Diffusion- and Perfusion-Weighted Imaging in Vasospasm After Subarachnoid Hemorrhage

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Background and Purpose—Better measures of cerebral tissue perfusion and earlier detection of ischemic injury are needed to guide therapy in subarachnoid hemorrhage (SAH) patients with vasospasm. We sought to identify tissue ischemia and early ischemic injury with combined diffusion-weighted (DW) and hemodynamically weighted (HW) MRI in patients with vasospasm after SAH.

Methods—Combined DW and HW imaging was used to study 6 patients with clinical and angiographic vasospasm, 1 patient without clinical signs of vasospasm but with severe angiographic vasospasm, and 1 patient without angiographic spasm. Analysis of the passage of an intravenous contrast bolus through brain was used to construct multislice maps of relative cerebral blood volume (rCBV), relative cerebral blood flow (rCBF), and tissue mean transit time (tMTT). We hypothesize that large HW imaging (HWI) abnormalities would be present in treated patients at the time they develop neurological deficit due to vasospasm without matching DW imaging (DWI) abnormalities.

Results—Small, sometimes multiple, ischemic lesions on DWI were seen encircled by a large area of decreased rCBF and increased tMTT in all patients with symptomatic vasospasm. Decreases in rCBV were not prominent. MRI hemodynamic abnormalities occurred in regions supplied by vessels with angiographic vasospasm or in their watershed territories. All patients with neurological deficit showed an area of abnormal tMTT much larger than the area of DWI abnormality. MRI images were normal in the asymptomatic patient with angiographic vasospasm and the patient with normal angiogram and no clinical signs of vasospasm.

Conclusions—We conclude that DW/HW MRI in symptomatic vasospasm can detect widespread changes in tissue hemodynamics that encircle early foci of ischemic injury. With additional study, the technique could become a useful tool in the clinical management of patients with SAH. (Stroke. 1999;30:599-605.)

Key Words: subarachnoid hemorrhage • cerebral ischemia • ultrasonography, Doppler, transcranial • magnetic resonance imaging • imaging, diffusion-weighted • imaging, hemodynamically weighted

Delayed cerebral ischemia due to vasospasm is one of the most devastating sequelae of subarachnoid hemorrhage (SAH) secondary to ruptured aneurysms. Usually, the diagnosis of vasospasm after SAH has been made by patient history and physical examination with CT,1 transcranial Doppler study (TCDs),2 and/or angiographic confirmation. The findings of headache, fever, elevated white blood cell count, drop in serum sodium, elevation in blood pressure, and delayed neurological deficit are helpful but not specific for vasospasm. In patients with SAH, there may be multiple causes for neurological impairment. It is often difficult to be certain whether ischemia due to vasospasm is in fact a contribution. A reliable test to detect brain ischemia is sorely needed in these extremely ill patients.

Although angiography is considered to be the standard for the diagnosis of vasospasm, it is invasive, can be associated with significant morbidity after SAH,3 and does not provide information about whether the tissue is ischemic; ie, it does not distinguish between angiographic versus symptomatic vasospasm. In recent years, TCDs has shown promise in the diagnosis of angiographic vasospasm by virtue of its ability to detect noninvasively increased middle cerebral artery (MCA) blood velocity associated with arterial narrowing.2,4,5 Studies have shown that the time course of flow velocity acceleration due to arterial narrowing from vasospasm correlates well with clinical grade, CT localization of subarachnoid clot, and angiographic data.6,7,8 More recent reports have demonstrated that the sensitivity of TCDs for the diagnosis of cerebral vasospasm after SAH can be low.9,10 While TCDs can interrogate the major intracranial vessels, TCDs cannot address questions that concern collateral flow, microvascular compromise, or infarcted tissue. Moreover, TCDs cannot...
differentiate between symptomatic and asymptomatic vasospasm.

Many authors have suggested the use of noninvasive cerebral blood flow (CBF) studies, such as xenon-CT, to measure tissue perfusion as an alternative to angiography and TCDs in the diagnosis and management of vasospasm. In fact, noninvasive CBF studies have proven useful in the identification of patients with initially reduced CBF values, who despite good clinical grade, are at risk for the development of vasospasm.

We sought to use newly developed MRI techniques to map the hemodynamic disturbances in patients with vasospasm. DWI detects the decrease in the diffusibility of water that occurs in an early phase of permanent ischemic brain injury. HWI tracks a rapid bolus of intravenous gadolinium during its first pass through the brain, which provides information about cerebral blood volume and flow. We sought to determine whether DWI and HWI were feasible in intensive care unit patients who had undergone aneurysm clipping.

Because vasospasm usually causes, at least initially, a reversible neurological deficit, we hypothesized that HWI abnormalities would be present in patients at the time they developed neurological deficit and before the appearance of matching DWI abnormalities. In addition, HWI should demonstrate territorial differences in brain vascular supply that correlate with patients’ clinical symptomatology and angiographic abnormalities. We hypothesized that DWI abnormalities that represent ischemic tissue injury, if present in treated patients, will be smaller than the regional blood flow abnormality. These techniques should be able to differentiate areas of brain that may be affected by ischemia secondary to vasospasm, infarction, postsurgical edema, or some combination thereof.

## Subjects and Methods

### Patient Selection

All patients admitted to our institution with SAH due to aneurysm rupture are admitted to the neuroscience ICU for preoperative and postoperative monitoring. After surgery, patients are routinely maintained in a relatively hypertensive and euvolemic state in anticipation of cerebral vasospasm. Daily clinical observations and TCDs measurements are used to detect vasospasm. Once vasospasm is detected, systolic blood pressure is elevated with phenylephrine, and hypervolemia (central venous pressure of 10 to 12 mm Hg) and hemodilution are instituted. If an ischemic deficit appears or progresses despite maximal medical therapy, then intra-arterial vasodilatation with papaverine and angioplasty are typically used. In this report, we describe 6 patients with symptomatic vasospasm and 1 with asymptomatic vasospasm admitted between March 1995 and October 1997 who were selected to have an MRI study to look for evidence of stroke. As a control, an eighth patient admitted in September 1995 who had a similar functional MRI study (systolic blood pressure was 160 mm Hg and central venous pressure was 8 mm Hg at the time of the study) performed 1 day after surgery for SAH. At that time, the TCDs did not show any evidence of vasospasm. Every patient had a head CT scan after the MRI study and preceding the angiogram. We hypothesized that HWI would show larger abnormalities than DWI in treated subjects with symptomatic vasospasm. To test this hypothesis, each MRI study was visually assessed by a neuroradiologist blinded to the symptomatology. Each scan was ranked as DWI=HWI, DWI<HWI, or DWI>HWI. DWI and HWI (all parameters) abnormalities were compared for distribution and size of region involved. Each patient was also ranked as symptomatic or nonsymptomatic. The angiogram closest in time to the MRI was evaluated for the degree of vasospasm in each of the vessels of the circle of Willis. This study was initiated with the approval of the Subcommittee on Human Studies at Massachusetts General Hospital.

### MRI Protocol

MRI is performed with a General Electric Signa 1.5-T MRI unit with an echoplanar retrofit from Advanced NMR Systems (Wilmington, Mass). We use the same acute stroke MR protocol, with 2 modifica-
was treated with daily intraarterial papaverine infusions for 3 days on days 9, 10, and 11 demonstrated vasospasm. The patient region of the anterior communicating artery. Repeat angiograms image is distorted immediately around the aneurysm clip, in the MCA watershed and MCA/PCA watershed territory. The MR est and most posterior territory of the inferior division of the left MCA; and c, the most posterior territory of the right MCA inferi- and most posterior territory of the inferior division of the left MCA; and c, the most posterior territory of the right MCA inferi- or division. DWI (A) showed foci of ischemic injury in the ACA/ MCA watershed and MCA/PCA watershed territory. The MR image is distorted immediately around the aneurysm clip, in the region of the anterior communicating artery. Repeat angiograms on days 9, 10, and 11 demonstrated vasospasm. The patient was treated with daily intraarterial papaverine infusions for 3

tions, as we have published earlier. We recently modified our DWI to include measurement of the full-diffusion tensor as described below. We have also modified our postprocessing to include maps of relative cerebral blood flow (rCBF) and tissue mean transit time (tMTT), also summarized below. When combined with MRI, our protocol requires \( \sim 30 \) minutes of patient time in the magnet (\( \sim 15 \) minutes of scan time). Follow-up CT or MRI was obtained at or before discharge. No special steps were required to minimize susceptibility effects in our study. Compared with standard T2–spin echo, fast–spin echo T2-weighted images are less sensitive to susceptibility effects, although echoplanar images are more sensitive to susceptibility artifacts. In axial images above the circle of Willis, the artifact from the nonferromagnetic clips used was minimal. Aneurysm clip artifacts were localized near the clip, where data were not interpretable, but away from the clip, image quality was sufficient (as the figures demonstrate). There were no artifacts because of the presence of subarachnoid blood. Trace-weighted DWI and relative cerebral blood volume (rCBV) images are computed by the MRI technologist at the MR console and are available typically within 10 minutes after the study is completed, and in many cases before the patient has left the scan. CBF and MTT images require additional postprocessing by a trained technician and an additional 20 minutes of computing time.

**Diffusion-Weighted MR Imaging**

Our technique samples the entire diffusion tensor. This consists of 6 high–b value single-shot images at each slice, which correspond to diffusion measurement in a given direction; followed by a single low-b value image. The high-b value we use is 1221 s/mm\(^2\), and the low-b value is 3 s/mm\(^2\). A summary of the parameters is: repetition time, 6 seconds; echo time, 118 ms; matrix, 256×128; field of view, 40×20 cm; slice thickness, 6 mm; and interslice gap, 1 mm. The complete 7-image tensor acquisition requires 42 seconds; we typically acquire 3 repetitions to improve the signal-to-noise ratio, which results in a total imaging time of 126 seconds. Generation of isotropic (tensor trace) DW images occurs offline on a networked workstation (Sparcstation 20, Sun Microsystems) and requires 5 to 10 minutes for data transfer and computation.

**Hemodynamic Imaging**

Hemodynamic imaging is obtained by the performance of spin-echo echo-planar imaging during the injection of 0.2 mmol/kg of gadodiamide or gadopentetate. We obtained 51 single-shot echo-planar imaging (EPI) images (TR, 1500 ms; TE, 75 ms) in each of the 10 slices or a total of 510 complete images acquired in 77 seconds, or 46 single-shot EPI images in each of 11 slices for 506 complete images acquired in 69 seconds. Contrast was administered intrave- nously with an MR-compatible power injector (Medrad Inc) at 5 cm\(^3\)/s. Data were then transferred to workstations for further analy- sis. In our protocol, the perfusion slices are supposed to be the same as the diffusion slices where there is overlap (11 of the 18). In some cases, this was not possible because of patient movement between scans or technologist error.

Determination of cerebral blood flow (CBF) from intravascular tracer can be performed in several ways: in a model-dependent approach, an empirical analytical expression is chosen to describe vascular retention of a contrast agent. In a model-independent approach, CBF and the vascular retention of a tracer are determined by nonparametric deconvolution. We have previously shown that rCBF values determined with model-dependent approaches may be in error if the vascular retention of tracer is systematically different among different areas of the brain. However, nonparametric decon- volution with singular value decomposition reproduces flow reason- ably independent of the underlying vascular structure, even at the modest signal-to-noise ratio obtainable with single-shot EPI in days on days 9, 10, and 11 with resolution of angiographic vasospasm. His neurological status improved gradually, and at the time of discharge, he had only some mild word finding diffi- culties and no motor deficit.
clinical practice. Consequently, rCBF was determined by deconvolving the tissue concentration–time curve with an arterial input function. To determine rCBV, the tissue concentration–time curve is numerically integrated, as described. The latter is manually selected by choosing voxels over the MCA that supplies the unaffected hemisphere. This method sensitively captures information on asymmetry of flow to the affected hemisphere, but it is not quantitative. Maps of rCBF and tMTT are then created with our model-independent approach. To date, analysis of the hemodynamic data sets has been unable to provide absolute quantitative flow measurements.

**Blood Pressure Management During MRI Study**

All patients were studied during treatment with intravenous phenylephrine to maintain blood pressure within previously set limits. Blood pressure was monitored by intra-arterial catheters with high-resistance tubing that lead from the MR room to a transducer and monitor outside the room. Phenylephrine was infused through an intravenous pump located outside the MR room connected to the patient’s central line by 20 ft of tubing.

**Results**

HW/DW imaging results and angiographic findings are illustrated in Table 1 for 8 patients. In 6 cases, the patient had neurological symptoms suggestive of clinical vasospasm. In each, the TMTT maps showed large regions of delayed or slow flow in the clinically appropriate vascular territory consistent with angiographically demonstrated vasospasm. In these 6 cases, DWI showed small, usually multiple, regions of ischemic injury within the region of abnormal tMTT. The rCBV maps were normal in all patients except in 1 patient in a region containing a large, angiography-related stroke (T2 abnormal). In one case (patient 8), DW/HW imaging was performed in a patient with SAH postclipping of a right MCA bifurcation aneurysm in whom angiogram did not show vasospasm. The MR study was normal in all respects. In all patients (6 of 8) with an abnormal neurological examination due to symptomatic vasospasm, the abnormality seen on rCBF and tMTT was much larger than the abnormality seen on the DWI sequence or rCBV (when present). In one patient (patient 6), angiographic and TCD studies suggested vasospasm but the patient remained asymptomatic even at low systolic blood pressure. HW/DW MRI studies were normal. The mean time between the onset of clinical deficit and the MRI study was 10.5 hours (between 9 and 12 hours).

Figures 1 through 3 document imaging findings in cases 1, 2, and 6, whereas Table 1 compares the clinical picture with
the MRI and angiographic findings in all patients. In all symptomatic patients, the CT scans performed immediately before the angiogram and immediately after the MRI showed ischemic changes in the areas of abnormal DW signal. These lesions persisted and were seen on the discharge head CT scans, whereas the territories that were abnormal on the rCBF and tMTT but normal on DWI appeared normal on the discharge studies. The apparent diffusion coefficient was reduced in all of the DWI lesions.

Discussion
Vasospasm after SAH is generally considered to be caused by periarterial blood clot. In 1980, Fisher and colleagues showed that the amount and location of subarachnoid blood seen on the initial CT scan is a strong predictor of vasospasm. Their system for grading the amount of subarachnoid clot is the most widely used feature for the estimation of the risk for vasospasm in individual patients.

When studied 10 to 12 days after SAH, 60% to 70% of patients with severe cisternal accumulation of blood have angiographic vasospasm. However, angiographic vasospasm does not always correlate with symptomatic vasospasm. Ischemic neurological deficit due to arterial narrowing occurs in ~30% of patients. In patients with SAH, neurological function is often severely impaired as a result of the initial hemorrhage, cerebrovascular surgery, hydrocephalus, or fever, as well as potential ischemia due to vasospasm. There is a need for sensitive and more specific methods of diagnosing clinically significant vasospasm. Ideally, treatment decisions about the use of hypertensive, hypervolemic therapy, or vasodilation through angioplasty or papaverine should be made with information about the state of the intracranial arteries, brain blood flow and metabolism, and degree of ischemic injury. Angiography is still the standard by which arterial vasospasm has been diagnosed in patients after SAH, but it is time consuming, is not without clinical risk, and does not give direct information about tissue perfusion.

Demonstration of elevated blood flow velocity and increase in turbulent flow by TCDs can provide an early clinical awareness of vasospasm that involves the circle of Willis. Because this method is noninvasive and can be repeated as often as necessary, it is commonly used to monitor for cerebrovascular vasospasm after SAH. However TCDs can fail to detect vasoconstriction if vasospasm occurs beyond insonated arteries, such as in the distal M2 portion of the

Figure 3. E.H. is a 39-year-old female with SAH initially designated as Hunt and Hess grade 2. The initial angiogram showed a right posterior communicating artery aneurysm, and the patient underwent successful clipping of the aneurysm on the day of admission. Four days after admission, she was found to have elevated right MCA velocities by TCDs. Two days later, an angiogram confirmed the presence of severe vasospasm of the supraclinoid right ICA, right M1, and right A1. The patient remained asymptomatic except for a severe headache. Vasospasm was initially treated with hypertension, hypervolemia, and hemodilution, but because of the lack of ischemic symptoms and despite the persistence of vasospasm by TCDs 9 days later, this therapy was discontinued and the patient underwent an MRI with DW and HW imaging. The study was performed initially with a systolic blood pressure of 84 mm Hg, and then neosynephrine was used to increase the SBP to 120 mm Hg. No abnormalities were seen on the DWI, rCBV, rCBF, or tMTT maps. Hypertension, hypervolemia, and hemodilution were then discontinued without any change in the neurological examination. Despite persistence of elevated TCDs velocities in the right MCA stem, the patient was discharged to home October 29, 1997, and was neurologically intact with a SBP ranging from 110 to 140 mm Hg. TCDs velocities remained elevated and severe headache continued, and the patient was readmitted November 13, 1997. A repeat angiogram (A) shows a severe distal right ICA stenosis, and the repeat MRI study with DWI (B), rCBF, and tMTT (C) maps was entirely normal. A diagnosis of right ICA dissection vs persistent stenosis because of vasospasm was made, and the asymptomatic patient was discharged on coumadin.
DWI and HWI in Vasospasm

MCA, in the A2 (anterior cerebral artery, ACA), in the P2 (posterior cerebral artery, PCA), or in the vertebrobasilar system. In severe vasospasm, decreases in CBF can occur that lead to a drop in blood velocity. Increased intracranial pressure or brain edema can increase the pulsatility of the waveform, which makes interpretation of higher velocities difficult. Patient movement, suboptimal insonation windows, aberrant vessel course, and clip artifacts may obscure the detection of pathological signals. Systemic hemodynamic, rheological, and metabolic factors may also confound the interpretation of flow velocity. Many studies have stressed the low sensitivity of TCDs to detect vasospasm. In addition, TCDs cannot differentiate between symptomatic and asymptomatic vasospasm and cannot detect changes in CBF with hypertensive, hypervolemic treatment.

A number of techniques are available for the measurement of regional CBF, including radioactive xenon clearance (using the intravenous or inhalational technique), stable xenon CT, single photon emission CT (SPECT), and positron emission tomography (PET). Several of these methods have been applied to patients with presumed vasospasm and appear very sensitive to the early detection of vasospasm. In most patients with SAH, these noninvasive techniques can help to delineate the location and severity of vasospasm and may help predict the development of vasospasm. SPECT has been used to study patients with cerebral ischemia after SAH. PET has provided physiological information by demonstrating that vasospasm is accompanied by increased oxygen extraction and increased blood volume, presumably secondary to arterial dilatation, to allow maintenance of adequate cerebral metabolic rate. The $^{133}$Xe technique has been used for clinical research and clinical studies for >20 years, has been repeatedly validated, and provides CBF measurements that are stable and reliable. The Xe/CT technique has limitations and possible disadvantages. These include the exposure to a relatively high level of radiation that allows the study of only 2 slices and the possible increase in intracranial cerebral pressure.

New MRI techniques recently validated in ischemic stroke experimental and human studies have considerable potential for aiding the diagnosis and treatment of acute ischemic stroke. DWI demonstrates regions of early ischemic injury. In animal experiments, DWI becomes abnormal in <30 minutes in an ischemic zone. In humans, DWI has also been abnormal in very early studies (40 minutes) after ischemic stroke. In humans, hemodynamic imaging in acute ischemic stroke is thought to identify regions of ischemia, whereas DWI is highly sensitive and specific in the diagnosis of irreversible ischemic injury. In ischemic stroke patients, rCBV is generally significantly reduced in the region of DWI abnormality or T2 abnormality in a more mature infarct. In many stroke patients, the region of abnormal rCBV is larger than the initial region of abnormal DWI, and the stroke enlarges into and may exceed the area of abnormal rCBV. rMTT and rCBF maps are based on additional analysis of the kinetics of blood flow as measured by the use of an intravascular tracer. The arrival and clearance time of the bolus of gadolinium are important physical features that underlie the calculated rCBF and tMTT. In patients with acute ischemic stroke, regions of decreased rCBF and increased tMTT are often found to encompass the DWI and rCBV abnormalities. In acute stroke patients, we have seen that infarct may or may not extend into these regions with normal rCBV but low rCBF and increased tMTT.

Our results in patients with vasospasm show that DWI can detect small regions of early ischemic injury within large regions of abnormal rCBF and tMTT. Widespread decreases in rCBF and tMTT occurred in each patient throughout regions supplied by vessels with demonstrated angiographic vasospasm. In contrast, the rCBV maps were relatively normal except in the case in which a large infarct had already occurred. These MR data are concordant with PET data that demonstrate a mismatch between blood flow and blood volume in regions affected by vasospasm after SAH. One interpretation of this pattern in patients with vasospasm and in patients with acute ischemic stroke is that increased collateral flow through maximally dilated microcirculation preserves cerebral blood volume in regions with reduced CBF.

In acute stroke patients, this pattern of normal rCBV, decreased rCBF, and increased tMTT occurred around large regions of decreased rCBV and abnormal DWI. In contrast, in these patients with vasospasm after SAH, this less severe decrease in rCBF with preserved rCBV was found to be the predominant abnormality. In this study, large brain regions with decreased rCBF and increased tMTT were seen in all patients with clinically symptomatic vasospasm, and the regional location of these HWI abnormalities correlated well with the angiographic findings. Our patients were receiving hypertensive treatment during the scans for their suspected symptomatic vasospasm, and the effect of the treatment on the hemodynamic pattern is unknown. In these patients who were treated aggressively to prevent infarction, the large areas of abnormal rCBF/tMTT did not evolve into stroke and were normal on the follow-up studies. In most patients, the neurological signs and symptoms correlated better with the anatomy of the blood flow abnormality rather than with the small regions of infarct. The flow reductions were also most likely longstanding given the long duration between symptom onset and scan. This underlies the sensitivity of HWI to detect levels of ischemia that cause neurological deficits but which are not severe enough to cause all such regions to infarct.

The specificity of these patterns for vasospasm in patients after SAH requires study of a larger patient cohort. HWI abnormality was not seen in 1 patient with angiographic and Doppler evidence of narrowing, but who remained without ischemic deficits even when blood pressure was unsupported. HWI abnormality was not seen in another patient after SAH who did not have a spasm on angiogram or clinical signs of vasospasm.

An advantage of MR imaging over other blood flow techniques is its ability to couple HWI with DWI, the latter a sensitive method that detects even small regions of ischemic injury. In this study, ischemic injury occurred as small foci of DWI hyperintensity in 6 of 6 patients with symptomatic vasospasm. Large infarcts, as in patient 3 and in patients with acute ischemic stroke, are associated with DWI abnormality in regions of reduced rCBV. It remains to be studied whether...
reduced rCBV occurs at some time as a necessary event to cause infarct in regions that initially demonstrate only reduced rCBF and increased MTT.

In this initial study, we demonstrate the ability of MRI to measure widespread vasospasm-related changes in tissue hemodynamics that surround small regions of ischemic tissue injury. The ability to detect these changes raises more questions than it answers but provides a potentially valuable tool to approach the important issues in vasospasm management. As a result of these early findings, serial HWI in patients with SAH should be studied for its ability to recognize a particular hemodynamic pattern that reliably accompanies symptomatic vasospasm. It will also be important to know if a particular HWI abnormality predicts which SAH patients will suffer infarction due to vasospasm. Early, serial studies are needed to determine whether reliable hemodynamic changes on HWI precede clinically significant vasospasm. Because it can be performed repeatedly, HWI also offers a potential method to determine whether various treatment options improve or worsen cerebral perfusion abnormalities. Finally, this study raises the question of whether HWI can someday be used as a guide to decide on best therapy for an individual SAH patient. This may be the most important long-term goal worthy of systematic study.

Acknowledgment
Supported by an American Heart Association grant to Dr Koroshetz.

References
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Stroke. 1999;30:599-605
do: 10.1161/01.STR.30.3.599

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