Susceptibility-weighted Imaging: Technical Essentials and Clinical Neurologic Applications

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Susceptibility-weighted imaging (SWI) evolved from simple two-dimensional T2*-weighted sequences to three-dimensional sequences with improved spatial resolution and enhanced susceptibility contrast. SWI is an MRI sequence sensitive to compounds that distort the local magnetic field (eg, calcium and iron), in which the phase information can differentiate. But the term SWI is colloquially used to denote high-spatial-resolution susceptibility-enhanced sequences across different MRI vendors and sequences even when phase information is not used. The imaging appearance of SWI and related sequences strongly depends on the acquisition technique. Initially, SWI and related sequences were mostly used to improve the depiction of findings already known from standard two-dimensional T2*-weighted neuroimaging: more microbleeds in patients who are aging or with dementia or mild brain trauma; increased conspicuity of superficial siderosis in Alzheimer disease and amyloid angiopathy; and iron deposition in neurodegenerative diseases or abnormal vascular structures, such as capillary telangiectasia. But SWI also helps to identify findings not visible on standard T2*-weighted images: the nigrosome 1 in Parkinson disease and dementia with Lewy bodies, the central vein and peripheral rim signs in multiple sclerosis, the peripheral rim sign in abscesses, arterial signal loss related to thrombus, asymetrically prominent cortical veins in stroke, and intratumoral susceptibility signals in brain neoplasms.

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Online supplemental material is available for this article.

IRI offers a broad range of contrast mechanisms that exploit key tissue properties including water content (spin density), T1, T2, diffusion, T2*, and susceptibility. There is growing interest in T2*-weight ed imaging and the underlying susceptibility effects in the form of both susceptibility-weighted imaging (SWI) (1,2) and quantitative susceptibility mapping (QSM) (3). The former has been available to clinicians for nearly 20 years, whereas the latter remains in a research mode after more than 10 years of development. Interpreting these different contrast mechanisms is not always straightforward and this is true with the subtleties associated with SWI.

SWI is the combination of a specific sequence and processing design developed to enhance the contrast in T2*-weighted images (1). Originally developed to look at deoxyhemoglobin in veins and cerebral microbleeds (CMBs), its applications have widened considerably. SWI combines a high-spatial-resolution, ideally fully flow-compensated (to avoid vascular dephasing caused by flow effects), and three-dimensional gradient-echo sequence with a phase mask to highlight paramagnetic and/or diamagnetic substances.

Different MRI vendors have proposed various techniques with the same intention to provide high-spatial-resolution sequences that enhance the susceptibility-contrast for clinical routine.

To avoid confusion or misunderstandings, our article will use the term SWI only for sequences that apply a specific filtering and phase multiplication (1) and the term SWI-like will be used as a generic term for all types of high-spatial-resolution susceptibility-enhanced heavily T2*-weighted sequences across all vendors.
Swi and related sequences improve the depiction of lesions and specificity to SWI and related sequences include visualization of the nigrosome 1, central vein and peripheral rim sign, arterial signal loss, asymmetrically prominent cortical veins, and intratumoral susceptibility signals.

**Technical Considerations**

**Essential Technical Considerations of Gradient-echo Imaging**

Conventional T2-weighted imaging typically uses spin-echo sequences that minimize susceptibility artifacts (even with fast implementations) because of repetitive refocusing of 180° pulses. However, T2*-weighted, SWI, or SWI-like sequences purposely enhance the effect of local field variations caused by tissue content such as blood products (ie, hemosiderin in CMB), iron content (often in the form of ferritin), calcium content, and deoxyhemoglobin in venous blood. These processes cause local variations in the magnetic field that lead to signal loss in the form of T2* (Fig 1).

Historically, susceptibility effects used a two-dimensional gradient-echo T2*-weighted sequence (4). Because of restrictions regarding the number of sections required and the intermediate repetition times used, whole-brain coverage used only a relatively short echo time (TE) composed of sensitization to T2* signal loss. These sequences also used a small flip angle, making the images spin-density weighted and making the cerebrospinal fluid high contrast relative to the surrounding tissues (5). The TEs around 20–25 msec at 1.5 T made only larger microbleeds visible because the visibility of CMBs depends on TE and spatial resolution. High-spatial-resolution three-dimensional gradient-echo sequences show much smaller CMBs, especially when longer TEs are used.

Spin dephasing in the presence of local variations in the magnetic field causes susceptibility-related signal loss and depends on spatial resolution and orientation of the object of interest (6). With current choices of TEs, if an object such as a vein or microbleed is about one-quarter of the voxel volume it will have the best cancellation effect (7). To highlight vessels or CMBs that are 250–500 μm in diameter, a voxel with dimensions 0.5 × 0.5 × 0.5 mm³ will maximize signal loss at a reasonably short TE. For practical reasons, we do not recommend the use of voxel sizes larger than 0.5 × 1 × 2 mm³. For venous blood (with a susceptibility of roughly 450 ppb, oxygen saturation of 70%, and a hematocrit of 45%), maximum signal loss occurs with a TE of around 23 msec at 3.0 T (46 msec at 1.5 T, and 9.8 msec at 7.0 T). The loss in magnitude for smaller objects will be less. Thus, the object might not be conspicuous despite a susceptibility effect in the phase images. Instead, the signal loss for bigger vessels will only occur at the edges of the vessels, creating a dark-line artifact around the vessel (7). Practically, a minimum-intensity projection (often more than four or five sections) highlights the continuity of the veins.

**Basic Underpinnings of SWI Postprocessing**

The concept of filtering the phase to highlight paramagnetic structures was a key advancement in developing SWI (8,9) and eventually in the use of the nomenclature SWI (1). Whereas any gradient-echo sequence can be reconstructed to produce magnitude and phase images, the diagnostic information in phase data is often corrupted by the effects of air and/or tissue interfaces and phase aliasing. But after high pass filtering the phase data, interesting contrast becomes available. The modification of filtered phase images can create a mask that highlights either paramagnetic (eg, hemosiderin or deoxygenated blood) or diamagnetic substances (eg, calcium, white matter fibers) depending on their positive and negative phase shifts. The creation of SWI data involves multiplying the phase mask (normalized between 0 and 1) several times (4 is usually enough to highlight most vessels while maintaining good signal-to-noise ratio) with the magnitude image to obtain the desired contrast (1). To enhance the visibility of veins and other sources of susceptibility, SWI is often postprocessed by using a minimum-intensity projection over multiple sections depending on the section thickness (Fig E1 [online]).

From a technical perspective, the term SWI is a particular processing method implemented on scanners manufactured by Siemens, United, and Neusoft. Similar susceptibility-weighted sequences exist, such as susceptibility-weighted angiography, or SWAN, by GE Healthcare and SWI with phase enhancement, or SWIp, by Philips. Susceptibility-weighted angiography uses magnitude images only, whereas SWI with phase enhancement also uses a phase mask. There are subtle differences between the vendors’ implementation of SWI-like sequences (10). Those vendors that use SWI in its original implementation use a phase mask to enhance the contrast. But those that use SWI-like weighted images such as susceptibility-weighted angiographic images or venous blood oxygen level–dependent images use the magnitude images from longer TEs. The former uses a weighted sum of longer TEs to keep the T2* dephasing effects but also enhances the signal-to-noise ratio, whereas the latter uses a single long echo from an echo-shifted approach by a steady-state free
similar to the proposition by Haacke et al (1) to sequences from any MRI vendor, which do not routinely apply this postprocessing pipeline. For example, SWI postprocessing can be applied to data from the multiecho susceptibility-weighted angiography (GE Healthcare) sequence by using the phase information to improve the susceptibility contrast (Fig 3).

**Phase Handedness and Geometry Dependence**

Another key issue is how the vendors display the phase information. A left-handed system means the phase is positive going clockwise, whereas a right-handed system (the usual choice) means the phase is positive going counterclockwise (because

Figure 1: Axial MRI scans of multiple traumatic cerebral microbleeds in a patient with alcoholism and repetitive falls. A, A conventional spin-echo T2-weighted (T2w) image depicts the posttraumatic gliosis in the right frontal pole but shows no microbleeds. B, A conventional intermediate-echo T2*-weighted 3.0-T image depicts some evidence of hemosiderin and bleeding. C, Susceptibility-weighted imaging (SWI) findings show diffuse microbleeds and vascular damage in the frontal lobes (arrows) and show the veins because of their inherent deoxyhemoglobin content.

Figure 2: Images show the effect of the application of susceptibility-weighted imaging (SWI) scan processing on standard two-dimensional (2D) T2*-weighted gradient-echo (GRE) imaging (left). The resulting SWI contrast-enhanced image improves the detectability of microbleeds (middle) on the basis of the same data set. Microbleeds are better visible after SWI postprocessing (arrows), some can only be seen after SWI postprocessing (arrowheads). (Reprinted, with permission, from reference 57.)
that is the direction the fingers of your right hand will curl when you start with them straight and then make a fist). Vendors’ sequence trade names are shown in Table 1. Depending on the use of left-handed versus right-handed systems, the image appearance changes (Fig 4).

There is no unique phase spatially outside an object. Both the phases inside and outside depend on geometry. For example, there is a dipole effect around each object (whether it is a CMB or a vein [paramagnetic] or calcium [diamagnetic]) that will change the phase as a function of the angle relative to the main field and position relative to the center of the object. By using these dipole effects, what is paramagnetic and what is diamagnetic can be better defined (Fig 5).

**Microbleeds versus Microcalcifications Imaging Tip**

Both microbleeds and microcalcifications appear hypointense on SWI-like sequences. Although it is possible, in principle, to discriminate microbleeds from microcalcifications on the basis of the phase shift, as described, this may be more challenging than expected in clinical routine. In general, small lesions with simple spherical configurations are often associated with a clear phase shift and reliably differentiated as either microbleeds or microcalcifications by using the dipole behavior of the magnetic field. However, larger and more geometrically complex lesions can display complex signal on phase images (Fig 6), which change from one section to the next. Therefore, discrimination of microbleeds from microcalcifications is less evident and sometimes inconclusive. Moreover, section thickness and sequence parameters influence the ability to use phase to make this determination. Ideally, QSM should be used to resolve this issue because it takes all phase information and maps into the source magnetic field that first produced the phase. In calcifications, the phase would be low contrast in a left-handed system (11). Veins or calcification in the pineal or choroid plexus gland can be used as references to help differentiate paramagnetic from diamag-
Physiologic Factors Affecting Venous Signal

In a way, SWI-like sequences can be considered a high-spatial-resolution three-dimensional version of blood oxygen level–dependent imaging. Because these sequences use a long echo (which causes T2* dephasing from the venous signal specifically), any changes in oxygen saturation can cause a dramatic gain or loss of contrast in the images (usually much higher than that observed on blood oxygen level–dependent images). A good example is when you drink 2 cups of strong coffee or an energy drink with 200 mg of caffeine quickly. Within 20 minutes a peak effect of vasoconstriction (and therefore reduced perfusion) will occur with an increase in conspicuity of the veins (Fig 8). Similar local effects can occur in stroke with respect to viewing asymmetrically prominent cortical veins. Another clinical example is the diminished conspicuity during gestational age in children, possibly related to additional oxygen delivery by faster flow.

QSM and True SWI

The next evolution of susceptibility imaging is the development of QSM, allowing quantification of the magnetic susceptibility (3). QSM is an inverse process that operates on the filtered phase (Fig E3 [online]). The advantage of QSM is that the final quantitative result is theoretically not dependent on geometry, TE, or field strength (although the latter two affect

Table 1: Overview of Susceptibility-Sensitive Sequences for MRI Vendors

<table>
<thead>
<tr>
<th>Handedness</th>
<th>Sequence Name</th>
<th>Paramagnetic: Probable Microbleed</th>
<th>Diamagnetic: Probable Microcalcification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left-handed</td>
<td></td>
<td>Hyperintense on phase images</td>
<td>Hypointense on phase images</td>
</tr>
<tr>
<td>Siemens</td>
<td>SWI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canon</td>
<td>FSBB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Philips</td>
<td>3D GRE raw data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right-handed</td>
<td></td>
<td>Hypointense on phase images</td>
<td>Hyperintense on phase images</td>
</tr>
<tr>
<td>United Neusoft</td>
<td>SWI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GE Healthcare</td>
<td>SWAN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Philips</td>
<td>3D SWIp</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note.— FSBB = flow sensitive black blood, GRE = gradient echo, SWAN = susceptibility-weighted angiography, SWI = susceptibility-weighted imaging, SWIp = SWI with phase enhancement, 3D = three-dimensional.
Susceptibility-tensor imaging is the next technical development, allowing for the determination of orientation-dependent magnetic susceptibility parameters (16). In principle, it is similar to diffusion-tensor imaging and might eventually allow three-dimensional mapping of brain white matter fiber orientations. This technique is still awaiting clinical application.

Summary of Technical Issues and Clinical Hints for the Application of SWI

The choice of imaging parameters will affect signal-to-noise ratio, contrast, spatial resolution, and visibility of the structures of interest (17). The flip angle is particularly important because it determines the contrast, image quality, and signal-to-noise ratio on the images. A low flip angle (lower than the Ernst angles for gray matter and white matter) increases cerebrospinal fluid signal and reduces motion artifacts from inflow at the expense of signal-to-noise ratio (7). A summary of the recommended imaging parameters is shown in Table E1 (online). There are technical differences between MRI sequences.
Figure 6: Clinical example of a patient with multiple probable microbleeds to demonstrate the effect of size and geometry of cerebral microbleeds on the phase images. A, A single punctiform lesion (arrows) has a clear hypointense signal on the phase image and is readily recognized as a microbleed in a right-handed MRI system. In lesions that are geometrically more complex, the interpretation of the phase images to discriminate microbleeds versus microcalcifications is less evident and may be inconclusive. B, Larger lesions have more complex appearance on phase images with partially hypointense (white arrows) and partially hyperintense signal (black arrows), which changes over sections (−2 to +2 on images). C, The same patient has more linear lesions (arrows) in frontal and parietal regions with radial orientation and more complex and discordant changes on the phase masks. SWAN = susceptibility-weighted angiography (GE Healthcare).

Figure 7: Multiecho susceptibility-weighted imaging (SWI) with and without flow compensation on the second echo. The short echo for most manufacturers is flow compensated (and for Siemens fully flow compensated for SWI) but the later echoes are not, or are at most in, the read direction. In this example, the first echo is 7.5 msec (A, C) and the second echo is 17.5 msec (B, D). The lower row is fully flow compensated for all echoes, whereas the top row is from the manufacturer’s clinical sequence with the same two echoes. The problem with not flow compensating the second echo (which is most useful for SWI) is that there can be remnant phase information in the arteries, and this can lead to artifacts in both the SWI and QSM data (arrows on E, F), which do not appear with the fully flow compensated data (G, H). (Images courtesy of Dr Yongsheng Chen, Wayne State University, Detroit, Mich.)
sequences. Generally, a flow-compensated sequence will have fewer ghosting artifacts, especially when low flip angles are used. Multiple-echo SWI can also be used to allow for higher quality susceptibility mapping and T2* calculations. Finally, high in-plane resolution will produce the best results for viewing the small medullary veins.

**Clinical Applications**

SWI-like sequences were initially mostly used to improve the depiction of lesions and signs already known from standard and vendors. The choice of imaging parameters is also dependent on field strength. The lower field strengths require longer TEs to acquire the same susceptibility effect (if the product of TE - B₀ is constant, the susceptibility effects will be the same across field strengths) and, therefore, longer repetition time and lower signal-to-noise ratio. But higher field strengths can use a shorter TE and repetition time and have better signal-to-noise ratio. This makes SWI particularly effective and safe at high field strengths because it uses a low flip angle, and the specific absorption rate is lower than conventional spin-echo

**Figure 8:** A–C, Minimum intensity projection of susceptibility-weighted imaging (SWI) data, D–F, cerebral blood flow maps, and, G–I, maximum intensity projection of quantitative susceptibility mapping (QSM) data show the dynamic changes in venous oxygen saturation because of, A, D, O, the administration of 200 mg of caffeine and, C, F, I, 1000 mg of acetazolamide. Minimum and maximum intensity projection images were projected over 64 sections or section slab with effective section thickness of 32 mm. The scale bar values for cerebral blood flow and QSM data are in milliliters per 100 g of tissue per minute and parts per billion. SWI data were acquired by using the following parameters: echo time msec/repetition time msec, 15/24; flip angle, 15°; bandwidth, 119 Hz per pixel; and voxel resolution, 0.5 X 0.5 X 0.5 mm³. (Images courtesy of Dr Sagar Buch.)
Clinical symptoms are often asymmetric in early stages of PD, and the dopamine uptake at dopamine imaging can be correspondingly asymmetric in the contralateral hemisphere. The N1 behaves similarly and may also show asymmetric abnormality in the contralateral hemisphere (19).

PD versus atypical parkinsonian syndromes.—On clinical grounds, the discrimination of PD versus atypical parkinsonian syndromes (eg, multisystem atrophy, multisystem atrophy putaminal type, multisystem atrophy cerebellar type, progressive supranuclear palsy, and corticobasal degeneration) may be challenging at early stages of the disease. Such a discrimination is relevant regarding prognosis and treatment. Dopamine imaging of the striatum and imaging of the N1 are abnormal in both PD and APS and cannot help to discriminate them (20). Structural MRI may depict additional imaging signs in APS (Table 2).

Consequently, the combination of N1 abnormalities at imaging and structural imaging results in a suggested decision tree differential diagnosis for PD and APS (Fig 10).

PD versus essential tremor and drug-induced parkinsonism.—At early stages of the disease in particular, the differential diagnosis of PD includes essential tremor and drug-induced parkinsonism. Dopamine imaging and the N1 are normal in both essential tremor and drug-induced parkinsonism (21,22). Unlike APS, there tend to be no other clinically significant structural brain abnormalities at MRI.
Dementia with Lewy bodies.—Lewy body accumulation occurs in both dementia with Lewy bodies and PD, which are considered to be a spectrum of disorders. If cognitive symptoms predominate, the clinical diagnosis is dementia with Lewy bodies. If motor symptoms predominate, the clinical diagnosis is PD, with clinical symptoms partially overlapping and evolving over time. Having shared underlying pathologic structure, dopamine imaging findings show abnormalities in PD and dementia with Lewy bodies. Likewise, the N1 is also abnormal in dementia with Lewy bodies (23–25). In the absence of other reliable structural markers at MRI for dementia with Lewy bodies, imaging of the N1 may resolve this so-called blind spot of MRI (Fig 11).

Technical considerations in imaging the N1.—It is challenging to image and evaluate the N1 sign and requires both a high-quality high-spatial-resolution SWI-like sequence and an experienced reader (26). The degeneration of N1 is not a binary normal or abnormal phenomenon but a continuous process. We therefore proposed a gradual rating scale from definitely normal to probably normal to probably abnormal to definitely abnormal (24) (Fig E5 [online]). In addition to the gradual abnormality described, there is also normal interindividual anatomic variability (26) (Fig 12).

In general, imaging at 3.0 T is preferred because of the ability to obtain higher spatial resolution with good signal-to-noise ratio, but imaging at 1.5 T may be achievable (24). Reduction of section thickness from 2 mm to 1.5 mm (3.0 T) or 1.6 mm (1.5 T) improved accuracy from 67% to 84% (24). Moreover, the appearance of the nigrosome is somewhat variable between vendors and even within a vendor from scanner to scanner (Fig 13).

In some patients, the N1 appears abnormal without clinical symptoms. It remains to be determined whether this represents a false-positive finding or signifies preclinical disease (as known from dopamine SPECT). Nevertheless, recent studies (26) have

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**Table 2: Summary of Key Imaging Findings**

<table>
<thead>
<tr>
<th>Disease</th>
<th>N1/Dopamine Imaging</th>
<th>Other Imaging Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD</td>
<td>Abnormal (18)</td>
<td>None* (18)</td>
</tr>
<tr>
<td>Findings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy (%)</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>Sensitivity (%)</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Specificity (%)</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>Dementia with Lewy bodies</td>
<td>Abnormal (23–25)</td>
<td>None (24,25)</td>
</tr>
<tr>
<td>Findings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy (%)</td>
<td>76/90</td>
<td></td>
</tr>
<tr>
<td>Sensitivity (%)</td>
<td>63/93</td>
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</tr>
<tr>
<td>Specificity (%)</td>
<td>79/87</td>
<td></td>
</tr>
<tr>
<td>APS (all)</td>
<td>Abnormal (20)</td>
<td>Dopamine imaging and N1 are abnormal in PD and APS and cannot readily discriminate between PD versus APS</td>
</tr>
<tr>
<td>Findings</td>
<td></td>
<td></td>
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<tr>
<td>Drug-induced parkinsonism</td>
<td>Normal (22)</td>
<td>Normal (22)</td>
</tr>
<tr>
<td>Findings</td>
<td></td>
<td></td>
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<tr>
<td>Accuracy (%)</td>
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<td></td>
</tr>
<tr>
<td>Sensitivity (%)</td>
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</tr>
<tr>
<td>Specificity (%)</td>
<td>85</td>
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</table>

Note.—Summary is of key imaging findings in Parkinson disease, dementia with Lewy bodies, atypical parkinsonian syndromes including progressive supranuclear palsy, multisystem atrophy putaminal type, multisystem atrophy cerebellar type, corticobasal degeneration, and differential diagnoses of essential tremor and drug-induced parkinsonism. APS = atypical parkinsonian syndrome, CBD = corticobasal degeneration, MSA-C = multisystem atrophy cerebellar type, MSA-P = multisystem atrophy putaminal type, N1 = nigrosome 1, PD = Parkinson disease, PSP = progressive supranuclear palsy.

*Abnormality is often asymmetric at early stages of the disease (19).
Figure 10: Schematic evaluation of nigrosome 1 (N1) in Parkinson disease (PD) and atypical parkinsonian syndrome (APS). Step 1 is to first rule out other pathologic causes by using standard imaging and then, step 2, evaluate N1. If N1 is abnormal, then check for focal atrophy to discriminate between PD and atypical parkinsonian syndrome. CBD = corticobasal deterioration, MSA-C = multisystem atrophy cerebellar type, MSA-P = multisystem atrophy putaminal type, PSP = progressive supranuclear palsy, SWI = susceptibility-weighted imaging.

Figure 11: A–D, Illustration of, A, abnormal nigrosome 1 (N1; black arrows) in patients with dementia with Lewy bodies (DLB), yet normal N1 (white arrows) in other types of dementia including Alzheimer dementia (AD) and frontal dementia/frontotemporal lobar degeneration (FTLD). [Reprinted and adapted, with permission, from reference 23.]
hypointensity on SWI scans in the center of the lesion (often aligning with the main longitudinal axis of ovoid lesions). The central vessel sign is best depicted on 3.0-T scans but not fully specific for multiple sclerosis, occurring in 40.9% of multiple sclerosis lesions and in 27.2% of vascular lesions (28). A cut-off greater than 45% in brain lesions with central vessel sign was suggested to discriminate multiple sclerosis from vascular (or other) lesions (28) (Fig 14).

Other features at SWI-like imaging in multiple sclerosis include central signal loss and the so-called hypointense rim sign (Fig 15). The latter has been linked to deposition of iron in macrophages and may reflect chronically active multiple sclerosis lesions. Rim lesions are best detected at 3.0 T or higher and are associated with more destructive features at MRI and a worse clinical prognosis (29).

Figure 12: Anatomic variation (arrows) in the appearance of the nigrosome 1 (N1). On the 3.0-T axial plane, susceptibility-weighted angiography (SWAN, GE Healthcare) shows, A, ovoid appearance; B, bow-like (ie, banana-shaped) appearance; C, triangular appearance; and D, in younger patients, the substantia nigra is less hypointense because of lower iron content and the high contrast of the N1 is less evident.

Figure 13: Different vendors, sequences, and imaging parameters can lead to slightly different appearance of the nigrosome 1 (arrows). (Reprinted and adapted, with permission, from reference 24.)

shown that although there is a high sensitivity in distinguishing patients with PD from healthy control patients if the N1 sign has disappeared, there remain false-negative findings where the N1 sign has not disappeared. Overall, however, the rate of true-negative findings is high.

The central vessel sign and peripheral rim sign in multiple sclerosis.—Multiple sclerosis is a demyelinating disorder caused by perivenular inflammation. Imaging criteria rely on the location of T2-weighted hyperintense lesions and contrast-enhanced lesions, which have important roles in diagnostic criteria (27). In some cases of patients suspected of having multiple sclerosis, notably in somewhat older patients with cardiovascular risk factors, it may be difficult to discriminate vascular-ischemic from demyelinating lesions. The central vessel sign is characteristically found in multiple sclerosis lesions by findings that show venous structures as a linear hypointensity on SWI scans in the center of the lesion (often aligning with the main longitudinal axis of ovoid lesions). The central vessel sign is best depicted on 3.0-T scans but not fully specific for multiple sclerosis, occurring in 40.9% of multiple sclerosis lesions and in 27.2% of vascular lesions (28). A cut-off greater than 45% in brain lesions with central vessel sign was suggested to discriminate multiple sclerosis from vascular (or other) lesions (28) (Fig 14).

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Another related imaging sequence, fluid-attenuated inversion recovery, which combines a T2-weighted fluid-attenuated
with multiple sclerosis who are treated with immunomodulatory drugs. A thin, uniformly linear, gyriform rim that is hypointense at SWI in the paradesional U-fibers occurs in patients with multiple sclerosis and definite progressive multifocal leukoencephalopathy, representing an end-point stage of the neuroinflammatory process in long-term survivors (31). Infratentorial progressive multifocal leukoencephalopathy lesions showed no signs of hypointense rim formation at SWI. One possible explanation for the specific location of SWI findings is the greater iron content in subcortical fibers and high density of iron-rich oligodendrocytes. The prognostic relevance of a hypointense rim at SWI in progressive multifocal leukoencephalopathy needs to be established (Fig 16).

**Susceptibility vessel sign in acute arterial stroke.**—In acute stroke with arterial vessel occlusion, SWI-like sequences may depict clot-related susceptibility changes known as the susceptibility vessel sign (Fig E6 [online]). For the prognosis of intravenous thrombolysis in acute stroke, a thrombus length longer than 8 mm identified by using SWI-like sequences predicts an unfavorable outcome (32). However, with the increasing application of endovascular treatment of acute stroke, the length of the thrombus is less relevant and not correlated with outcome.

**Progressive multifocal leukoencephalopathy.**—Progressive multifocal leukoencephalopathy is a subacute progressive infection in the central nervous system that is from reactivation and replication of JC virus. The disease is associated with the human immunodeficiency virus and acquired immunodeficiency syndrome, and other immunocompromised or immunosuppressed patients, now commonly observed in patients inversion recovery contrast and T2*-weighted contrast in a single image (30), allows for simultaneous assessment of white matter lesions and the central vessel sign notably for evaluating multiple sclerosis lesions.

**Figure 14:** Images from 3.0-T axial plane susceptibility-weighted angiography (SWAN, GE). A, Image in a 41-year-old man with multiple vascular risk factors. The white matter lesion (arrow) did not have a central vessel sign. B, Images in a 41-year-old man with first diagnosis of multiple sclerosis. The majority of white matter lesions had a central vessel sign (arrows).

**Figure 15:** A, Image in a 16-year-old girl with known multiple sclerosis. B, In a minority of lesions, a peripheral rim sign (arrow) is present. It is an emerging sign currently thought to reflect iron deposition in macrophages in chronically active multiple sclerosis lesions.
a potential physiologic response that physically increases the diameter of the veins in the region. The asymmetrically prominent cortical vein territory matches the affected territory seen on mean transit time images. If perfusion is restored and mean transit time returns to normal, usually the asymmetrically prominent cortical veins sign vanishes, indicating that the blood oxygen saturation in that region has returned to normal. Comparing the region occupied by asymmetrically prominent cortical veins with that seen on diffusion- or perfusion-weighted images can help predict infarct size growth and outcome. Diffusion and perfusion mismatch predicts a favorable response to treatment. But the use of asymmetrically prominent cortical vein region as a third measure adds a physiologic component not considered in the other two modalities: oxygen extraction fraction. SWI and diffusion-weighted imaging mismatch has been strongly related to perfusion- and diffusion-weighted imaging mismatch (35,36), suggesting a role for SWI-like sequences in conjunction with standard stroke sequences (Fig 17).

The presence or absence of asymmetrically prominent cortical veins may correlate with infarct size and outcomes. The presence of any subtype of asymmetrically prominent cortical veins can be associated with poor outcome regardless of therapy (37). Most studies have been retrospective and bound by the 6-hour period of treatment. For patients outside of that period, no viable treatment changes on the basis of SWI exist beyond antiplatelet therapy. Studies that correlate the asymmetrically prominent cortical vein finding with a worse outcome may involve patients who have persistent-misery perfusion without the ability to treat it because of the 6-hour time limit. A poor outcome is predictable in that scenario because a penumbra with a high oxygen extraction fraction (showing asymmetrically prominent cortical veins) goes untreated because of the short treatment time and, therefore, the infarct grows in size. SWI for acute stroke is not commonplace because of logistical priorities at most stroke centers that focus on

(33). Moreover, the susceptibility vessel sign may be variable in appearance (eg, because of technical differences between SWI-like sequence implementation).

**Asymmetrically prominent cortical veins.**—Deoxyhemoglobin acts as an endogenous susceptibility agent to increase venous conspicuity. In the acute stage of ischemic stroke, arterial occlusion greatly reduces oxygen delivery. As brain tissue continues to use the oxygen in the area of reduced perfusion, the relative concentration of deoxyhemoglobin increases, causing cortical veins in the affected area to appear larger and lower contrast on SWI-like sequences, which creates asymmetrically prominent cortical veins (34) accompanied by

Figure 16: MRI scans in a 31-year-old man who is positive for HIV and has confirmed progressive multifocal leukoencephalopathy. A, B, On axial fluid-attenuated inversion recovery MRI scans, high signal intensity abnormality is observed in the frontal lobe on both sides and in the white matter of the right hemisphere. C, D, On corresponding susceptibility-weighted images, a linear hypointensity is on the cortical side of the progressive multifocal leukoencephalopathy lesions.
Intratumoral susceptibility signals in neoplasms.—In brain tumors, SWI findings can reveal features that remain undepicted at conventional MRI, referred to as intratumoral susceptibility signals. These are linear or dot-like intratumoral areas of low signal on susceptibility images, most likely related to intratumoral microhemorrhage, calcification, and neovascularization. By using phase images, it is possible to identify calcifications (comparable to CT) linked specifically to oligodendroglioma. Intratumoral susceptibility signals occur in a high percentage of high-grade gliomas but are mostly absent in lymphoma (38). Within the group of gliomas, intratumoral susceptibility signals seem less able to help CT, but this area is expected to develop further now that MRI is increasingly performed at the acute phase in stroke centers.

Figure 17: Patient with stroke and asymmetrically prominent cortical veins. A, Time-of-flight angiographic image shows a severely occluded right middle cerebral artery. B, Perfusion MRI scan shows that the mean transit time was affected in most of the right hemisphere. C, Many asymmetrically prominent cortical veins are evident on the quantitative susceptibility map maximum intensity projection image and, D, susceptibility-weighted image. The asymmetrically prominent cortical veins represent the area with a reduction in perfusion and subsequent increase in deoxyhemoglobin, delineating where a salvageable penumbra exists. Acquisition parameters at 1.5-T SWI were as follows: repetition time msec/echo time msec, 49/40; flip angle, 15°. (Images courtesy of Luo Yu, MD, and Miller Fawaz, MS.)

Figure 18: Images in a 74-year-old man who presented with aphasia and was found to have a high-grade left temporal glioma at 1.5-T MRI (top). Note the intratumoral susceptibility signals on axial susceptibility-weighted imaging (SWI), which indicated microhemorrhage and vessel proliferation. Images in a 57-year-old woman who presented with behavioral changes because of a lymphoma (bottom). SWI did not show any intratumoral susceptibility signals despite marked homogeneous enhancement. FLAIR = fluid-attenuated inversion recovery, Gd = gadolinium-chelate enhanced.
predict tumor grade than does perfusion MRI (39), but they are related to the isocitrate dehydrogenase 1 mutation status. A developed grading scale for intratumoral susceptibility signals (40) focuses on dot-like and fine linear intratumoral susceptibility signals only (grade 0, no intratumoral susceptibility signals; grade 1, one to five intratumoral susceptibility signals; grade 2, six to 10 intratumoral susceptibility signals; and grade 3, more than 10 intratumoral susceptibility signals), showing a good correlation with abnormal perfusion values (Fig 18).

**Dual rim sign in abscess.**—In cases of brain abscess, SWI can differentiate between pyogenic and fungal abscesses. This may also be helpful diagnostic clue to discriminate the lesion versus other ring-enhancing lesions, notably glioblastoma or metastasis (41). More recently, a dual rim sign, the combination of a hypointense and a hyperintense rim, was proposed as a diagnostic sign in favor of pyogenic abscess, whereas a fungal abscess typically shows an ill-defined and thick hypointense rim (Fig 19) (42). Rarely dot-like and linear low-contrast areas at SWI, indicating hypervascularization, occur in pyogenic abscesses in the early capsular stage.

**Imaging Signs with Enhanced Visibility on SWI-like Sequences**

CMBs occur in a variety of diseases including aging and dementia (dementia from Alzheimer disease in particular) and...
vascular disease. They are markers of vascular disease and may occur preferentially in specific spatial locations such as hypertensive CMBs typically in the basal ganglia or CMBs in cerebral amyloid angiopathy with a peripheral or lobar predilection. Imaging of CMBs is a key application of SWI-like sequences because in general more CMBs can be detected compared with routine T2*-weighted imaging. The detection rate of CMBs depends on field strength, section thickness, and type of susceptibility weighting. For example, in a memory clinic setting, 20% of individuals with mild cognitive impairment had CMBs on T2*-weighted images, but 40% had CMBs on SWI scans (43). CMBs occur in a variety of diseases, as discussed in detail in a recent review article (43) (Fig 20). Therefore, we only summarized the key imaging findings of CMBs in Table 3.

SWI in Traumatic Brain Injury
An important application of SWI-like imaging is the detection of hemorrhage in traumatic brain injury. In general, moderate and severe traumatic brain injuries have evident posttraumatic lesions visible on unenhanced CT images. The situation is fundamentally different in mild traumatic brain injury, where it can be challenging to depict posttraumatic lesions at neuroimaging (Fig 21). The depiction of microbleeds (hemorrhagic diffuse axonal injuries or shearing injuries in this context) is of key importance for patient prognostication but also from a medical and legal perspective. Similar to the discussion of microbleeds, SWI-like will depict more lesions than CT or standard T2* (44,45), and lesions remain visible for many years, even though their numbers may slightly reduce over time (46).

Diffuse axonal injury may be accompanied by diffuse vascular injury (47). Diffuse vascular injury visible at SWI consists of convergent-type hemorrhages in the supratentorial white matter distributed along the perimedullary veins, which drain into the septal vein (Fig 22). Existence of bead-like or convergent bead-like supratentorial hemorrhages (diffuse vascular injury) at SWI are associated with a poor outcome (47). The exact discrimination of diffuse axonal injury versus diffuse vascular injury and the clinical implications remains to be elucidated in future studies.

Superficial Siderosis
Superficial siderosis is another imaging sign observed at susceptibility imaging. It consists of linear signal loss following the pia on the surface of the brain, and when it occurs on either side of a sulcus it creates a tram-track sign. It is important to discriminate be-

**Figure 20:** Imaging findings show the effect of technical parameters in the depiction of cerebral microbleeds (CMBs). A, B, CMBs (arrows in B) in typical location of thalamus in hypertension are more evident and more numerous at axial SWI compared with T2*-weighted imaging. C, D, Microbleeds/hemorrhagic diffuse axonal injuries in mild to moderate traumatic brain injury (arrows in C, D) are better depicted at susceptibility-enhanced imaging compared with T2*-weighted imaging (effect of susceptibility enhancement and section thickness). E, F, Small microcavernomas are radiologically indistinguishable from cerebral microbleeds, but the presence of associated larger size cavernomas in familial cavernomatosis allows for a correct diagnosis. SWAN = susceptibility-weighted angiography (GE Healthcare).
principle, but SWI-like sequences may provide more conspicuous findings. QSM has the potential of a more objective imaging marker in the future.

The so-called eye of the tiger (Fig 23) sign of the pallidum is the most well-known imaging marker and occurs typically in pantothenate kinase–associated neurodegeneration, formerly known as Hallervorden-Spatz disease. Other diseases have iron deposition with a slightly different distribution.

**Motor Neuron Disease**

Amyotrophic lateral sclerosis is the most common motor neuron disease affecting both upper and lower motor neurons. Typical imaging findings include high signal on...
Figure 22: A, Noncontrast-enhanced CT scan of the brain in a young man after motor vehicle crash shows intraparenchymal hemorrhage in the left frontal lobe and smaller hyperdensities in the subcortical regions of the right hemisphere. B, Axial T2-weighted MRI findings confirmed the manifestation of hemorrhages with associated edema. C, D, Susceptibility-weighted imaging shows multiple round and linear hypointensities in both hemispheres representing diffuse vascular injury.

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T2-weighted fluid-attenuated inversion recovery images of the pyramidal tract and hypointense signal at susceptibility imaging of the primary motor cortex (Fig 24). However, this imaging finding is not specific to amyotrophic lateral sclerosis and also occurs in less common motor neuron diseases such as primary lateral sclerosis. Again, findings are known from T2*-weighted imaging but more evident at SWI. QSM might become a more objective imaging marker in the future.

Venous Sinus Thrombosis
SWI-like sequences may depict clots in dural sinus thrombosis, notably at early stages a few days after the clinical symptom onset (49). Because there are other established MRI techniques for the depiction of sinus thrombosis, the added value of susceptibility imaging remains moderate. The added value might be more relevant for superficial cortical venous thrombosis. However, the variability of susceptibility imaging between different MRI vendors is considerable. Even within each vendor, there are multiple parameters (eg, flow compensation). Collectively, SWI-like sequences might provide additional diagnostic clues for superficial vein thrombosis, and suspicious imaging findings should be confirmed by using other MRI sequences. Again, findings are more evident on SWI-like sequences compared with T2* sequences (Fig 25).

Vascular Malformations
Another possible application of susceptibility imaging includes various types of vascular malformations. In arteriovenous malformations, SWI may depict so-called silent intralvesional microhemorrhage (50). Moreover, SWI may depict the arterio-venous shunting in brain vascular malformation with a sensitivity of 93%, specificity of 98%, and excellent interobserver agreement of 0.94 (51). The same group (15) used SWI after the injection of gadolinium chelate, whereas SWI normally is performed without contrast material injection. At postcontrast SWI, arteries appear even more hyperintense because of the enhanced time-of-flight effect, whereas veins become hypointense because of an even more pronounced T2* effect. Postcontrast SWI further improved sensitivity to 100% and specificity to 100% to depict the shunt (15).
Table 4: Overview of Key Imaging Findings of Superficial Siderosis in Various Diseases

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Key Imaging Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trauma</td>
<td>Residual superficial siderosis can occur anywhere, oftentimes of the convexity. Other trauma-related findings such as diffuse axonal injuries or brain contusion may be associated.</td>
</tr>
<tr>
<td>CAA</td>
<td>Superficial siderosis has a predilection for parieto-occipital regions. Other imaging findings such as cerebral microbleeds in a peripheral distribution, white matter alterations and lacunes may be associated.</td>
</tr>
<tr>
<td>Ruptured aneurysm</td>
<td>Clinical history of ruptured aneurysm, subarachnoid hemorrhage in acute stage may develop into superficial siderosis later on</td>
</tr>
<tr>
<td>RCVS</td>
<td>Predilection of superficial siderosis at the convexity. Look for associated transient vasoconstriction. Clinical presentation thunderclap headache.</td>
</tr>
<tr>
<td>Cryptic vascular malformations of posterior fossa and spinal (eg, cavernoma)</td>
<td>Superficial siderosis oftentimes most pronounced in posterior fossa</td>
</tr>
</tbody>
</table>

Note.—CAA = cerebral amyloid angiopathy, RCVS = reversible cerebral vasoconstriction syndrome.

Figure 23: A, Coronal T2-weighted fluid-attenuated inversion recovery image and, B, axial susceptibility-weighted minimum-intensity projection image show typical “eye of the tiger” sign of the pallidum (arrows) in pantothenate kinase-associated neurodegeneration (formally known as Hallervorden-Spatz disease). (Reprinted, with permission, from reference 58.)

Figure 24: A, Typical hypointense linear signal in the motor cortex area on susceptibility image in amyotrophic lateral sclerosis, associated with hyperintense signal on, B, T2-weighted fluid-attenuated inversion recovery image along the pyramidal tract. Note that those findings are not specific for amyotrophic lateral sclerosis and may occur in primary lateral sclerosis, for example. (Reprinted, with permission, from reference 58.)
In a similar manner, magnitude images may discriminate different components of vascular malformations and contribute to the detection of the draining vein (52).

Although this is an interesting concept, the technical variability of the various susceptibility sequences across the different MRI vendors is important to consider. Moreover, even within a given MRI sequence or vendor, there may or may not be a variable degree of flow compensation mechanism in the susceptibility sequence. The studies we referenced (15,50–52) used single MRI systems, and it remains to be determined how well those results transfer to other MRI systems.

Vascular Variants

Capillary telangiectasia and developmental venous anomaly.—Capillary telangiectasia is a common incidental finding at brain MRI with typical location in the pons, but it can occur elsewhere in the brain (Fig E8 [online]). Although it is often isointense on T2-weighted and fluid-attenuated inversion recovery images, these lesions may cause confusion on postcontrast images because of their persistent enhancement. SWI-like sequences can make an important contribution (53) by showing marked susceptibility effects consistent with the histologic finding of dilated venous structures. Developmental venous anomalies are more frequently seen and best seen by using SWI-like sequences (Fig E9 [online]). Sometimes developmental venous anomalies are associated with cavernomas, which are a diagnostic clue if present.

Sturge-Weber syndrome.—Sturge-Weber syndrome is another disease with abnormal veins. Usually, a contrast agent is administered to image children with this disease. But SWI and QSM may serve as a surrogate to the administration of contrast agent, and are possibly more sensitive to the venous,
Figure 27: Example of a traumatic cervical spinal cord injury (arrows) on, A, sagittal T1-weighted, B, sagittal T2-weighted, and, C, axial T2-weighted images. Susceptibility-weighted imaging (E, phase; F, magnitude) shows intramedullary hemorrhage more clearly than, D, axial T2*-weighted imaging (D). (Reprinted, with permission, from reference 55.)

oxygen saturation, and calcification elements of the disease. By using high spatial resolution, SWI-like sequences performed in roughly 5 minutes can depict common signs of Sturge-Weber syndrome like impaired cortical veins and abnormal deep venous collaterals (54) (Fig 26).

**SWI-like imaging in the spine.**—Applications of susceptibility imaging in the spine remain scarce. As a clinically relevant application, susceptibility imaging can depict posttraumatic intramedullary hemorrhage (55). In a series of 23 patients with acute cervical spine trauma, SWI findings demonstrated additional intramedullary hemorrhage in two of the five patients with spinal contusion at conventional MRI, indicating that susceptibility imaging is more sensitive than conventional MRI in depicting hemorrhage in acute cervical spinal cord injury (Fig 27). However, SWI-
like imaging remains challenging at the level of the spine and notably the cervical spinal cord because of pulsation and respiration artifacts. **SWI-like imaging in children.**—Similar to imaging in adults, SWI-like imaging findings provide diagnostic information for a wide range of diseases in children, including neonatal imaging (hemorrhages), metabolic and neurodegenerative diseases (iron deposition and QSM for myelin structure), acute trauma (blood), neoplasm (calcification and blood), and a variety of vascular diseases.

The distribution of intratumoral susceptibility signals in pediatric tumors differs somewhat compared with adults (56).

**Conclusion**

Susceptibility-weighted imaging (SWI) and SWI-like sequences were initially intended to enhance susceptibility contrast and conspicuity compared with standard gradient-echo T2*-weighted imaging. However, because of the enhanced susceptibility contrast, numerous clinical signs and applications emerged that are specific to high-spatial-resolution, three-dimensional, SWI-like sequences. Because SWI-like image contrast depends entirely on the imaging parameters and its implementation, and because quality can vary between vendors, the reader should be aware of the fundamental technical aspects for a successful data acquisition and image interpretation.

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