fig. 1). The timing of the deficit, the elevated baseline CBF, and the blunted acetazolamide response suggested that the deficit in this case was related to either CBF redistribution, diminished local vasomotor responsiveness, or a combination of both. Baseline flow values and acetazolamide response normalized and the symptoms resolved by 12 days after embolization.

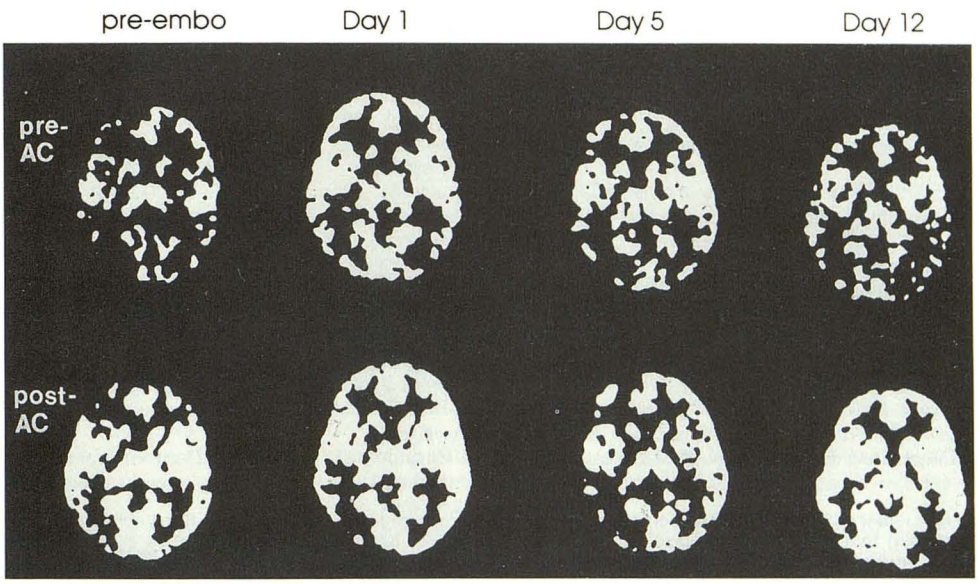
Not all near-site parenchymal areas demonstrated diminished vasoreactivity following embolization. In fact, some parenchymal areas showed normalization of previously diminished responsiveness to acetazolamide. The percentage of parenchymal areas demonstrating normalization of acetazolamide response varied among individual patients, but was greatest more than 10 days after embolization. It is possible that vessels supplying these areas were maximally dilated owing to decreased perfusion pressure before embolization. Since they were maximally dilated they were incapable of dilating further in response of acetazolamide. In time, vasomotor responsiveness may be restored following embolization owing to normalization of intravascular pressure.

Though quantitative, the xenon CT CBF technique is subject to anatomic pixel-to-pixel variation in blood flow. The

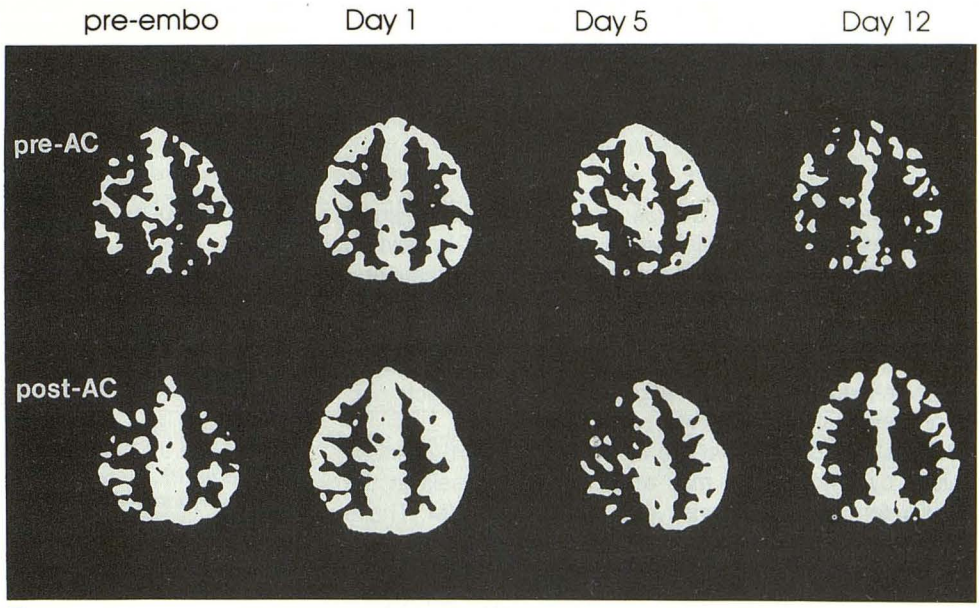
Fig. 1.—Continued.

*E* and *F*, Serial contrast-mode xenon CT CBF studies at lateral ventricular (*E*) and supraventricular (*F*) levels. Window width = 2, window level = 60. CBF ≥ 60 ml·100 $g^{-1}$·$min^{-1}$ is white; CBF < 60 ml·100 $g^{-1}$·$min^{-1}$ is black. embo = embolization, AC = acetazolamide challenge.

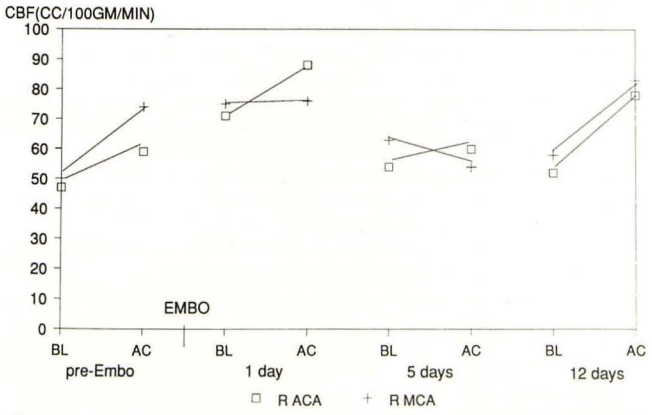
*G* and *H*, Line graphs depict mean R ACA (*squares*) and R MCA (*crosses*) cerebral blood flow (CBF) before and at various times after embolization (EMBO) at ventricular (*G*) and supraventricular (*H*) levels. Before embolization (pre-Embo), preacetazolamide or baseline (BL) CBF is normal. Acetazolamide challenge (AC)–induced flow augmentation is greater in R MCA than in R ACA distribution at supraventricular level. One day after embolization, left upper extremity paresis developed. Interval CBF study showed elevated baseline CBF and diminished AC response in R MCA distribution. By 5 days after embolization, AC response in R MCA distribution at ventricular level and both R MCA and R ACA distributions at supraventricular level have become paradoxical: CBF decreased in response to AC. By day 12, both blunted AC response and neurologic deficit have resolved.



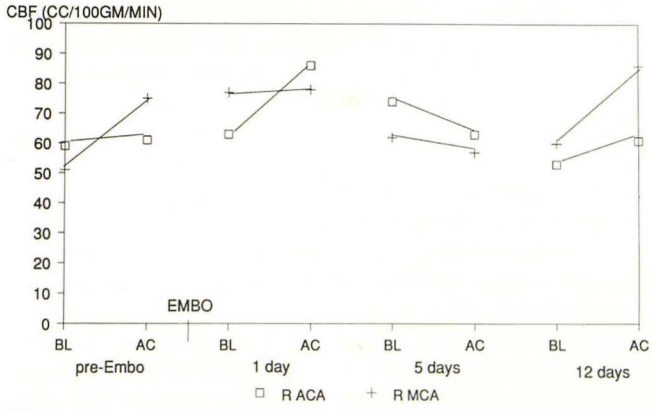

E




F




G




H

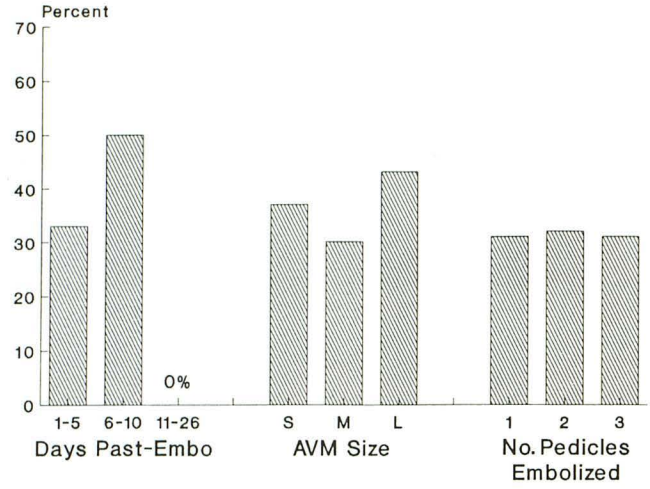



**Fig. 2.—Bar graph depicts (1) percentage of parenchymal areas (regions of interest) that had normal acetazolamide challenge response before embolization but showed diminished response after embolization vs days after embolization (Embo), (2) preembolization arteriovenous malformation (AVM) size (small [S], medium [M], and large [L]), and (3) number of pedicles embolized. The percentage of areas with diminished acetazolamide challenge cerebral blood flow augmentation response peaked during days 5–9 ($p < .001$) but did not vary significantly with either AVM size or number of pedicles embolized ($p > .1$).**

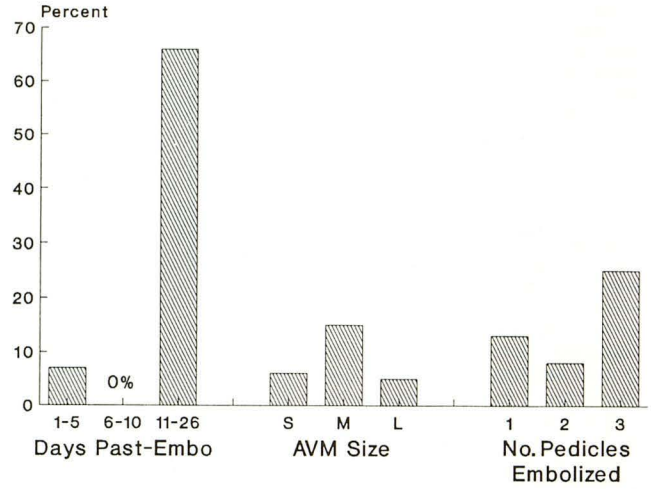



**Fig. 3.—Bar graph depicts (1) percentage of parenchymal areas (regions of interest) showing normalization of acetazolamide challenge response in relation to days after embolization (Embo), (2) preembolization arteriovenous malformation (AVM) size (small [S], medium [M], or large [L]), and (3) number of pedicles embolized. Percentage of areas showing normalization of acetazolamide challenge was greatest after 10 postembolization days ($p < .001$), but did not vary significantly with initial AVM size or number of pedicles embolized ($p > .05$).**

pixel-to-pixel variation as well as the inevitable inclusion of some white matter and sulci within individual ROIs yields a significant standard deviation for local blood flow measurements. However, analysis of comparable ROIs before and after acetazolamide challenge as well as before and after embolization allows assessment of normal or abnormal acetazolamide-induced local CBF augmentation that reflects normal or abnormal vasoreactivity, respectively.

Our results suggest that the local hemodynamic changes induced by embolization may affect normal vessels in the vascular territories of arteries that supply the AVM. These hemodynamic changes may result in an abnormal vasoreactivity that is time-dependent. It is less pronounced 10 days or more after embolization. These results support the concept of staged AVM embolization [38].

The timing of multistaged AVM treatment is controversial. Some authors have recommended a short time interval between embolization and surgery to prevent the reconstitution of the AVM nidus through collateral circulation [38–40]. We have observed that recruitment rarely occurs quickly after partial nidus embolization [41]. Therefore, we believe that our results support a time delay between successive stages of embolization or between embolization and surgery to allow the cerebral vasculature to accommodate the hemodynamic changes caused by embolization. The timing of staged procedures should be individualized owing to the variability of hemodynamic effects among individual patients. However, serial CBF studies combined with a vasoreactivity challenge, such as with acetazolamide, can aid in determining when hemodynamic equilibration has occurred following embolization.

ACKNOWLEDGMENTS

We thank Margaret Sachse and Debra Lee Stokes for editorial assistance.

REFERENCES

1. Nornes H, Grip A. Hemodynamic aspects of cerebral arteriovenous malformation. *J Neurosurg* **1980**;53:456–464
2. Spetzler RF, Selman WR. Pathophysiology of cerebral ischemia accompanying arteriovenous malformations. In: Wilson CB, Stein BM, eds. *Intracranial arteriovenous malformations.* Baltimore: Williams & Wilkins, **1984**:24–31
3. Feindel W, Yamamota YL, Hodje CP. Red cerebral veins and the cerebral steal syndrome: evidence from flurosium angiography and microregional blood flow by radioisotopes during excision of an angioma. *J Neurosurg* **1970**;35:167–179
4. Tarr RW, Johnson DW, Rutigliano M, et al. Use of acetazolamide-challenge xenon CT in the assessment of cerebral blood flow dynamics in patients with arteriovenous malformations. *AJNR* **1990**;11:441–448
5. Marks MP, O'Donahue J, Fabricant JI, et al. Cerebral blood flow evaluation of arteriovenous malformations with stable xenon CT. *AJNR* **1988**;9:1169–1175
6. Wade JPH, Hochinski V. Cerebral steal: robbery or maldistribution. In: Wood JH, ed. *Cerebral blood flow: physiological and clinical aspects.* New York: McGraw-Hill Book Company, **1987**:Ch. 6, 467–480
7. Deutsch G. Blood flow changes in arteriovenous malformations during behavioral activation. *Ann Neurol* **1983**;13:38–43
8. Menon D, Weir B. Evaluation of CBF in arteriovenous malformation by the xenon-133 inhalation method. *Can J Neurol Sci* **1979**;6:411–416
9. Homan RW, Devous MD, Sokely EM, et al. Quantification of intracerebral steal in patients with arteriovenous malformations. *Arch Neurol* **1986**;43:779–785
10. Takeuchi S, Kikuchi H, Karasawa J. Cerebral hemodynamics in arteriovenous malformations: evaluation by single-photon emission tomography. *AJNR* **1987**;8:193–197

11. Rogg J, Rutigliano M, Yonas H, Johnson DW, Pentheny S, Latchaw RE. The acetazolamide challenge: imaging techniques designed to evaluate cerebral blood flow reserve. *AJNR* **1989**;10:803–810
12. Sullivan HG, Kirsbury TB, Morgan MS, et al. The RCBF response to Diamox in normal subjects and cerebrovascular disease patients. *J Neurosurg* **1987**;67:525–534
13. Hauge A, Nicolaysen G, Thoresen M. Acute effect of acetazolamide on cerebral blood flow in man. *Acta Physiol Scand* **1983**;117:233–239
14. Corter S, Lee J, Severinghaus JW. The effects of acetazolamide on cerebral blood flow and cerebral tissue $pCO_2$. *Anesthesiology* **1968**; 29:471–477
15. Gotoh F, Meyer JS, Tonita M. Carbonic anhydrase inhibition and cerebral venous blood gasses and ions in man. *Arch Intern Med* **1966**;117:39–46
16. Ehrenreich DL, Burns RA, Alman RW, et al. Influence of acetazolamide on cerebral blood flow. *Arch Neurol* **1961**;5:227–233
17. Solomon RA, Michelsen DJ. Defective cerebrovascular autoregulation in regions proximal to arteriovenous malformations of the brain: a case report and topic review. *Neurosurgery* **1984**;14:78–82
18. Fleisher AS, Kricheff J, Ransohoff J. Postmortem findings following the embolization of an arteriovenous malformation. *J Neurosurg* **1972**;27: 606–609
19. Kvam DA, Michelsen WAJ, Quest DO. Intracerebral hemorrhage as a complication of artificial embolization. *Neurosurgery* **1980**;7:491–494
20. Batjar HH, Devous MD, Meyer YJ, et al. Cerebrovascular hemodynamics in arteriovenous malformation complicated by normal perfusion pressure breakthrough. *Neurosurgery* **1988**;22:503–509
21. Day A, Friedman W, Sypert G, et al. Successful treatment of normal perfusion pressure breakthrough syndrome. *Neurosurgery* **1982**;11: 625–630
22. Mullan S, Brown F, Patronas N. Hyperemic and ischemic problems of surgical treatment of arteriovenous malformation. *J Neurosurg* **1979**;51: 757–764
23. Halbach VV, Higashida RT, Heishima GB, et al. Normal perfusion pressure breakthrough occurring during treatment of carotid and vertebral fistulas. *AJNR* **1987**;8:751–756
24. Spetzler RF, Wilson CB, Wienstein P, et al. Normal perfusion pressure breakthrough theory. *Clin Neurosurg* **1978**;25:651–672
25. Spetzler RF, Martin NA. A proposed grading system for arteriovenous malformations. *J Neurosurg* **1986**;65:476–483
26. Gur D, Wolfsen SK, Yonas H, et al. Progress in cerebrovascular disease: local cerebral blood flow by xenon-enhanced CT. *Stroke* **1982**;13: 750–758
27. Yonas H, Good W, Gur D, et al. Cerebral blood flow by xenon-enhanced computed tomography: clinical experience. *Radiology* **1984**;152:435–442
28. Yonas H, Wolfsen SK, Gur D, et al. Clinical experience with the use of xenon-enhanced CT blood flow mapping in cerebral vascular disease. *Stroke* **1984**;15:443–450
29. Shirahata N, Henriksen L, Vorstrup S, et al. Regional cerebral blood flow assessed by $^{133}Xe$ inhalation and emission tomography: normal values. *J Comput Assist Tomogr* **1985**;9:861–866
30. Murzelaar JP, Marmarou A, DeSalles AAF, et al. Cerebral blood flow and metabolism in severely head injured children. Part I: Relationship with GCS score, outcome, ICP, and PVI. *J Neurosurg* **1989**;71:63–71
31. Hoedt-Rasmusenk. Regional cerebral blood flow: the intra-arterial injection method. *Acta Neurol Scand* **1967**;43:17–79
32. Murphy JP. *Cerebrovascular disease.* Chicago: Year Book Medical, **1954**
33. Barnett GH, Little JR, Ebrahim ZY, et al. Cerebral circulation during arteriovenous malformation operation. *Neurosurgery* **1987**;20:836–842
34. Jungreis CA, Horton JA, Hecht ST. Blood pressure changes in feeders to cerebral arteriovenous malformations during therapeutic embolization. *AJNR* **1989**;10:575–577
35. Jungreis CA, Horton JA. Pressure changes in the arterial feeder to a cerebral AVM as a guide to monitor therapeutic embolization. *AJNR* **1989**;10:1057–1060
36. Duckwiler G, Dion J, Vinuela F, Jabour B, Martin N, Bentson J. Intravascular microcatheter pressure monitoring: experimental results and early clinical evaluation. *AJNR* **1990**;11:169–175
37. Batjer HH, Purdy PD, Giller CA, et al. Evidence of redistribution of cerebral blood flow during treatment for an intracranial arteriovenous malformation. *Neurosurgery* **1989**;25:599–605
38. Andrews BT, Wilson CB. Staged treatment of arteriovenous malformations of the brain. *Neurosurgery* **1987**;21:314–323
39. Spetzler RF, Martin NA, Carter LP, et al. Surgical management of large AVMs by staged embolization and operative excision. *J Neurosurg* **1987**;67:17–28
40. Stein BM, Wolpert SM. Arteriovenous malformations of the brain. II. Current concepts and treatment. *Arch Neurol* **1989**;37:69–75
41. Dawson RC III, Tarr RW, Hecht ST, et al. Treatment of arteriovenous malformations of the brain with combined embolization and stereotactic radiosurgery: results after 1 and 2 years. *AJNR* **1990**;11:857–864


The reader's attention is directed to the commentary on this article, which appears on the following pages.