MR Flow Imaging in Vascular Malformations Using Gradient Recalled Acquisition

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Twenty patients with known or suspected intracranial vascular lesions were evaluated with gradient recalled MR (GRASS) imaging, and the results were compared with those obtained by standard spin-echo MR, CT, and angiography. GRASS imaging with a short TR (40 msec) and a partial flip angle (60° or 70°) demonstrated flow-related enhancement within vascular structures in nearly all cases. The only exception to the enhancement of flowing blood was when slow flow was encountered within venous structures oriented parallel to the imaging plane, in which case flow signal void occurred. GRASS imaging was particularly useful for differentiating flowing blood from calcium or air, or for delineating vascular structures adjacent to the inner table of the skull. The major limitation of the technique is the presence of hemosiderin, which causes marked signal dropout due to the exquisite sensitivity of GRASS to magnetic susceptibility effects.

When signal loss is encountered during MR imaging of suspected vascular malformations it may be difficult to differentiate between flow signal void, calcium, air, and iron in the form of hemosiderin [1–5]. Characteristics of flowing blood on T1- and T2-weighted images, such as flow-related (paradoxical) enhancement [2, 6] and even-echo rephasing [2, 4, 6] on T2-weighted images, are helpful when present; however, they cannot be reliably demonstrated in all patients.

Several investigators have shown recently that MR may be used to preferentially enhance blood flow within vessels [2, 3, 7, 8]. Kucharczyk et al. [2] demonstrated the use of single-slice spin-echo sequences to detect increased signal from flowing blood entering the imaging plane at 90°. Flow-related enhancement obtained from these spin-echo images was seen mostly within venous structures. Other reported techniques utilize reversal of the slice-selection gradient to refocus proton spins and obtain flow-related enhancement by a variety of methods [7–9]. We investigated the use of a single-slice gradient recalled MR technique (GRASS) for enhancing flowing blood to help determine the vascular nature of a lesion.

Materials and Methods

Our series consists of a retrospective evaluation of 20 patients with known or suspected vascular malformations or highly vascular tumors. Patient selection was based on characteristic CT and conventional spin-echo MR studies, angiographic results, and/or surgical information. Fifteen patients had an arteriovenous malformation (AVM), three patients had venous angiomas, and two had cavernous hemangiomas. Contrast-enhanced CT showed characteristic enhancing lesions in the areas of abnormal arteriovenous shunting in AVMs, and linearly enhancing deep white matter structures in venous angiomas. All patients with an AVM had angiograms that showed the lesion; and of three patients with venous angioma, two were verified angiographically. Table 1 is a summary of the types of lesions found within the study group.

All patients had standard spin-echo MR imaging on a 1.5-T GE Signa scanner. T1-weighted sagittal images were obtained with 600/25 (TR/TE). The T2-weighted sequences consisted of either 2000/20,80 or 2500/20,40,60,80. The latter (symmetric) sequence was used for the

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evaluation of even-echo rephasing. Slice thickness was 5 mm with a 1.5-mm interslice gap. Immediately after completion of the conventional spin-echo sequences, single-slice GRASS (gradient recalled acquisition in a steady state) images were obtained. The details of this pulse sequence technique have been published elsewhere [9]. For our GRASS imaging parameters we chose a TR of 40 msec to allow sufficient time for unsaturated spins to enter the imaging plane over a wide range of flow velocities and still provide a short enough repetition time to minimize longitudinal relaxation of the background protons. We used a TE of 12 msec, which is the shortest echo time available on our system, and was chosen to maximize signal. A tip angle between 60° and 70° was selected in order to highly saturate the stationary protons and thus increase the contrast between inflowing spins and surrounding tissue. Slice thickness was 5 mm with no interslice gap, there were four signal excitations, a matrix size of 128 × 256, and a 24-cm field of view. Flow compensation (gradient moment nulling) was used in conjunction with this sequence to suppress phase-shift artifacts. Imaging time for a single slice was approximately 20 sec, and generally six to 10 consecutive slices through the region of interest were obtained, resulting in a total imaging time of 2.0 to 3.3 min. GRASS images were obtained in sagittal, coronal, or axial planes on the basis of the appearance and location of the lesion on conventional imaging techniques. The plane that was thought to best define the morphology of the lesion was chosen and no attempt was made to orient the imaging plane in any way with respect to the direction of blood flow. A spin-echo T1-weighted sequence in the same plane as the GRASS image was usually obtained for anatomic correlation.

Data from all sequences were correlated and evaluated for the presence of flow-related enhancement, even-echo rephasing, and flow signal void. We also evaluated the ability to detect feeding and/or draining vessels, hemosiderin deposition, methemoglobin, and presence of mass effect or edema. Studies were reviewed retrospectively and the above parameters were arbitrarily assigned numerical values of 0 = absent, 1 = equivocal, and 2 = present. The diagnostic adequacy of the images was assessed subjectively together with a determination of the confidence level for detecting the presence or absence of flow.

Results

The 20 patients in our series all had known or suspected vascular lesions. With multislice spin-echo technique, neither the T1- nor T2-weighted sequences demonstrated flow-related enhancement within the abnormality. Using single-slice GRASS imaging, 12 (60%) of 20 studies showed enhancement (white vessels on a gray background) within the lesion. All three venous angiomas demonstrated flow-related enhancement, although areas of flow signal void were present when the draining vein was parallel with the plane of the slice (Figs. 1 and 2). All the spin-echo images of AVMs demonstrated flow signal void in areas of high blood flow, and all these areas correlated with flow-related enhancement demonstrated on GRASS images. The results are summarized in Table 2.

Even-echo rephasing was detected in seven of 15 patients who had T2-weighted symmetric spin-echo studies, while in the other eight studies there was no evidence of even-echo rephasing. When even-echo rephasing was present, generally only parts of the vascular lesion showed increased signal while other areas remained black (flow signal void).

Detection of edema was superior with spin-echo T2-weighted images as compared with both T1-weighted and GRASS images. Delineation of feeding vessels was present in 13 of 20 T1-weighted studies and in 12 of 20 studies with GRASS and T2-weighted spin-echo images. GRASS images better demonstrated surface vessels as white against the black skull (Fig. 3).

All 20 spin-echo studies were judged adequate for interpretation. Fifteen of the GRASS studies were adequate for evaluation of the study parameters; however, in three cases the images were uninterpretable, and the two remaining cases were judged equivocal. In four of the five inadequate or equivocal studies, a significant region of signal loss was encountered due to magnetic susceptibility effects caused by hemosiderin. This was confirmed by correlation with the T1- and T2-weighted spin-echo images [1]. In these cases increasingly T2-weighted images also demonstrated progressive signal loss, although in each case the area of signal loss was smaller compared with the GRASS image. The increased sensitivity of GRASS sequences for detecting magnetic-susceptibility-related signal loss was demonstrated by the larger area of signal void present on GRASS images as compared with spin-echo images (Figs. 4 and 5).

TABLE 1: Summary of Distribution of Lesions

Diagnosis	No. of Cases	No. Proved
AVM	15	14
Venous angioma	3	2
Cavernous hemangioma	2	2

Discussion

Blood flow effects seen on spin-echo MR range from decreased signal (flow signal void) to increased signal (flow-related enhancement and even-echo rephasing) [2, 3, 7, 8, 10–12]. Kucharczyk et al. [2] reported using a single-slice spin-echo technique to demonstrate flow-related enhancement within areas of slow and moderate flow. They demonstrated the velocity dependence of maximum flow-related enhancement on repetition time (TR) and section thickness (Δz), and showed that for flowing spins entering the imaging plane at an incident angle of 90° the relationship between maximum flow-related enhancement and velocity was $v = \Delta z/TR$. It follows for constant section thickness that as TR decreases the flow velocity at which maximum flow-related enhancement is detected increases. If flowing spins enter the imaging plane at some oblique angle, the signal enhancement will depend on the angle of incidence as well as the velocity, TR, and section thickness. The venous angioma shown in Figure 1 demonstrates flow-related enhancement within portions of the draining vein oriented at right angles to the imaging section, and flow signal void when the vein is close to parallel.

Using a form of single-slice gradient recalled MR known as GRASS (gradient recalled acquisition in a steady state [9]) with a very short TR, we obtained significant and reproducible

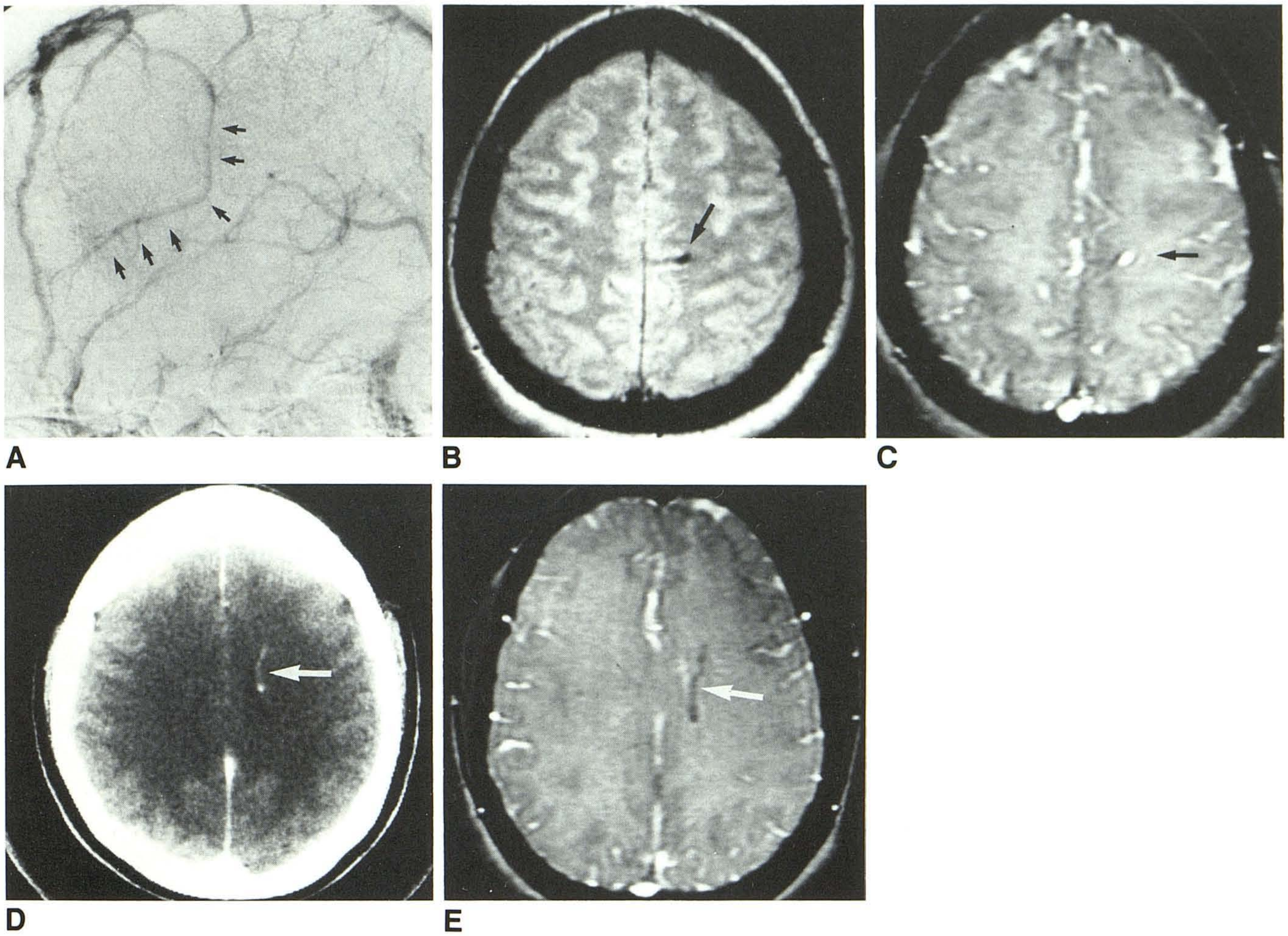


Fig. 1.—*A*, Late venous phase of internal carotid arteriogram. Lateral view shows a venous angioma (*arrows*) that originates within the brain coursing horizontally and then vertically to drain into superior sagittal sinus.

B, Spin-echo T2-weighted axial image through vertical portion of draining vein shows flow signal void (*arrow*).

C, GRASS image at same level as 1B shows flow-related enhancements (*arrow*) when flow enters 90° to imaging plane.

D, Contrast-enhanced CT scan through horizontal portion of vein (*arrow*).

E, GRASS image at same level as 1D shows flow signal void (*arrow*) when vein is oriented parallel (or almost parallel) to imaging plane.

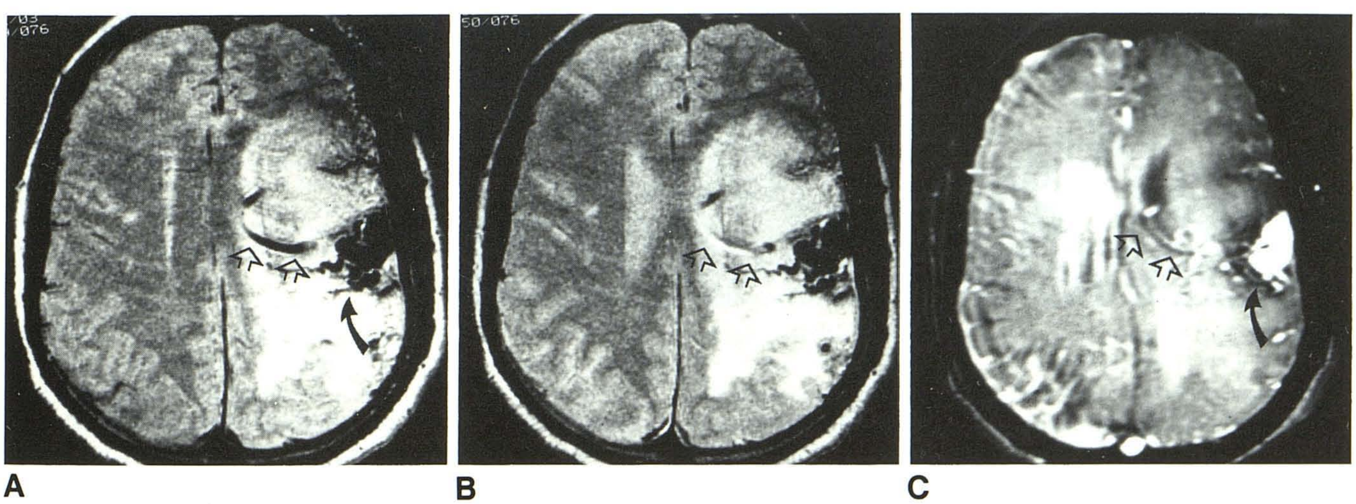


Fig. 2.—*A*, Spin-echo image (2500/20) shows flow signal void in a left temporal AVM (*curved arrow*) and a draining vein (*open arrows*).

B, Spin-echo image (2500/40) demonstrates even-echo rephasing within draining vein (*open arrows*).

C, GRASS image shows flow-related enhancement within large AVM (*curved arrow*) but partial flow signal void when slowly flowing draining vein is parallel to imaging plane.

TABLE 2: Comparison of Spin-Echo and GRASS Images

Condition	Present			Absent			Equivocal		
	T1	T2	GRASS	T1	T2	GRASS	T1	T2	GRASS
FRE	0	0	12	19	19	5	1	1	3
EER[a]		7			5			3	
FSV	14	13	3	2	2	12	4	5	5
FV	13	12	12	5	6	7	2	2	1
HS	2	6	7	15	13	12	3	1	1
MHG	3	3	2	16	16	18	1	1	0
Mass effect or edema	3	4	1	16	15	18	1	1	1
Adequate for interpretation	20	20	15	0	0	3	0	0	2

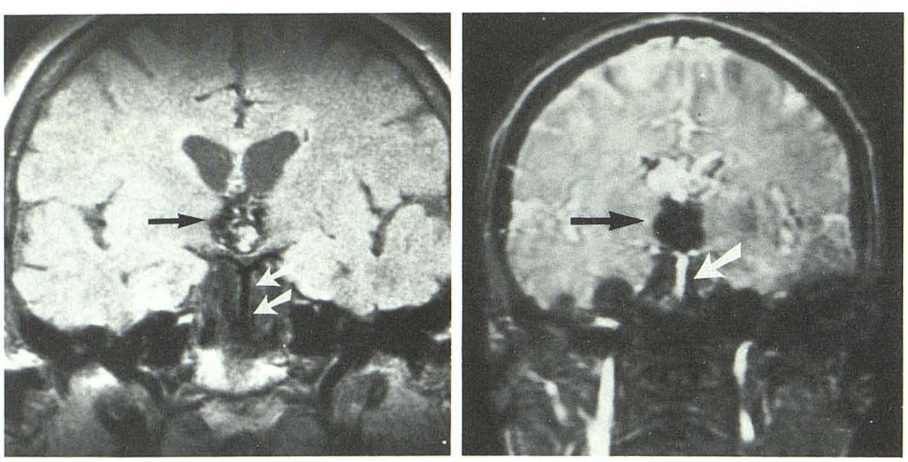
[a] 15 patients in EER group, 20 in all others.

Note.—FRE = flow-related enhancement, EER = even-echo rephasing, FSV = flow signal void, FV = feeding vessels, HS = hemosiderin, MHG = methemoglobin.

A B

Fig. 3.—*A*, Spin-echo spin-density image shows flow signal void within vessels adjacent to inner table of skull (*arrows*).

***B*, GRASS image through same plane with marked flow-related enhancement differentiating flow from bone.**



A B

Fig. 4.—*A*, Thalamic AVM with areas of hemorrhage (*black arrow*). T1-weighted image contains inhomogeneous signal from the lesion, which may contain some flow. Note flow signal void within normal basilar artery (*white arrows*).

***B*, GRASS image demonstrates loss of signal from within areas of chronic hemorrhage (*black arrow*). Note flow-related enhancement within basilar artery (*white arrow*).**

flow-related enhancement within highly vascular lesions containing both rapid and slow flow that were seen as areas of flow signal void on standard spin-echo images. GRASS demonstrates increased sensitivity for displaying flow-related enhancement because of the short TR, which both saturates the stationary spins within the imaging plane and allows imaging of faster moving spins. Gradient refocusing also enables protons flowing through the imaging plane to give back a relatively high signal.

Both arterial and venous structures showed increased signal, and vessels perpendicular, oblique, and parallel to the imaging plane contained high signal with one notable excep-

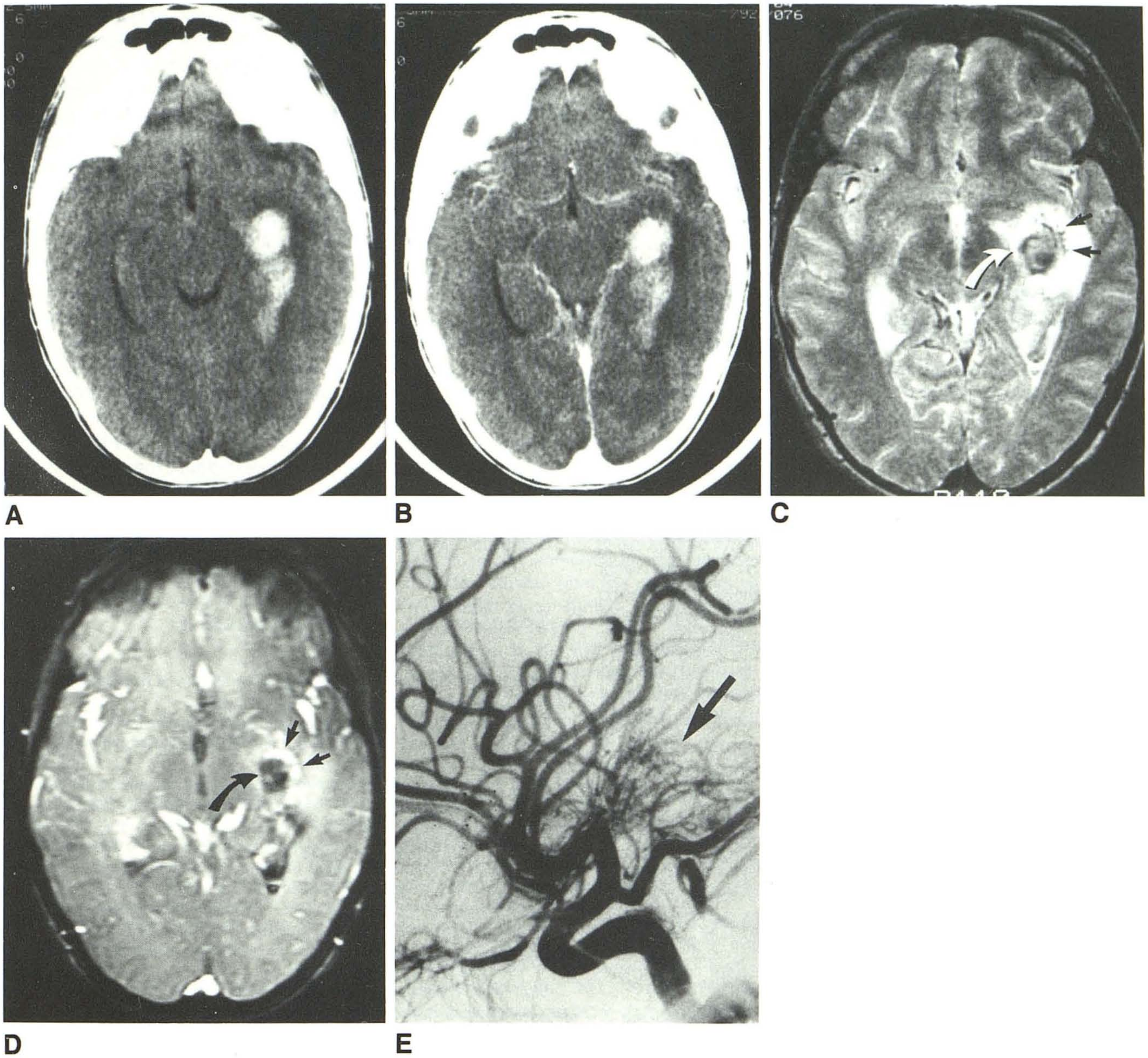


Fig. 5.—*A*, Non-contrast-enhanced CT scan shows acute hemorrhage from a left temporal lobe AVM.
B, Contrast-enhanced CT scan shows no discernible enhancement.
C, Spin-echo T2-weighted sequence demonstrates heterogeneous signal from AVM (*curved arrow*) and a curvilinear signal loss laterally (*black arrows*), which may be either blood flow or hemosiderin from chronic hemorrhage.
D, GRASS image shows some signal loss within AVM (*curved arrow*), which is probably due to deoxyhemoglobin; but curvilinear flow-related enhancement (*small arrows*) indicates blood flow at periphery of lesion.
E, Lateral arteriogram shows abnormal feeding vessels to this vascular malformation.

tion. When slow flow was encountered parallel to or within the imaging plane during image acquisition, flow-related enhancement was incomplete or absent (as demonstrated by the venous angiomas). Similarly, two subsequent cases of nasopharyngeal cavernous hemangioma with very slow flow within the mass did not show detectable flow-related enhancement with GRASS. This was not the case with rapid flow in the imaging plane, as demonstrated by excellent enhancement of AVMs of all sizes and by visualization of the carotid arteries and jugular veins on coronal GRASS images. Thus, we may qualitatively define slow blood flow as flow within venous angiomas, capillary hemangiomas, and some normal veins, and rapid flow within larger veins and dural sinuses, arteries, and AVMs. The flow signal void seen in slow-flowing veins parallel to the plane of the slice was thought to be caused by two phenomena. The first relates to the fact that with slow in-plane flow the protons are partially saturated and the proportion of unsaturated in-flowing protons is markedly reduced. The second phenomenon appears to be a phase-shift-related signal loss due to misregistration of signal outside the blood vessel [13, 14]. This latter effect is the result of temporal delay between the phase- and frequency-encoding gradients during which time the moving proton changes position within the imaging volume.

Delineation of some feeding vessels was seen in 12 of 20 cases, although the anatomy was in no way detailed enough to substitute for angiography. This is especially helpful when the feeding and draining vessels are adjacent to the inner table or near the base of the skull. GRASS imaging is also helpful when trying to distinguish flow signal void from calcium deposits or air.

This study shows the feasibility of using GRASS for definition of vascular abnormalities. The technique can demonstrate flow enhancement in a high percentage of cases (60% in our series), and can often confirm flow when spin-echo images are equivocal. GRASS is also more reliable than even-echo rephasing, which demonstrates flow in only a small proportion of cases (47%) and usually is only present in portions of the lesion (Fig. 4).

GRASS has several limitations. Perhaps the most important is the exquisite sensitivity of the technique to changes in local proton magnetic susceptibility. This was most problematic when chronic hemorrhage was present in the form of hemosiderin. Intracranial hemorrhage will have variable signal characteristics depending upon age [1, 4, 5], but with chronic hemorrhage and the deposition of iron as hemosiderin, local changes in the magnetic susceptibility of surrounding protons can cause profound signal loss that at times may be difficult to tell from flow signal void, calcium, or air. The loss of signal in areas of chronic hemorrhage is readily appreciated on heavily T2-weighted images, but this effect is magnified when using gradient refocused echo techniques [1, 5]. In four of our cases, the GRASS images were uninterpretable due to severe signal loss within the structure of the abnormality and extending from the area of iron deposition so as to obliterate signal from normal surrounding brain. In cases of acute hemorrhage, flow information may be present but incomplete (Fig. 5).

Acquiring spin-echo images in the single-slice mode is necessary for flow enhancement [2, 12], but with the standard spin-echo imaging technique it is inefficient and cumbersome for routine clinical imaging of the whole head. With very short repetition times, GRASS imaging can be used with single-slice imaging, and several contiguous sections can be acquired within short imaging times, usually under 3 min. Routine spin-echo images remain essential for the complete evaluation of intracerebral vascular lesions, since using GRASS imaging parameters to improve flow enhancement causes a loss of anatomic detail, and the GRASS images contain poor T2 information.

The main advantage of MR over CT and angiography is its ability to define vessels and other vascular abnormalities without a contrast agent. The detection of flow signal void on spin-echo MR is characteristic of rapidly flowing blood [3, 6, 12], and there are pitfalls and areas of ambiguity in interpretating flow signal void, such as calcium, hemosiderin deposition, air, and vessels adjacent to cortical bone. We have found a convenient MR imaging sequence that can reliably differentiate flowing blood in these lesions, that can be performed rapidly during the routine MR examination, and that occasionally obviates the need for further radiologic examinations.

In summary, GRASS imaging of the CNS appears reliable for distinguishing flow from calcium, air, and iron and for defining vessels adjacent to bone. This technique can aid in establishing patency and flow in the dural venous sinuses, jugular veins, and normal arterial structures; but the limitations of slow in-plane flow and hemosiderin deposition must be recognized. It is emphasized that a lack of flow-related enhancement in areas of chronic hemorrhage may not reflect a lack of flow but rather the inability to detect it. Because of all its limitations, GRASS should be considered complementary to standard spin-echo imaging in defining vascular lesions.

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