

SUSCEPTIBILITY-WEIGHTED IMAGING IN MAGNETIC RESONANCE IMAGING

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Pak J Neurol Sci 2008; 3(1): 27-31

Magnetic resonance (MR) imaging has revolutionized the field of neuroimaging. Not only does it allow visualization of gross anatomy in exquisite detail but with the addition of imaging techniques such as diffusion-weighted imaging (DWI) and spectroscopy, it is now possible to interrogate cellular structure and function. One longstanding criticism of MR has been the relative difficulty in the detection of hyper-acute and acute hemorrhages especially when compared with computerized tomography (CT). A relatively new addition to the MR armory, susceptibility-weighted imaging (SWI) addresses this and is increasingly being used in situations such as detection of acute bleed in stroke, microhemorrhages, and other diseases.

SWI is a T2-weighted gradient echo post-processing reconstruction technique that accentuates the paramagnetic properties of blood products and is very sensitive for the detection of intravascular venous deoxygenated blood as well as extravascular blood products.¹ This technique was developed by Dr. Mark Haacke and co-workers who originally called it 'high-resolution blood oxygen level-dependent venography' (HRBV).^{1,2} It was renamed 'susceptibility-weighted imaging' as its mechanism is based on the susceptibility differences between two tissues and it has wider application than evaluating venous structures of the brain.^{1,3}

Paramagnetic properties of deoxyhemoglobin allow SWI to detect microhemorrhages and visualize the minute vessels of the brain that are not seen by conventional imaging. Two situations where SWI has shown clinical potential are in the detection of hemorrhage in early stroke and diffuse axonal injury (DAI) in brain trauma.^{4,5} Hemorrhagic lesions visible in SWI are significantly higher than those detected by conventional imaging techniques such as CT. Studies have also shown benefit in neurologic disorders, arterio-venous malformations, occult venous disease, multiple sclerosis, trauma, tumors and functional brain imaging.^{3,6-11}

PRINCIPLES

SWI is a new term; however, it is not a new concept. Refinement of previous technology has allowed us to expand its application to study various conditions and pathologic states. SWI is a T2-weighted gradient echo sequence that exploits the magnetic properties of tissues due to local inhomogeneities in the magnetic field. Although the term was coined by Haacke et al in 2004,¹ the use of the basic principles on which it is based had been described in clinical applications by Reichenbach et al much earlier.¹² The contrast mechanism used in SWI is primarily associated with the magnetic susceptibility difference between oxygenated and deoxygenated hemoglobin, leading to a phase difference between the regions containing deoxygenated blood and their surrounding tissues, resulting in signal intensity cancellation.¹³ Most blood products, including deoxyhemoglobin, methemoglobin, and hemosiderin have unpaired electrons, and are therefore paramagnetic. The greater the number of unpaired electrons, the greater is the paramagnetic effect. Paramagnetic substances tend to suppress the MR signal. This property is exploited to make hemorrhages visible on MR images that accentuate signal intensity loss from rapid spin dephasing.⁸

IMAGING TECHNIQUE

SWI is based on high-resolution volume acquisition techniques.¹⁴ Gradient refocused echo type (GRE-type) and spin echo-type echo-planar imaging sequences are sensitive to susceptibility effects. GRE sequences are preferred because they are extremely sensitive and do not rephase the decay arising due to magnetic field inhomogeneities and magnetic susceptibility.¹⁵ They also have considerably better resolution as compared with echo-planar sequences. SWI parameters are as follows: repetition time (TR), 600 to 800 ms; echo time (TE), 30 to 50 ms; and flip angle, 10° to 30°.¹⁶ These parameters have been applied to the detection of hemorrhagic

lesions^{4,5,17} and clots.¹⁸ They have short acquisition times which result in fewer movement artifacts and shorter therapeutic delay.¹⁹

SWI is not just a scanner derived image and requires extensive post-processing. This post-processing involves manipulation of the phase mask and magnitude images. Although this may be carried out manually, some manufacturers include this as an automatic option.¹³

CLINICAL APPLICATIONS

Susceptibility-weighted imaging (SWI) is highly sensitive to venous vessels, intravascular blood and breakdown blood products and iron-containing tissues.^{1,3} This gives SWI tremendous applications making it extremely useful in various clinical conditions. Currently it is used mainly to detect hemorrhage in stroke and diffuse axonal injury in patients with traumatic brain injury (TBI). SWI has also shown promise in evaluation of brain tumors as well as neurodegenerative disorders associated with intracranial calcifications or iron deposition.²⁰

Diffuse Axonal Injury

Diffuse Axonal Injury (DAI) is known to be a common mechanism of injury in TBI. It is caused by shearing stress, primarily in white matter, involving tearing of axonal fibers due to forces during acceleration, deceleration and rotation of the brain.²¹ The degree of insult depends on the magnitude of the force and the rate of deceleration associated with the tissue. MRI has given us the ability to detect DAI and define patterns of injury with DAI predominantly involving the frontal white matter, corpus callosum, brainstem, and diencephalon.²²

DAI may be associated with hemorrhagic or non-hemorrhagic lesions. Conventional imaging for DAI can miss microhemorrhages, which result in false negatives. This could have great impact on management and treatment resulting in fatal results in patients with DAI. SWI with its sensitivity to venous blood and its break down products can provide useful information in patients with DAI resulting in better outcomes.^{3,8,23}

The literature shows that the presence of hemorrhage in DAI lesions may give patients a poorer prognosis compared with the absence of hemorrhage.^{24,25} With the development of SWI improved detection of intracranial hemorrhages in DAI patients is possible.²⁶ In a study by Tong et al SWI was compared with conventional technique for the detection of DAI.⁸ They depicted significantly more hemorrhages than conventional GRE MR imaging, suggesting greater benefit in diagnosing DAI with SWI.⁸

This would yield additional neurologic imaging information that can improve the evaluation, treatment, and management of patients with traumatic brain injury and suspected DAI.

Cerebral infarction and hemorrhage

Stroke is an acute neurological injury in which the blood supply to a part of the brain is interrupted. It involves a sudden loss of neuronal function due to disturbance in cerebral perfusion such as when the blood supply to the brain is abruptly interrupted or when blood vessels in the brain rupture resulting in a blood spill. There are two types, classified as ischemic and hemorrhagic stroke. Hemorrhagic stroke is a feared complication. Undiagnosed bleed in stroke patients can lead to fatal complications and death. CT is considered the gold standard for hemorrhage detection, although it too has limitations. CT can miss microbleeds and petechial hemorrhages in ischemic infarction. Gradient echo imaging has shown to be good in detecting hemorrhage; however, it is best detected by SWI. Furthermore, the ability to detect early blood products in patients with acute stroke has made SWI a powerful technique in the evaluation of stroke patients.^{21,27}

Studies have shown the ability of SWI in detecting intracerebral hemorrhage (ICH) in hyperacute and acute stroke.^{4,5} Hyperacute hematoma appears as an isointense to hyperintense center with a hypointense periphery (deoxyhemoglobin).^{4,5} Signal changes progress from the periphery toward the center of the hematoma.^{28,29} Patel et al were able to show hypointense lesions in 6 patients with ICH imaged between 2.5 and 5 hours from symptom onset.⁴ The earliest detection of hemorrhage reported is 23 minutes from symptom onset by Linfante et al.⁵ In a prospective, blinded, randomized trial of 124 patients, 62 patients with ICH showed a sensitivity and accuracy of 100% in comparison with CT.³⁰ Subarachnoid hemorrhage has been shown to be detected by SWI; however, sufficient evidence regarding the sensitivity of SWI is still not available.³¹

Use of thrombolysis may cause bleeding in patients who have old microbleeds.³² Approximately 12% to 20% of MRI-examined stroke patients have small deposits of hemosiderin which appear as hypointense areas.³³ It is unclear if these old microbleeds could be treated safely with thrombolysis or can cause thrombolytic-induced ICH.³³

Other areas of development involve early detection of spontaneous hemorrhagic transformation before thrombolytic therapy and early detection of post-

thrombolytic hemorrhagic transformation after thrombolytic therapy.^{6,34} CT may miss early bleeding within 3 hours of thrombolytic therapy due to presence of contrast extravasation.³⁴ SWI detection of intra-arterial clot may change management of stroke patients. Demonstration of arterial occlusion beyond 3 hours may be required to continue thrombolytic therapy. Hyperdense middle cerebral artery (MCA) sign at plain CT scan can be correlated with signal loss along the MCA territory. These susceptibility changes can be attributed to the high deoxyhemoglobin content of fresh clots.¹⁸

Brain tumor

The development of SWI has opened new horizons in the evaluation of brain neoplasm. To understand brain tumor, it is important to also understand the angiographic behavior of tumors including vascularity and microhemorrhages. Better detection of hemorrhage, calcification, and increased vascularity by SWI may further help in establishing the tumor status.⁹ Calcification in tumors may indicate lower grade while increased vascularity suggests higher tumor grade. Administration of paramagnetic contrast dye and comparing SWI images after and before injecting dye will help differentiate abnormal tumor vascular supply with hemorrhage as the latter would not change in signal intensity; however, the former would, with contrast injection.⁹

Neurodegenerative disorders

Neurodegenerative diseases associated with increased iron levels in the brain can be detected by SWI. Haacke and colleagues looked at establishing a baseline phase behavior in MRI to determine normal versus abnormal iron content in the brain.³⁵ They established a baseline of phase differences between tissues in a number of regions of the human brain as a means of detecting iron abnormalities using magnetic resonance imaging (MRI). They found that using phase as an iron marker may be useful for studying absorption of iron in diseases such as Parkinson's, Huntington's, neurodegeneration with brain iron accumulation (NBIA), Alzheimer's, multiple sclerosis (MS), and other iron-related diseases.³⁵ The basal ganglia contain the highest levels of iron in the brain. Post-mortem studies indicate a disruption of iron metabolism in the basal ganglia of patients with neurodegenerative disorders such as Alzheimer's disease (AD) and Huntington's disease (HD).³⁶ Susceptibility effects form the basis of a whole class of contrast agents and are helpful in terms of detecting areas of brain hemorrhage or discriminating physiologically iron-containing anatomic structures such as the nucleus ruber or substantia nigra, especially in patients with

neurodegenerative parkinsonian disorders or the striatonigral variant of multiple system atrophy (MSA-P).³⁷ The sensitivity of MRI in depicting MS lesions in the brain is very high; however, its specificity is low.³⁷ SWI enables us to visualize venous architecture in great detail in relation to MS lesions in the brain including the perivenous location of MS lesions.⁷

Sturge-Weber Syndrome

Sturge-Weber Syndrome (SWS) is a disorder of a primitive persistent vascular plexus, resulting in a pial angioma. Loss or progressive worsening of normal cortical venous drainage since birth results in abnormal venous drainage in the deep venous system.³⁸ SWI is helpful in the evaluation of this vascular malformation and for venous shunt surgery in patients with SWS.³⁸ Fishbein et al described T2 shortening in the white matter of the affected hemisphere and suggested that this may be due to increased deoxyhemoglobin in the capillaries and from shunting of venous blood through the deep medullary veins.³⁹

FUTURE

SWI is a new imaging technique with tremendous scope and applications. A large number of studies and research is ongoing to look at different uses of SWI. As long as there is susceptibility difference between tissues, it can be utilized in various clinical areas. In time, SWI may not only be limited to the brain.³ Its susceptibility abilities may play a major role in disease processes in other regions of the body besides brain as long as susceptibility artifacts are produced.³ Hopefully the studies underway will bear out the tremendous potential of this technique that early experience has shown. SWI may become integral in the workup of cerebrovascular disorders, CNS tumors and neurodegenerative disorders.^{4,5,7,8,9,24,37,38}

CONCLUSION

Susceptibility Weighted Imaging is a new MRI sequence that exploits the magnetic properties of tissues due to local inhomogeneities in the magnetic field. Studies have shown its benefit in patients with stroke and diffuse axonal injury. A great amount of research is ongoing to discover the true potential of SWI in other hemorrhagic conditions, brain neoplasms and neurodegenerative diseases. SWI adds only a few minutes to the current protocol of brain MRI. But its use may benefit patients greatly with significant improvement in patient care and management.

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