Clinical Use of Nuclear Magnetic Resonance Imaging in Stroke

L. Dana DeWitt, M.D.

SUMMARY There are many positive aspects to the use of MRI in the evaluation of cerebrovascular disease. First, the MR imaging technique appears to be essentially without hazard. It does not rely on ionizing radiation, and no intravenous injections of contrast agent are necessary. MRI exploits the tissue's inherent biophysical characteristics to provide superior contrast. Infarctions are well delineated by MRI, often better and earlier than CT. Because of the lack of MRI signal from bone and thus the lack of transverse artifact from bone often seen with CT, lesions in the posterior fossa are very well visualized. With MRI it is possible to obtain images in the transverse, coronal, and sagittal planes, which provides for good evaluation of lesion size and extent. Ateriovenous malformations have been visualized by MRI, but it is still too early to know whether MRI has any detection capability over CT in this disorder. Subdural hematomas have been well visualized by MRI, including cases of isodense subdural not visualized by CT. On the other hand, MRI has not proven to have any advantage over CT in the evaluation of intracerebral hemorrhage, hemorrhagic infarction, and subarachnoid hemorrhage. In fact, for detection of intracerebral hemorrhage and subarachnoid hemorrhage, CT may be better at the present time. In chronic infarction the surrounding area of Wallerian degeneration may cause the area of infarction to appear larger than it actually is. Hopefully, with further research into the use of different pulse sequence techniques and with good neuropathological correlation, the present limitations of MRI can be eliminated. The future holds much promise and excitement for the use of MRI in evaluation of stroke syndromes. In addition to proton imaging, new imaging research uses other nuclei, such as phosphorus, for the spectral analysis of adenotriphosphate and inorganic phosphate and the measurement of pH. Paramagnetic contrast agents may permit detection of pathological conditions not yet evident by current imaging techniques. Through the use of different pulse sequence techniques and secondary devices such as surface coils, detection of blood flow and imaging of vessels may be possible.

WHEN CERTAIN ATOMIC NUCLEI are placed in a magnetic field and stimulated by radiowaves of a particular frequency, they will re-emit some of the absorbed energy in the form of radio signals. This phenomenon is known as nuclear magnetic resonance (NMR) and was first described in the 1940's. Lauterbur devised a method of determining the location of stimulated nuclei by spatially encoding the emitted signal so that it could be used to create an image of the distribution of nuclei within the sample. This resulted in the implementation of NMR imaging (MRI) of biological systems in living animals and humans. The clinical usefulness of MRI is now widely apparent.

Because protons (1H) are among the most easily detected of NMR-sensitive nuclei and because there is a high concentration of proton-rich water and lipids in biological systems, especially the brain, most current clinical MRI is generated using the 1H resonance. The resultant image intensity is a function of the distribution of proton density, modified by the relaxation times, T1 (spin-lattice) and T2 (spin-spin). The extent to which the parameters of proton density and T1 and T2 relaxation times contribute to image intensity can be varied by the use of different imaging methods, in particular different radiofrequency pulse sequences. MRI images are determined by the physical and chemical characteristics of tissues, as opposed to their pathology or anatomy. An understanding of the nature of the physicochemical properties underlying image intensity and knowledge of the imaging technique used are needed to appreciate fully the implications of the resultant images.

Techniques

The principles of MRI and details of pulse sequences have been outlined in detail elsewhere. Briefly, the most commonly used pulse sequences at present are inversion recovery (IR) and spin-echo (SE). With the inversion recovery technique the image intensity is related to T1. Water has a very long T1; CSF, which behaves like water, has a relatively long T1 and appears dark on inversion recovery sequences. Gray matter has a higher water content, a lower lipid content, and a longer T1 than white matter, providing for excellent gray-white matter discrimination. The inversion recovery sequence has also been noted to provide good lesion detection in numerous pathological conditions.

The spin-echo pulse sequence highlights primarily T2 relaxation time; it exhibits very little gray-white...
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matter contrast but is also excellent for lesion detection. Since the range variations of T2 in different tissues and pathological conditions do not necessarily parallel those of T1, spin-echo sequences can provide important additional information. The spin-echo sequence is now often used to provide both T1 and T2 data.

Although the spin-echo sequence is optimal for providing T2 information, the technique can be varied to permit "weighting" of the amount of T1 and T2 contribution within an NMR image by altering the echo time as well as the recovery time of the pulse sequence. When the pulse sequence is utilized for T2 weighting, tissues with a long T2 will have a greater signal intensity than those with a short T2 and will appear brighter (the signal decays more slowly). When the spin-echo sequence is used in a manner to provide T1-weighting, regions with a short T1 will appear brighter, and those with a long T1 will appear darker; this type of pulse sequence also provides for better anatomical detail.

Because the T1 and T2 characteristics of different lesions vary, different pulse sequences must be used in an attempt to obtain the best lesion detection. The physician supervising the imaging can maximize the results by tailoring the pulse sequences to the nature of the suspected lesions and by deciding whether the pathology will be best visualized with transverse, coronal, or sagittal views. The importance of these decisions must be emphasized: if the pulse sequences and orientations used are not correct, there is a chance that the lesion may be missed.

Stroke Syndromes

Embolic and Thrombotic Infarction

Initial MRI studies in ischemic stroke were performed in animal models. Abnormal images were noted within 3 hours and sometimes as early as 30 minutes after symptomatic carotid artery ligation in gerbils and as early as 2 hours in rats after carotid ligation and blood clot embolism. Although there have been no reports of human imaging done this early after stroke, abnormal image intensity has been noted in the region of infarction at less than 24 hours when CT was still negative.

In early infarcts the inversion recovery technique may demonstrate only subtle alterations in the gray matter-white matter contrast in the region of infarction, something not usually seen with CT. Characteristically, thrombotic or embolic infarctions have prolonged T1 and T2 relaxation times in areas corresponding to well-known vascular distributions. Thus, on images derived from pulse sequences with T1-weighting (prolonged T1), the area of infarction will appear as an area of decreased image intensity or dark (Fig. 1 top). On images with T2-weighting (prolonged T2), the corresponding area will have increased image intensity or appear bright (Fig. 1 bottom). Watershed infarcts appear as areas of prolonged T1 and T2 relaxation times in the border zone between the anterior and middle cerebral arteries and middle and posterior cerebral arteries. These infarcts mainly involve the cortex, but deep watershed infarcts can be seen as well. Recently, a "halo" of moderately prolonged T2 surrounding an area of more prolonged T2 in chronic infarction has been noted, representing Wallerian degeneration.

MRI appears at present to be as good as, and in many cases better than, CT for the evaluation of ischemic infarction. For early lesion detection MRI is clearly better than CT because MRI is known to show well-demarcated areas of prolonged T1 and T2 relaxation times. Whether some of the early MRI changes seen in acute infarction might represent reversible ischemia is still not known. A case of subarachnoid hemorrhage with vasospasm has been reported in which the MRI showed prolonged T1 and T2 at the time that the patient developed neurological deficits. However, when the patient's deficits resolved, the...
MRI was not repeated to see if it had returned to normal. In addition, since edema is seen on MRI as an area of prolonged T1 and T2, in acute infarction edema would not be distinguishable from infarction in most cases; this problem is also encountered with CT. With further experimentation with different MRI pulse sequences and quantitation of T1 and T2 relaxation times, MRI might in the future be able to differentiate infarction, ischemia, and edema.

As mentioned above, MRI in chronic infarction may show regions of Wallerian degeneration as well as infarction; these have been observed with CT as well. Because of the excellent gray-white matter delineation that can be obtained with MRI, cerebral cortex can be visualized, and subcortical gray matter can be distinguished from surrounding white matter or CSF. Since the anatomy of the sylvian fissure area is well visualized on MRI and coronal views are easily obtainable, MRI is better than CT for the study of neurobehavioral syndromes. The absence of artifact from bone makes MRI far superior to CT for visualizing infarction in the posterior fossa (Fig. 2).

Lacunes
Lacunar infarcts are well demonstrated by MRI; they are generally small, circular areas of prolonged T1 (dark) and prolonged T2 (bright) deep in the white matter. Occasionally, in cases of multiple lacunar infarcts, discrepancies between prolongation of T1 and T2 have been noted; only further study will establish whether such findings can be correlated to the age of the infarct.

MRI appears to be better than CT for the detection of lacunes; in cases of multiple lacunes, MRI has been noted to demonstrate more lesions than CT. Because of the lack of MRI signal from rigid bone, and thus the lack of bone artifact in the posterior fossa (something frequently seen with CT), lacunes in the brainstem are also better visualized with MRI than with CT.

Intracerebral, Subdural, and Subarachnoid Hemorrhage
Hematomas have different characteristics on MRI depending on the age of the hemorrhage. Some observers have found that acute intracerebral hemorrhages have a short T1 relaxation time and appear bright on inversion recovery images, as well as a short T2 relaxation time (dark on spin-echo images), both results similar to those of white matter. This characteristic of hematomas can sometimes make small, deep hemorrhages in the white matter undetectable. Often, however, the hematoma will be surrounded by edema, which has marked prolonged T1 and T2 relaxation times. Therefore, on inversion recovery images the bright area of hematoma will be surrounded by a dark rim of edema, and on spin-echo images a dark area of hemorrhage will be surrounded by a bright region of edema. Chronic hematomas have also been noted to appear bright on inversion recovery images (short T1), but they have been found to have a long T2 and appear bright on spin-echo. With the current MRI experience, CT is better for detection of intracerebral hemorrhage at present.

These same characteristics of a short T1 (bright) on inversion recovery studies and long T2 (bright) on spin-echo studies have been noted in studies of subdural hematomas. In one study of five patients, MRI demonstrated the subdural hematoma in all patients, while in two of the five, the subdural hematomas were in the isodense phase and were not visualized by CT. Therefore, although CT and MRI are probably equally good for evaluation of acute subdural hematomas, there is evidence that MRI is clearly better for more chronic lesions that may be in the CT isodense phase.

The results of MRI evaluation of subarachnoid hemorrhage have been variable. In two cases of acute subarachnoid hemorrhage (12 hours and 29 hours post bleed), when CT clearly showed subarachnoid blood, the inversion recovery studies showed no definite ab-
normalities. In the 12 hours post bleed case, a spin-echo study with a short echo delay showed a high signal intensity corresponding to the region of blood seen on CT. In a case of intracerebral hemorrhage subarachnoid extension of blood was identified by its short T1 (brightness) on an inversion recovery study. At present, CT is better than MRI for evaluation of subarachnoid hemorrhage.

Hemorrhagic Infarction

In most MRI studies hemorrhagic infarction has been noted to have the same characteristics as hemato-
mai, i.e., short T1 (bright) and long T2 (bright). These results are probably obtained because in most MRI studies of hemorrhagic infarction, patients have been chosen for study on the basis of noncontrast CT showing a region of high attenuation consistent with blood. In a single case where the CT was negative for blood but neuropathological correlation showed hemorrhagic tissue, the MRI demonstrated a mildly pro-
longed T1 and T2. If the pathological correlation had not been done, the lesion on MRI would have been mistaken for ischemic infarction as opposed to hemor-
rhagic infarction.

In summary, if there is hemorrhagic infarction with a resultant hematoma, CT will be as good as or better than MRI for lesion detection. However, if the CT is negative for blood, MRI will probably not be any more helpful than CT in demonstrating hemorrhagic tissue.

Arteriovenous Malformations

Arteriovenous malformations have been demonstrated by MRI. Serpiginous, low-image intensity vasc-
ular structures have been seen in addition to associat-
ed parenchymal changes. Since CT also demonstrates arteriovenous malformations well, it is still too early to know which is better. At present, CT is probably best for demonstration of these lesions as long as contrast can be used; however, if there is a contraindication to the use of dye, MRI would be very useful.

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