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Turbo Spin-Echo Diffusion-Weighted MR of Ischemic Stroke

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PURPOSE: **Our objective was to determine whether a multisection technique, diffusion-weighted half-Fourier single-shot turbo spin-echo (HASTE) imaging, can compensate for the drawbacks common to other diffusion-weighted techniques; specifically, the need for echo-planar technology and the presence of susceptibility artifacts in areas close to the skull base.**

METHODS: **Forty subjects who were referred to the stroke service with signs of acute (less than 24 hour) neurologic dysfunction were included in this prospective study. MR imaging of the brain was performed with diffusion-weighted echo-planar and diffusion-weighted HASTE sequences. The images obtained with both sequences were analyzed for the presence of hyperintensities corresponding to ischemic lesions as well as for the presence of image artifacts and distortions.**

RESULTS: **Diffusion-weighted HASTE images showed areas of hyperintensity corresponding to the infarcts present on diffusion-weighted echo-planar imaging studies without distortion or susceptibility artifacts in all the patients who had a stroke. Twelve patients had no acute ischemic lesions; of these, five had other findings, six had normal findings, and in one patient, a hyperintensity seen on diffusion-weighted echo-planar images proved to be an artifact on diffusion-weighted HASTE images.**

CONCLUSIONS: **Diffusion-weighted HASTE is equal to diffusion-weighted echo-planar imaging in the detection of early ischemia. Because of the absence of significant image distortions and other artifacts, diffusion-weighted HASTE permits fast multiplanar imaging in artifact-prone regions, such as the posterior fossa and the inferior frontal and temporal lobes. Diffusion imaging can be performed on conventional systems with strengths of 1.5 T that do not have echo-planar imaging capabilities.**

Diffusion-weighted imaging of the brain (1) is increasingly used in the investigation of acute stroke (2). At first, diffusion-weighted imaging was difficult to perform in stroke patients because the methods proposed were motion-sensitive and slow and only single-section sequences were available (3, 4). Echo-planar imaging of the brain allowed collection of a full set of diffusion-weighted sections, covering the whole brain in a very short time (2). As attitudes toward ischemic stroke evolve, along with the development of potentially neuroprotective drugs, diffusion-weighted imaging is increasingly being considered a marker for effective treatment (5). Diffusion-weighted echo-planar imaging requires expensive hardware that is not widely available, and it is associated with strong susceptibility artifacts near the skull base that cause image distortions (6) and make it difficult to measure stroke volume accurately. Therefore, alternative techniques to diffusion-weighted echo-planar imaging are currently under investigation, such as navigated spin-echo or line-scan diffusion-weighted techniques (7, 8). One such technique, diffusion-weighted half-Fourier single-shot turbo spin-echo (HASTE) imaging is a combination of a spin-echo diffusion preparation with a single-shot turbo spin-echo technique, which has recently been implemented on both high- and low-field systems (P. M. Jakob et al,

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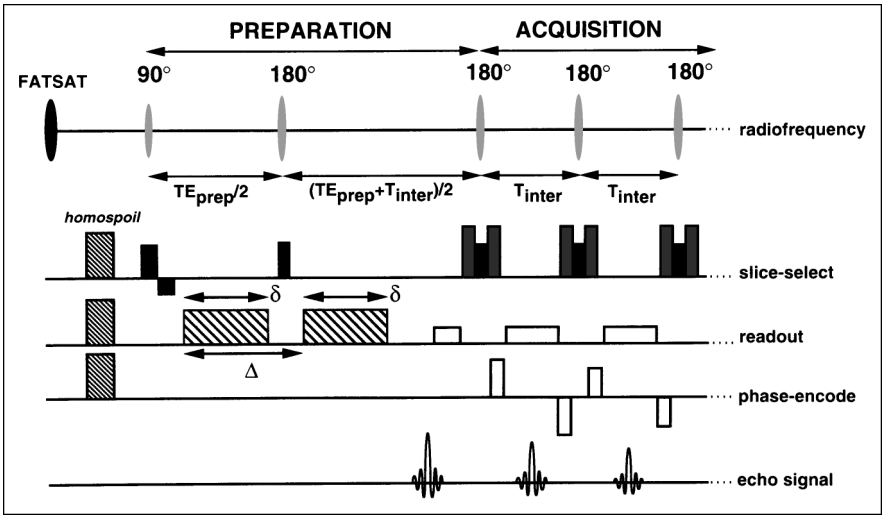

FIG 1. Schematic representation of the basic diffusion-weighted HASTE sequence. Sensitization to diffusion is achieved by a preparation period (spin-echo scheme with diffusion gradients, denoted by *hatched patterns* and $TE_{prep}/2$). The transverse magnetization at the end of the preparation period is imaged by a HASTE sequence. Gradient pulses (*positive and negative black blocks*) indicate the section (slice) selection gradients and section (slice) select rephasing gradients. Gradient pulses (*gray patterns*) correspond to balanced pairs of crusher gradients in section (slice) direction around the refocusing pulses.

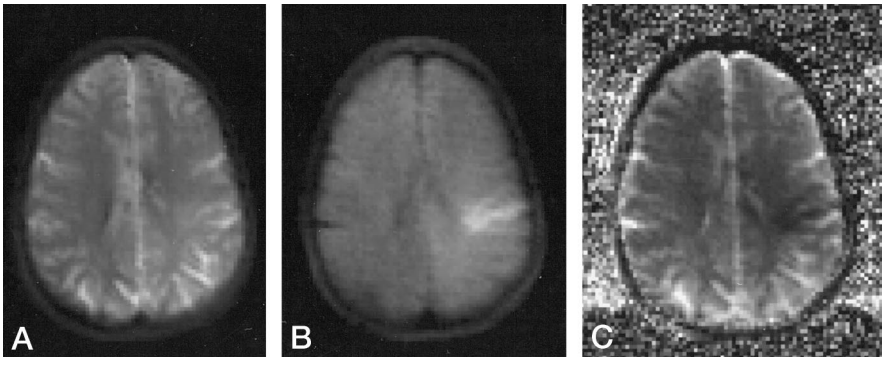

FIG 2. A 55-year-old man with acute onset of right-sided hemiparesis. Imaging was performed 8 hours after onset of symptoms.

A, Diffusion-weighted image at the minimum *b* value (0) at the level of the corona radiata shows the absence of disease.

B, Diffusion-weighted HASTE trace image (TE, 122; matrix, 128 × 64) at the maximal *b* value shows the presence of a hyperintensity in the left-sided motor cortex.

C, ADC trace map shows the typical drop in image intensity in the same area, corresponding to an acute stroke.

"Cardiac-Gated Diffusion-Weighted Imaging of the Human Brain with the HASTE Sequence," presented at the annual meeting of the International Society for Magnetic Resonance in Medicine, Vancouver, Canada, April 1997). In the present study, diffusion-weighted HASTE sequences were compared with diffusion-weighted echo-planar sequences on a 1.5-T system to determine their relative capacity for detecting the hyperintensity associated with acute ischemia.

Methods

Forty patients (22 men and 18 women, 27 to 96 years old) were included in this prospective study over a period of 6 months. All patients were admitted to the emergency department of our institution because of new signs of neurologic dysfunction consistent with a possible infarct. In all cases, imaging was performed within 24 hours of onset. The patients were examined initially by a neurologist trained in stroke management, who referred them for further work-up with magnetic resonance (MR) and diffusion-weighted imaging. The patients or their closest relatives were given detailed explanations about the procedure before being asked to sign consent forms, according to the guidelines of the hospital. Twelve patients, 10 of whom had a stroke, were examined within the first 6 hours of symptom onset. The earliest imaging study was performed 3 hours after symptom onset. The final diagnosis was based on findings at clinical follow-up and late imaging.

All patients were examined on a Siemens Vision 1.5-T echo-planar imaging system (Siemens, Erlangen, Germany). After acquiring a three-plane localizer image, we obtained conventional axial spin-echo T1-weighted (440/12 [repetition time/echo time]), T2-weighted (3800/90), and proton density-weighted (3800/22) sequences in 20 sections covering the whole brain. For diffusion-weighted echo-planar imaging we used only two b values (0 and 1000 s/mm^2). Typical imaging parameters included an echo time of 118, a matrix size of 128 × 128, a field of view of 260 × 260, a section thickness of 7 mm with no gap between sections, and the same section setting as for the previous sequences. The MR diffusion sequence at b = 1000 was run three times, with diffusion gradients applied in each of the x, y, and z directions. To minimize the effects of diffusion anisotropy, an average of all three diffusion directions was calculated to give the trace of the diffusion tensor. The images obtained with the gradients in the three separate directions contained information about the anisotropy caused by the myelin fibers, along which, water movement is known to create hyperintensities on diffusion-weighted images. It is necessary to sum the images to obtain a trace that only shows lesions as hyperintensities. No special head restraints were used apart from the standard padding. No cardiac or respiratory gating was used for the echo-planar studies. For diffusion-weighted HASTE images (Fig 1), the parameters included an echo time 122 with an interecho time of 3 milliseconds, a matrix size of 128 × 64, and a field of view of 300 × 300 mm. The gradient was applied in the z direction only in all cases, with two b values (b = 0 and b = 920 s/mm^2). In a few select cases (n = 11), when a stroke was detected (Fig 2A), the gradient was applied in the

x and y directions as well, and trace images could be calculated (Fig 2B) along with apparent diffusion coefficient (ADC) maps (Fig 2C). Because of its sensitivity to brain motion and cerebrospinal fluid pulsations, cardiac gating was performed with diffusion-weighted HASTE at 0 milliseconds after the R wave. Total acquisition times were approximatively 1 minute for diffusion-weighted echo-planar images and 1 minute 15 seconds for diffusion-weighted HASTE images. The total time for acquiring three image sets with the gradient applied in the three directions was therefore almost 4 minutes with diffusion-weighted HASTE sequences. In five cases, diffusion-weighted imaging was also performed in the coronal plane, and both diffusion-weighted HASTE and diffusion-weighted echo-planar imaging were performed in eight case. The diffusion-weighted echo-planar imaging obtained with the gradient applied in the z direction were compared with equivalent diffusion-weighted HASTE images and evaluated for the presence of hyperintensities corresponding to areas of restricted diffusion of acute ischemic lesions seen on the images obtained at a maximal b value.

Results

Clinically useful diffusion-weighted imaging sets were obtained with diffusion-weighted echo-planar imaging and diffusion-weighted HASTE sequences in 39 patients. The images obtained at minimal and maximal *b* values were judged to be useful with both sequences. In one case, patient motion was so severe that there was complete signal loss on both diffusion-weighted echo-planar imaging and diffusion-weighted HASTE images. This examination was considered to be of no diagnostic value.

Diffusion-weighted echo-planar images revealed cerebral hyperintensities corresponding to a stroke in 28 patients, and diffusion-weighted HASTE images showed comparable lesions in 27 patients. These lesions were not visible prospectively on the conventional T1- and T2-weighted images (Fig 3A). The size, extent, and number of strokes detected were identical on both diffusion-weighted echo-planar images (Fig 3B) and diffusion-weighted HASTE images (Fig 3C) in all patients who had ischemia. Twenty-two strokes were located in the territory supplied by the middle cerebral artery (MCA: Figs 2–5) and five were found to correspond to strokes in the posterior circulation (Fig 6 and 7). During the time of this investigation, there were no hemorrhagic strokes.

The diffusion-weighted HASTE images did not display any of the distortions usually present on diffusion-weighted echo-planar imaging sections. In all cases, the diffusion-weighted echo-planar studies contained hyperintense artifacts in the basal temporal lobes on both axial and coronal images (Figs 6 and 7); diffusion-weighted echo-planar sequences were associated with image distortions close to the skull base, especially in the basal temporal lobes. In one case, these hyperintensities were close to an actual stroke in the medial temporal lobe (Fig 6C). The diffusion-weighted HASTE sequences did not contain any hyperintensities corresponding to those artifacts (Fig 6D), and they contained some additional anatomic information in the region of the soft tissues of the head and neck (Fig 6B), even though this information was of no value for the present study.

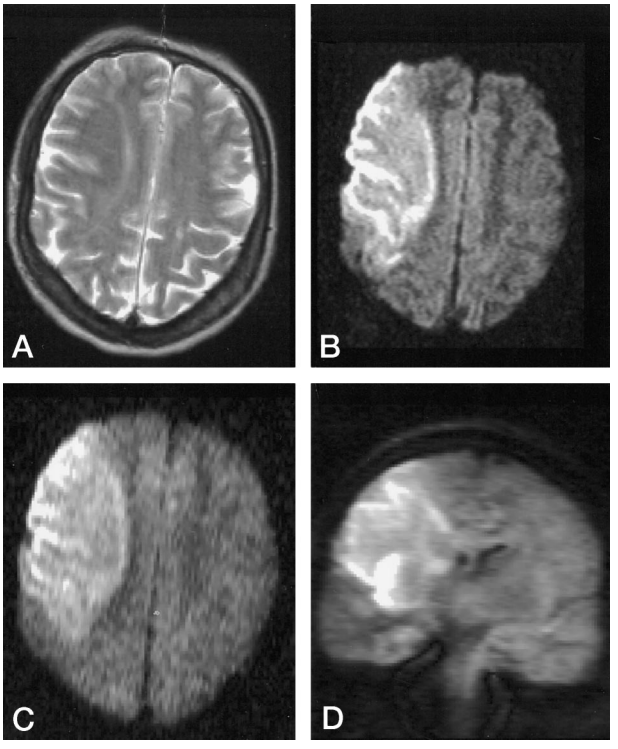

FIG 3. A 67-year-old man 16 hours after acute left-sided hemiparesis.

A, Conventional T2-weighted image (3800/90) shows no abnormality.

B, Diffusion-weighted echo-planar image (echo time, 118; matrix, 128 × 128) shows an extensive acute infarct in the right MCA territory.

C, Diffusion-weighted HASTE image (echo time, 122; matrix, 128 × 64) at the same level confirms the large MCA infarction.

D, Coronal diffusion-weighted HASTE image (echo time, 122; matrix, 128 × 64) shows the extent of the infarct.

In one case, diffusion-weighted echo-planar images showed the presence of a hyperintensity in the right cerebral cortex that was not visible on the diffusion-weighted HASTE images and that proved to be due to an echo-planar reconstruction artifact in an unusual location. In retrospect, this artifact could clearly be seen on the echo-planar susceptibility-weighted images, which were also routinely obtained. This case was therefore judged to be false positive on diffusion-weighted echo-planar images.

In 11 patients, we found no hyperintensities corresponding to an acute stroke. In five patients, lesions were detected with both diffusion-weighted HASTE and diffusion-weighted echo-planar imaging that did not correspond to acute ischemia. In addition to the artifact described above, we found one old cerebellar stroke, one case of extensive chronic small-vessel disease (in both cases, the minimal-*b*-value images and conventional T2-weighted images showed the typical hyperintense lesions expected), and two brain tumors (one glioblastoma and one cerebellar metastasis), the nature of which was evident when looking at the T2-weighted images. In six cases, there were no lesions to be seen either on diffusion-weighted echo-planar imaging sequences or on diffusion-weighted

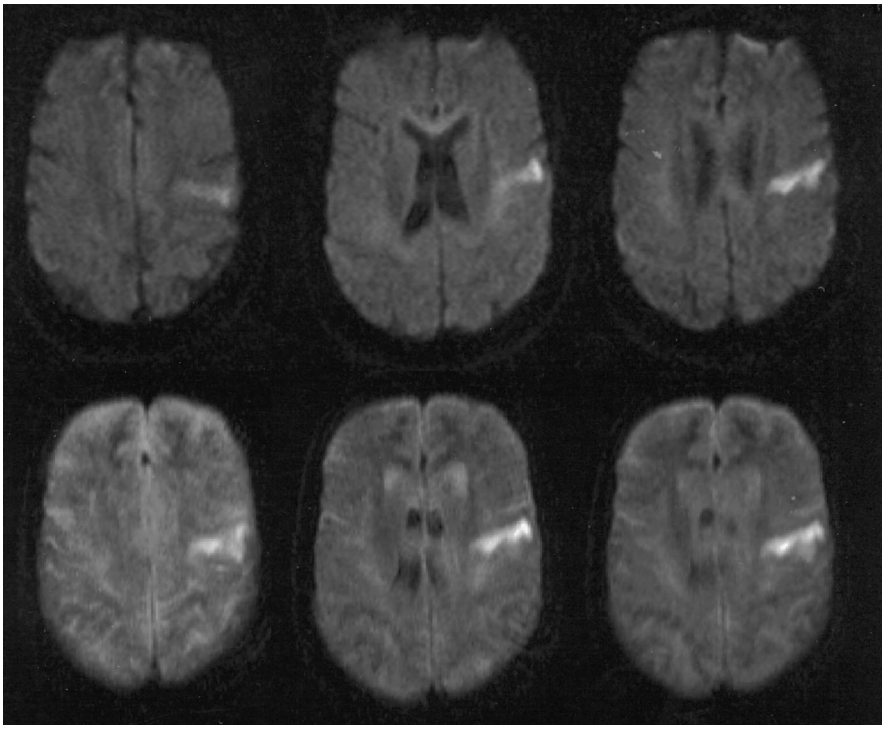

FIG 4. A 64-year-old woman 12 hours after acute onset of right-sided weakness. Diffusion-weighted HASTE images (echo time, 122; matrix 128 × 64) show the presence of a hyperintense lesion in the left-sided motor cortex.

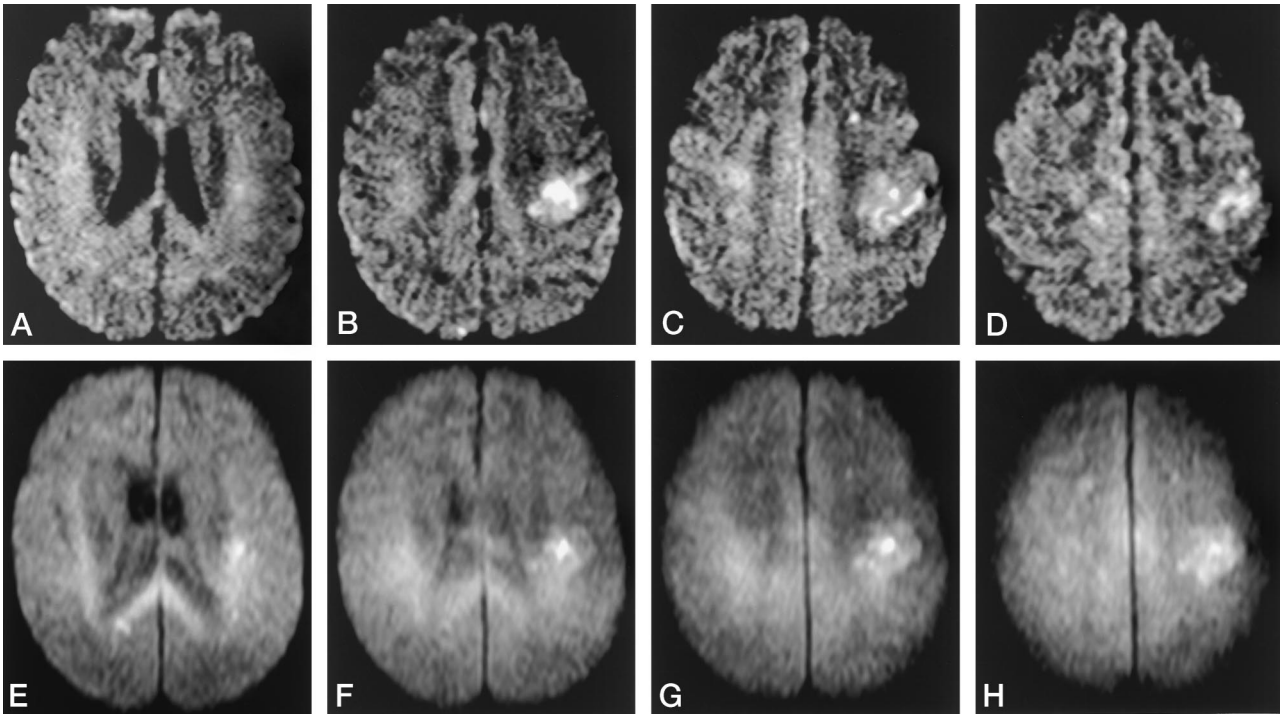

FIG 5. Comparison of diffusion-weighted echo-planar with diffusion-weighted HASTE sequences in a 75-year-old man with acute onset of right-sided hemiparesis 8 hours after onset. Diffusion-weighted echo-planar images (echo time, 118; matrix 128 × 128) at the maximum *b* value show an acute infarct in the left-sided motor cortex (*A–D*) confirmed by the diffusion-weighted HASTE images (echo time, 122; matrix 128 × 64) (*E–H*).

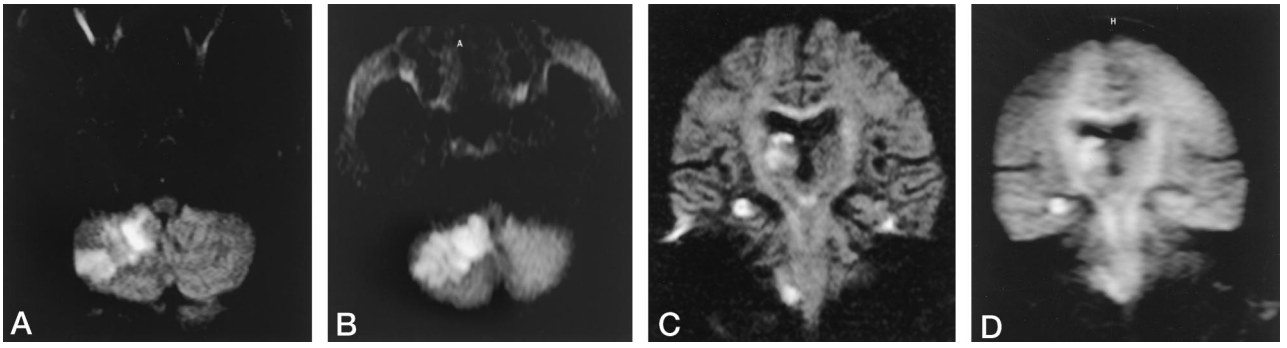

FIG 6. Diffusion-weighted images in a 63-year-old woman with acute onset of ataxia. Imaging was performed 10 hours after initial symptoms occurred. Axial diffusion-weighted echo-planar image (echo time, 118; matrix, 128 × 128) (*A*) shows the presence of an acute hyperintense infarct in the right cerebellar hemisphere. This hyperintensity is also seen on the diffusion-weighted HASTE image (*B*) (echo time, 122; matrix, 128 × 64). Coronal diffusion-weighted echo-planar image (echo time, 118; matrix, 128 × 128) shows the presence of hyperintense changes in the mesial temporal lobe and the posterior right thalamus as well as susceptibility-induced hyperintense changes in the basal temporal lobes (*C*) that are not present on the diffusion-weighted HASTE image (echo time, 122; matrix, 128 × 64) (*D*). The infarct in the cerebellum is seen in the coronal plane on both sequences.

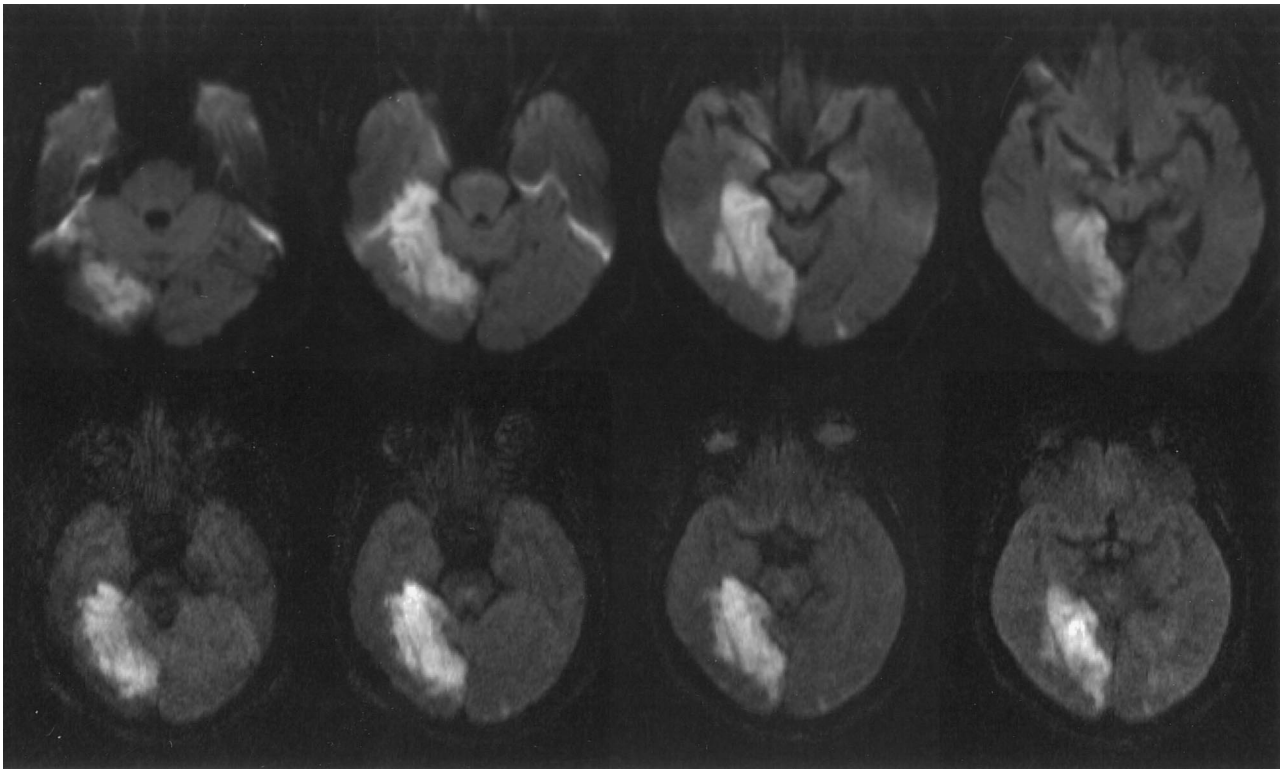

FIG 7. Acute right-sided basal occipital infarction in a 50-year-old man 9 hours after initial symptoms occurred. Diffusion-weighted echo-planar images (echo time, 118; matrix, 128 × 128) (*upper row*) show the presence of a right-sided posterior cerebral artery infarct, but also are associated with hyperintense echo-planar imaging artifacts in the temporal lobes. The infarct is also clearly seen on the diffusion-weighted HASTE images (echo time, 122; matrix, 128 × 64), but without susceptibility artifacts (*lower row*).

HASTE images. Although the clinical diagnosis in these patients remained stroke, it must be assumed that the lesions were very small infarcts, possibly in the internal capsule or brain stem, that were below the resolution of the technique. Follow-up imaging with echo-planar and T2-weighted sequences at 1 week remained negative. Diffusion-weighted HASTE imaging did not prove advantageous or disadvantageous for the patients who were imaged very early (within 6 hours).

The signal-to-noise ratio of the diffusion-weighted HASTE images was less than that of the diffusion-weighted echo-planar images. All observers were able to detect the strokes equally well on both diffusion-weighted echo-planar imaging and diffusion-weighted HASTE sequences, and both methods had the same

diagnostic value. The quality of the diffusion-weighted HASTE images was also judged to be less sharp in all cases (eg, Figs 5 and 6). When diffusion-weighted imaging was performed in the coronal plane, the diffusion-weighted HASTE images did not display the hyperintense susceptibility artifacts that were seen close to the skull base and sinonasal cavities on the diffusion-weighted echo-planar imaging studies.

Discussion

Because therapeutic options in the acute setting of stroke have been limited until recently, little emphasis has been put on the emergency diagnosis of cerebral infarction; however, owing to recent advances in knowledge about the pathophysiology of events leading to ischemia (9, 10), with subsequent development of potentially efficient neuroprotective and thrombolytic therapies (11, 12), attitudes are rapidly evolving. Although experienced interpreters have been shown to be able to recognize subtle signs of tissue damage with the use of such conventional imaging methods as computed tomography (CT) (13, 14) or T2-weighted MR imaging, these signs are either nonspecific or difficult to detect in the first hours after the onset of cerebral ischemia (15, 16). In such circumstances, diffusion-weighted imaging can be a sensitive technique for the diagnosis of stroke in an acute setting (17). Indeed, diffusion-weighted imaging has been shown to be able to depict ischemic lesions a few minutes after stroke onset in experimental animal models and to show reversibility of lesions after reperfusion or neuroprotective treatment (10, 18).

Because diffusion techniques are intrinsically extremely sensitive to motion, they were at first difficult to implement with patients in whom imaging was problematic. Therefore, fasting imaging techniques were deemed necessary. Most currently available fast diffusion techniques rely on echo-planar imaging (19, 20). Echo-planar imaging techniques, while very fast, have the disadvantage of being associated with severe image distortion, which makes coregistration with high-resolution anatomic images difficult and also creates potential inaccuracies in measurements of stroke volume. Other methods for acquiring fast diffusion-weighted sequences while compensating for motion artifacts that are currently under investigation include navigated spin-echo techniques or line-scan diffusion imaging. With navigated spin-echo techniques, complex motions are compensated for by performing a spin-echo diffusion-weighted sequence followed by a navigator spin-echo sequence. Navigated spin echo, like diffusion-weighted HASTE does require cardiac gating, but the acquisition times are long, partly because it is necessary to perform image postprocessing. Line-scan diffusion imaging is immune to motion artifacts and can be implemented on both high- and low-field scanners, but only one section at a time can be acquired, necessitating longer imaging times for a whole-brain data set than required for either diffusion-weighted echo-planar or HASTE sequences.

Because recent retrospective studies have shown the sensitivity and sensibility of diffusion-weighted echo-planar imaging to be high (S. J. Warach, R. R. Edelman, "On the Sensitivity and Specificity of DWI of Human Stroke: Analysis of 122 Cases," presented at the annual meeting of the American Society of Neuroradiology, Seattle, Wash, June 1996), and because there is no real accepted standard of reference for the diagnosis of stroke, it was decided to use diffusion-weighted echo-planar imaging as the standard against which to compare the diffusion-weighted HASTE studies. All patients were therefore examined on the same 1.5-T scanner at the same time with both diffusion-weighted HASTE and diffusion-weighted echo-planar imaging. Diffusion-weighted HASTE is a modified turbo spin-echo single-slot diffusion technique. The single-shot technique is judged important for diffusion-weighted imaging because it is important to freeze macroscopic movement or any effects related to physiological movements (cerebrospinal fluid and cardiac pulsations). With such a technique, a complete set of 20 sections covering the whole brain can be acquired in 1 minute 15 seconds. Although it is not quite as fast as currently available echo-planar imaging techniques, it does allow imaging with the diffusion gradient applied in all three directions (x, y, and z). The acquisition of these three data sets makes the calculation of trace images (ie, images without information about anisotropy effects) possible; they will, however, lengthen the examination time. Because of this, we chose to compare the images obtained at a maximum b value with the gradient switched in the z direction with both techniques. The presence of the anisotropy information did not cause any error in diagnosis. Diffusion-weighted HASTE also allows collection of images acquired at different b values and therefore makes it possible to obtain apparent diffusion coefficient (ADC) maps and values that have been shown to be of importance in the setting of acute stroke (Fig 2C). Indeed, owing to the presence of intracellular membranes, there is a natural restriction to movement that makes measurement of the real diffusion difficult; ADC maps which are generated by obtaining at least two same images at two different b values, give an estimate of the real diffusion change. By determining the ADC values, it should be possible to determine the time course of ischemia in the detected lesion (G. Schlaug et al, "Time Course of the Apparent Diffusion Coefficient [ADC] in Human Stroke," presented at the 34th International Joint Conference on Stroke and Cerebral Circulation, Anaheim, Calif, February 1997).

Although CT has generally been the accepted method of choice for imaging acute intracranial hematomas, recent evidence leads us to believe that new MR techniques, such as gradient-echo sequences or even diffusion-weighted imaging, could be very sensitive for the detection of acute blood (21, 22). If these data are confirmed, this could strengthen the role of MR imaging as the method of choice for examining patients with signs of acute urologic dysfunction, which would be of major interest in this new era of cost-conscious medicine, since it would elimi-

nate the need to perform more than one study initially. In our series, however, there were no hematomas, probably because there were no patients with hematomas referred for MR imaging during the period of the study.

Diffusion-weighted HASTE imaging enabled detection of all ischemic lesions seen on diffusion-weighted echo-planar images, and it produced images without the usual distortions caused by susceptibility artifacts close to the skull base and sinonasal cavities. HASTE also made it possible to acquire coronal diffusion-weighted images (Figs 3D and 6D) without the substantial susceptibility artifacts and anatomic distortion usually present in the basal temporal lobes and posterior fossa structures on coronal diffusion-weighted echo-planar images. While an experienced interpreter will easily recognize, in most cases, the hyperintensities associated with diffusion-weighted echo-planar imaging, this might not be true for less practiced radiologists; indeed, the hyperintensities close to the skull base seen on all diffusion-weighted echo-planar images might be confused for infarcts in the basal temporal lobes (Figs 6 and 7), brain stem, or cerebellum. This is of importance not only in patients with posterior fossa ischemia but also in patients with infarcts in the middle cerebral artery, where the basal temporal lobes might be implicated.

It was agreed that although all lesions were equally visible with both methods, the images acquired with diffusion-weighted HASTE had a less sharp appearance than those obtained with diffusion-weighted echo-planar imaging. Despite the high resolution potentially offered by diffusion-weighted HASTE, this lack of sharpness could be due to the higher motion sensitivity of the method, the slightly lower signal-to-noise ratio, or the point spread function of the diffusion-weighted HASTE images, or, most likely, to a combination of all three factors.

Volumes of cerebral ischemia, as determined from diffusion-weighted echo-planar imaging sequences, have been shown to be of use as markers of clinical severity and eventual neurologic outcome (23, 24); however, the image distortions often present on these images might render these volumes inaccurate. By their very nature, any diffusion sequence will be motion-sensitive, and this is true in the case of HASTE, especially since the half-Fourier transformation heightens its sensitivity to flow. Therefore, this sequence is extremely sensitive to both brain movement and cerebrospinal fluid pulsation: it is necessary to apply cardiac gating in order to measure diffusion in a quiet phase of the cardiac cycle. This gating can be done either with the usual chest electrode or with a peripheral finger electrode. Also, since diffusion-weighted HASTE does not require the strong magnetic fields and gradients associated with echo-planar imaging, it additionally offers the possibility of performing diffusion-weighted imaging with low-field magnets, such as 1.0-T systems that are not capable of performing echo-planar imaging. Two versions of the diffusion-weighted HASTE sequence are currently implemented at our site: one that runs on a 1.0-T magnet and one that is installed on the 1.5-T system. This capability enables most centers equipped with MR units to obtain diagnoses of acute stroke rather than limiting the benefits of this technique to a few select institutions. Indeed, when diffusion-weighted imaging is available on conventional MR systems, it will have reached its full potential.

Conclusion

We have found that diffusion-weighted HASTE sequences are an important addition to the existing techniques for imaging acute stroke because they provide fast single-shot diffusion-weighted images on scanners not capable of echo-planar imaging, are less prone to artifacts, and provide more anatomically accurate diffusion-weighted images.

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