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Review

3D double inversion recovery MR imaging: Clinical applications and usefulness in a wide spectrum of central nervous system diseases

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ABSTRACT

Double inversion recovery (DIR) imaging provides two inversion pulses that attenuate signals from cerebrospinal fluid and normal white matter. This review was undertaken to describe the principle of the DIR sequence, the clinical applications of 3D DIR in various central nervous system diseases and the clinical benefits of the 3D DIR compared with those of other MR sequences. 3D DIR imaging provides better lesion conspicuity and topography than other MR techniques. It is particularly useful for diagnosing the following disease entities: cortical and subcortical abnormalities such as multiple sclerosis, cortical microinfarcts and cortical development anomalies; sulcal abnormalities such as meningitis and subacute/chronic subarachnoid hemorrhage; and optic neuritis caused by multiple sclerosis or neuromyelitis optica.

Introduction

Double inversion recovery (DIR) imaging simultaneously suppresses signals from the cerebrospinal fluid (CSF) and white matter (WM) [1]. Although not a new technique, it has gained increasing attention over the last 10 years. Following introduction of the 3D sequence, DIR came to be known as particularly useful for detecting cortical lesions in multiple sclerosis (MS) [2]. However, its usefulness for several other central nervous system (CNS) diseases has also been increasingly reported [3–10].

This article presents the clinical applications and usefulness of 3D DIR imaging for various CNS diseases.

DIR sequences

DIR sequence was first reported in 1994 by Redpath et al. [1]. This sequence provides two inversion pulses that attenuate signals from CSF and WM to achieve superior delineation between gray matter and WM (Fig. 1) [1]. Actually, DIR imaging was initially performed using 2D multislice sequences at 1.5T, but poor spatial resolution and the presence of flow and pulsation artifacts have limited the application of 2D DIR imaging [1,11,12]. Therefore, a multislab 3D DIR sequence was developed by inserting a second inversion pulse into 3D multislab fluid-attenuated inversion recovery (FLAIR). Although the multislab 3D DIR sequence enables increased detection of intracortical MS lesions and improves the differentiation between juxtacortical and WM–gray matter lesions, it introduces flow artifacts and signal intensity differences between slabs [2,13]. Single-slab 3D MR sequence has a long echo train and variable flip angles for refocusing radiofrequency pulses, which produces high-quality images covering the entire brain without introducing flow artifacts from blood or CSF [13]. Consequently, multislab 3D DIR imaging was replaced by single-slab 3D DIR imaging.

Recently, 3T MRI with 2D or 3D DIR sequences have been used for evaluating brain lesions [4–10,14–32] because the sensitivity of cortical lesion detection is improved significantly at 3T compared with that at 1.5T because of the increased signal-to-noise ratio (S/N) [15]. Advancements in MR technology, such as parallel imaging and 32-channel head coil arrays, have caused decreased acquisition times and increased S/N, leading to the production of high-quality DIR images with reasonable acquisition times. The benefits of 3D DIR imaging versus 2D DIR imaging include higher spatial resolution, multiplanar reconstruction, and the absence of inflow artifacts, which improve the detection of small cortical lesions and faint sulcal abnormalities [13,14]. Now, 3D DIR

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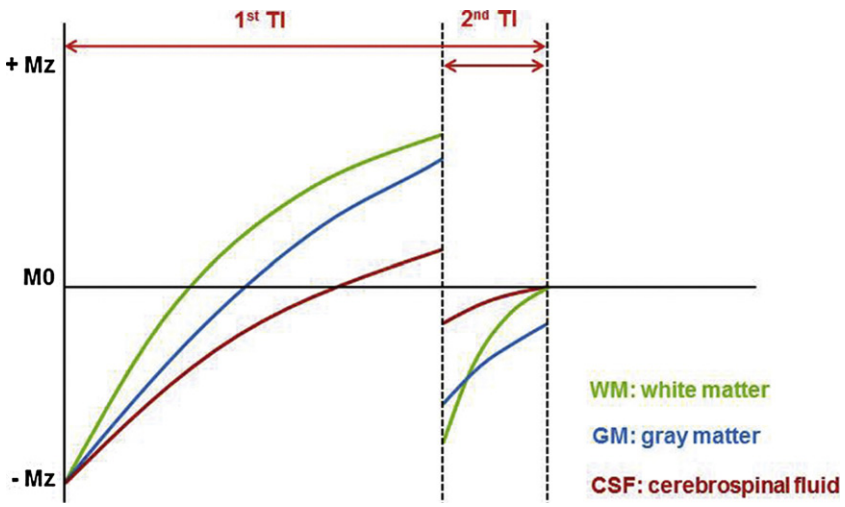

Fig. 1. DIR provides two inversion pulses, which attenuate the cerebrospinal fluid as well as all white matter.

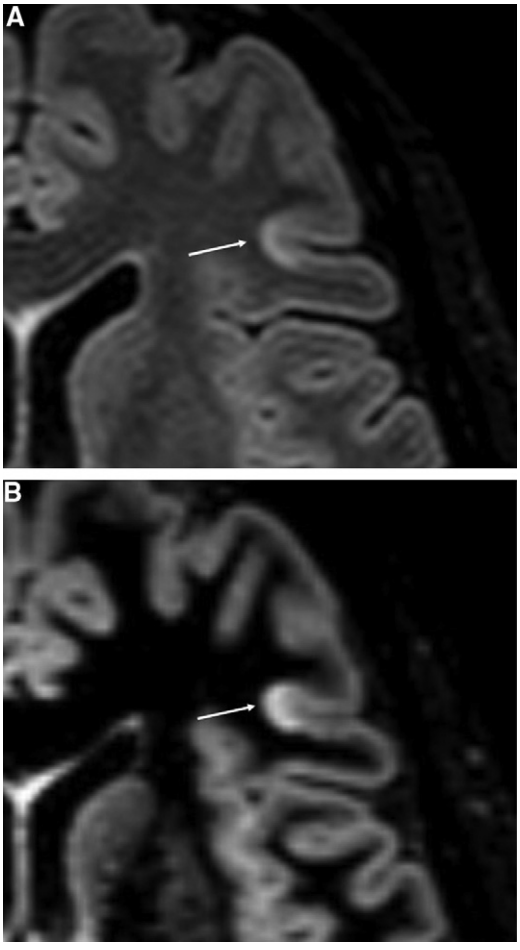

Fig. 2. A 45-year-old woman with MS examined using 3D FLAIR and 3D DIR imaging. (A) 3D FLAIR and (B) 3D DIR images of the left frontal lobe show a cortical MS lesion (arrows A and B). The lesion is more conspicuous and lesion topography is better depicted on the 3D DIR image (arrow B) than on the 3D FLAIR image (arrow A).

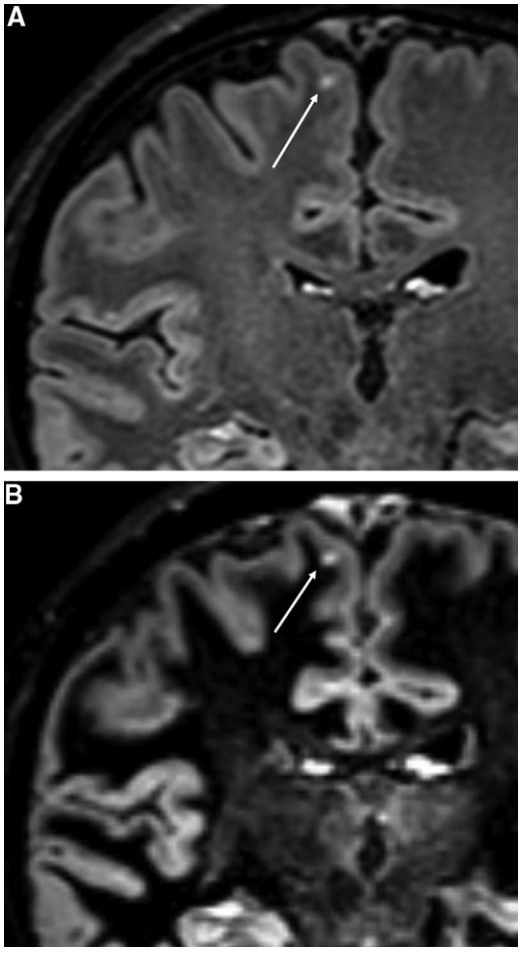

Fig. 3. A 38-year-old man with MS examined using coronal 3D FLAIR and 3D DIR imaging. (A) Coronal 3D FLAIR and (B) 3D DIR images of the right frontal lobe show a juxtacortical MS lesion (arrows A and B). Lesion topography is better depicted on the 3D DIR image (arrow B) than on the 3D FLAIR image (arrow A).

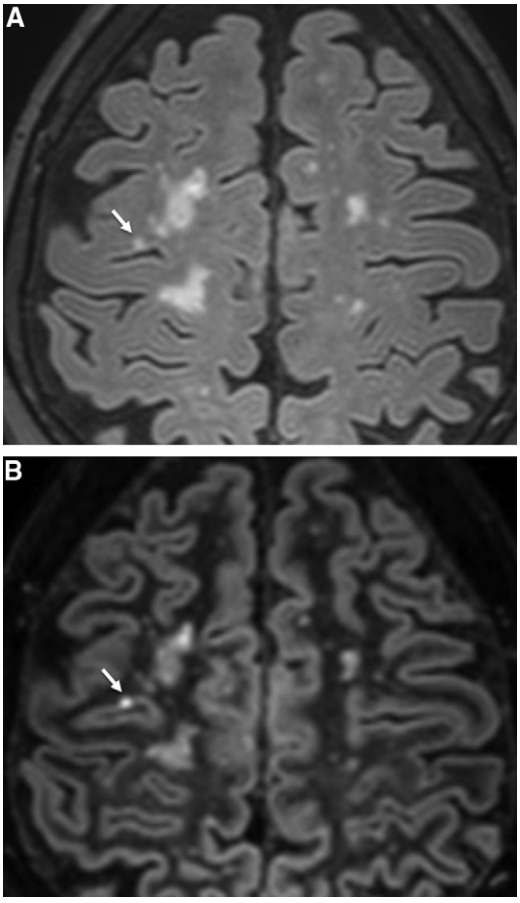

Fig. 4. A 79-year-old woman with dementia deriving from Alzheimer's disease examined using 3D FLAIR and 3D DIR imaging. (A) 3D FLAIR and (B) 3D DIR images of a CMI in the right frontal lobe (arrows A and B). The CMI is more easily detectable with 3D DIR imaging (arrow B) than with 3D FLAIR imaging (arrow A).

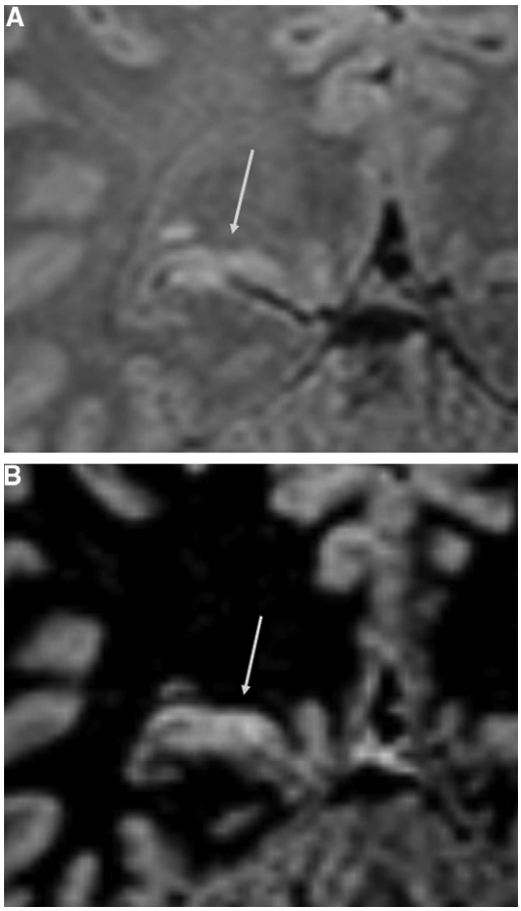

Fig. 5. A 40-year-old woman with FCD. (A) Coronal 3D FLAIR and (B) 3D DIR images show the presence of FCD. Thickening of the cortex with mild hyperintensity is visible in the right parietal lobe (arrows A and B). The FCD lesion is more conspicuous on the 3D DIR image (arrow B).

imaging can be implemented on MR scanners from various vendors including Philips, Siemens and GE. In this article, we demonstrate the application of 3D DIR sequences at 3T MRI for various CNS diseases.

MR imaging protocol

Images were obtained using a 3-T MR scanner, the Ingenia (Philips Health Care, Best, The Netherlands), with a 32-channel phased-array head coil. The parameters of 3D DIR were the following:

- 250 mm field of view; matrix of 208 × 163 (256 × 256 after reconstruction; in-plane resolution, 0.98 mm × 0.98 mm);
- 0.65 mm section thickness with overcontiguous slice; TSE factor 173;
- repetition time (ms)/echo time (ms) of 5500/shortest (approximately 293 ms);
- long inversion time (ms)/short inversion time (ms) of 2550/450;
- fat suppression with spectral presaturation inversion recovery;
- number of signals acquired, two;
- 5 min 13 s acquisition time.

Clinical applications

Following data aggregation from the picture archiving database of our institution, several representative cases illustrating the diagnostic value of 3D DIR imaging were identified. They are presented below.

Multiple sclerosis

Although MS is typically regarded as a WM disease in which focal demyelinated plaques and diffuse WM injuries are present in all disease stages, cortical demyelination is also a prominent histopathological change in this disease, particularly in patients with primary progressive or secondary progressive MS [33]. Several new MR techniques such as synthetic MRI and pseudo-continuous arterial spin labeling have been used to evaluate MS lesion detection or investigate relationship with disability [34–36]. In addition, recent studies have suggested that disease progression and the extent of physical disability and cognitive impairment are closely associated with the degree of gray matter damage [37–40]. In patients presenting with a clinically isolated syndrome (CIS), MRI can support and substitute clinical information for MS diagnosis demonstrating disease dissemination in space and time and helping to rule out other conditions that can mimic MS. In a cohort of 80

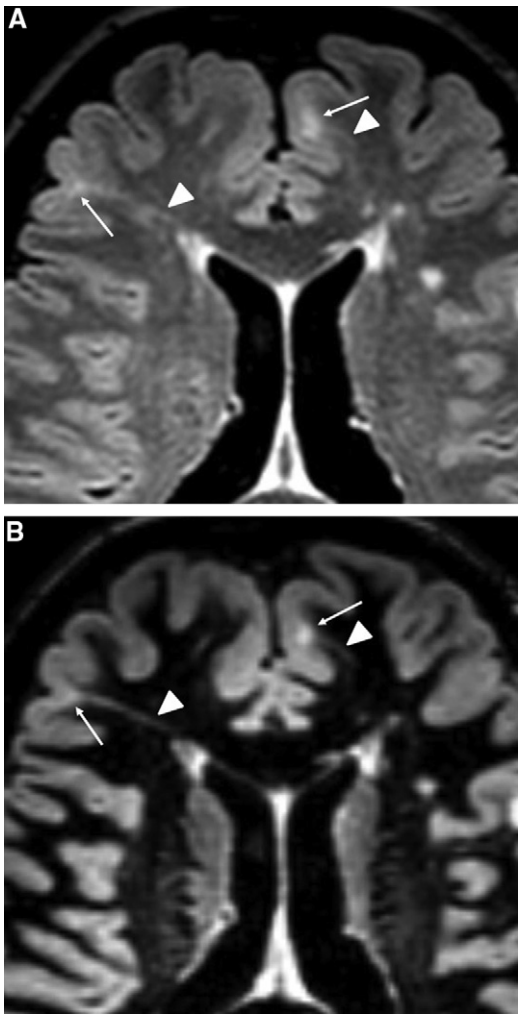

Fig. 6. A 44-year-old woman with TSC examined using 3D FLAIR and 3D DIR imaging. (A) 3D FLAIR and (B) 3D DIR images show the presence of cortical tubers (arrows A and B). The cortical tubers are more clearly delineated on the 3D DIR image than on the 3D FLAIR image (arrows A and B). Radially oriented white matter bands are also depicted more clearly on the 3D DIR image than on the 3D FLAIR image (arrowheads A and B).

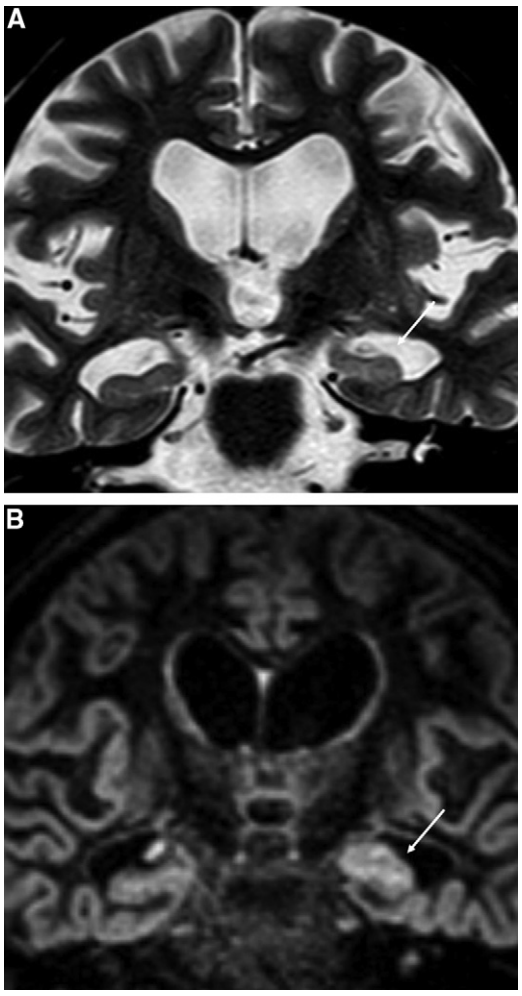

Fig. 7. A 67-year-old man with epilepsy examined using coronal 3D DIR and 2D STIR imaging. (A) Coronal 2D STIR and (B) 3D DIR images showing left hippocampal sclerosis (arrows A and B). The hippocampal abnormal hyperintense signal of the left hippocampus is more conspicuous on the 3D DIR image than on the 2D STIR image.

CIS patients with 4-year follow-up, the accuracy of MRI diagnostic criteria for MS was increased when considering the presence of at least intracortical lesions on baseline scans [41]. In relapse-onset MS, cortical lesions accumulate over time and are associated with disability progression.

Using DIR at 3T, 192% more pure intracortical MS lesions was reportedly demonstrated while T2-weighted and FLAIR sequences detected more significantly lesions in the WM [15]. 3D DIR imaging at 3T particularly improves the sensitivity of the detection of cortical MS lesions and enables better discrimination between juxtacortical and WM–gray matter lesions (Figs. 2 and 3). Over the last 10 years, the investigation and assessment of gray matter lesions, particularly cortical lesions, in MS patients using 3D DIR imaging has become the subject of extensive research [13,17,21–23,27,29–31,42–48].

Cortical microinfarcts

Cortical microinfarcts (CMIs) have been reported as an important risk factor for dementia [49]. Neuropathological reports have described that CMIs are commonly observed at autopsy in the brains of patients with severe cerebral amyloid angiopathy [50]. Although microinfarcts have been investigated extensively in autopsy studies [51,52], they have been regarded as “invisible” on MRI [53]. However, visualization of CMIs in vivo using high-resolution MRI at 7T [54,55] and 3T [5,24,56] has been reported recently. Furthermore, the combination of 3D FLAIR and 3D DIR imaging at 3T has recently been shown to detect CMIs reliably in patients with cognitive disorder (Fig. 4) [5,24]. CMIs were defined as small cortical hyperintense lesions, which were not contiguous to WM hyperintensities, with maximum diameter of 5 mm and round or elliptical shape [55]. Although CMIs are small lesions, they can cause perilesional and remote deficits, which might lead to cognitive dysfunction [57].

Focal cortical dysplasia

Focal cortical dysplasia (FCD) lesions comprise neurons with atypical morphology and organization. Characteristic findings include aberrant radial or tangential lamination of the neocortex

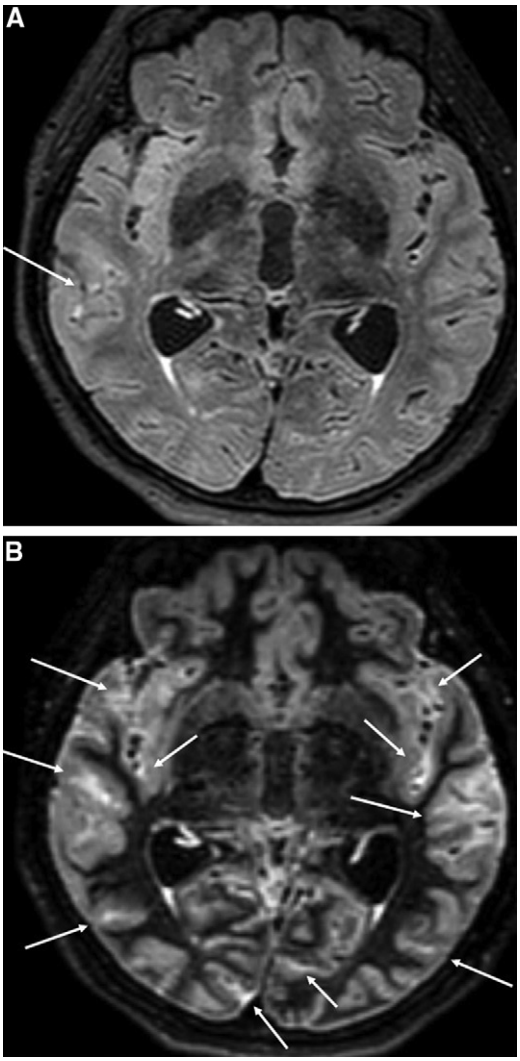

Fig. 8. A 66-year-old woman with subacute SAH (13 days after onset). (A) 3D FLAIR and (B) 3D DIR images showing subacute SAH. The SAH lesion is more clearly and extensively visible on the 3D DIR image than on the 3D FLAIR image (arrows A and B).

(FCD type I) and cytological abnormalities (FCD type II). The major change since prior classification is the introduction of FCD type III, which occurs in combination with hippocampal sclerosis (FCD type IIIa), or with epilepsy-associated tumors (FCD type IIIb). FCD type IIIc is found adjacent to vascular malformations, whereas FCD type IIId can be diagnosed in association with epileptogenic lesions acquired in early life [58]. MRI features of FCD include cortical thickening and blurring of the gray matter–WM junction and the presence of the transmantle sign, which refers to a linear area of abnormal signal in the WM extending from the cortex to the ventricle. Transmantle sign is almost exclusively observed in type II FCD. Despite these characteristic features, FCD can be subtle on MRI. For that reason, the 3D DIR sequence is useful for detecting it (Fig. 5) [9,25,26,59,60]. The use of two MRI acquisitions, DIR and another sequence such as magnetization prepared rapid acquired gradient echoes, would complement the evaluation of lesional epilepsy [25].

Tuberous sclerosis complex

Tuberous sclerosis complex (TSC) is an autosomal-dominant disorder caused by a mutation in tumor suppressor gene TSC1 (chromosome 9q34) or TSC2 (16p13) [61], which results in hamartoma formation in multiple organ systems. Most patients with TSC have CNS lesions, including supratentorial cortical tubers (often with adjacent WM abnormalities), subependymal nodules and subependymal giant cell astrocytomas. The current classification of malformations of cortical development is based on the type of disrupted embryological process and the resulting morphological anomalous pattern of findings. An ideal classification is expected to include knowledge of biological pathways. It has been demonstrated recently that alterations affecting the mechanistic target of rapamycin (mTOR) signalling pathway result in diverse abnormalities such as dysplastic megalencephaly, hemimegalencephaly, gangliоglioma, dysplastic cerebellar gangliocytoma, FCD type IIb and brain lesions associated with TSC. Similarly to FCD type IIb, TSC is related to dysfunction in the mTOR pathway that results in cell dysplasia and overgrowth, indicating that FCD and cortical tubers share similar pathophysiology and histology [62]. Several investigators have reported that DIR images help to depict cortical tubers and that they might be complementary in the MRI evaluation of patients with TSC [3,9,26]. Cortical tubers, as well as radially oriented WM bands, are better outlined on 3D DIR images than on 3D FLAIR images (Fig. 6) [26].

Polymicrogyria

Polymicrogyria, an extremely common cortical development malformation, is characterized by cerebral cortex overfolding and abnormal cortical layering. Reportedly, not all cortical development malformations show abnormal signal intensity on 3D DIR imaging [26]. However, Granata et al. have reported that 3D DIR imaging is highly reliable for the detection of cortical abnormal hyperintensity and gray matter–WM junction blurring [9].

Heterotopias

Neuronal heterotopia, which results from abnormal migration during fetal development, refers to the presence of neurons in any region other than the cortex. The suppression of signals from normal WM achieved using 3D DIR imaging enables increased conspicuity of small foci of heterotopic gray matter [26].

Hippocampal sclerosis

The most common finding in patients with intractable temporal lobe epilepsy is hippocampal sclerosis, the MRI features of which include hippocampal atrophy, T2 hyperintense signals and internal architecture disruption. 2D DIR imaging reveals extremely high signal intensity in the hippocampus, which is characteristic of patients with hippocampal sclerosis [18,19]. Recently, 3D DIR imaging has been shown to be beneficial in terms of increasing the conspicuity of asymmetric signals in the hippocampus [63] (Fig. 7). However, the internal architecture of the hippocampus is reportedly depicted better on T2-weighted imaging [26].

Anterior temporal lobe white matter abnormal signal

Anterior temporal lobe white matter abnormal signal (ATLAS) ipsilateral to the seizure focus on T2-weighted imaging is reportedly regarded as an indicator of seizure laterality [64]. Actually, ATLAS is visible as an increased signal in the anterior temporal lobe WM or loss of gray matter–WM demarcation in 33% of patients with medically refractory temporal lobe epilepsy [65]. Several investigators have reported that 3D DIR imaging at 1.5T can detect abnormal

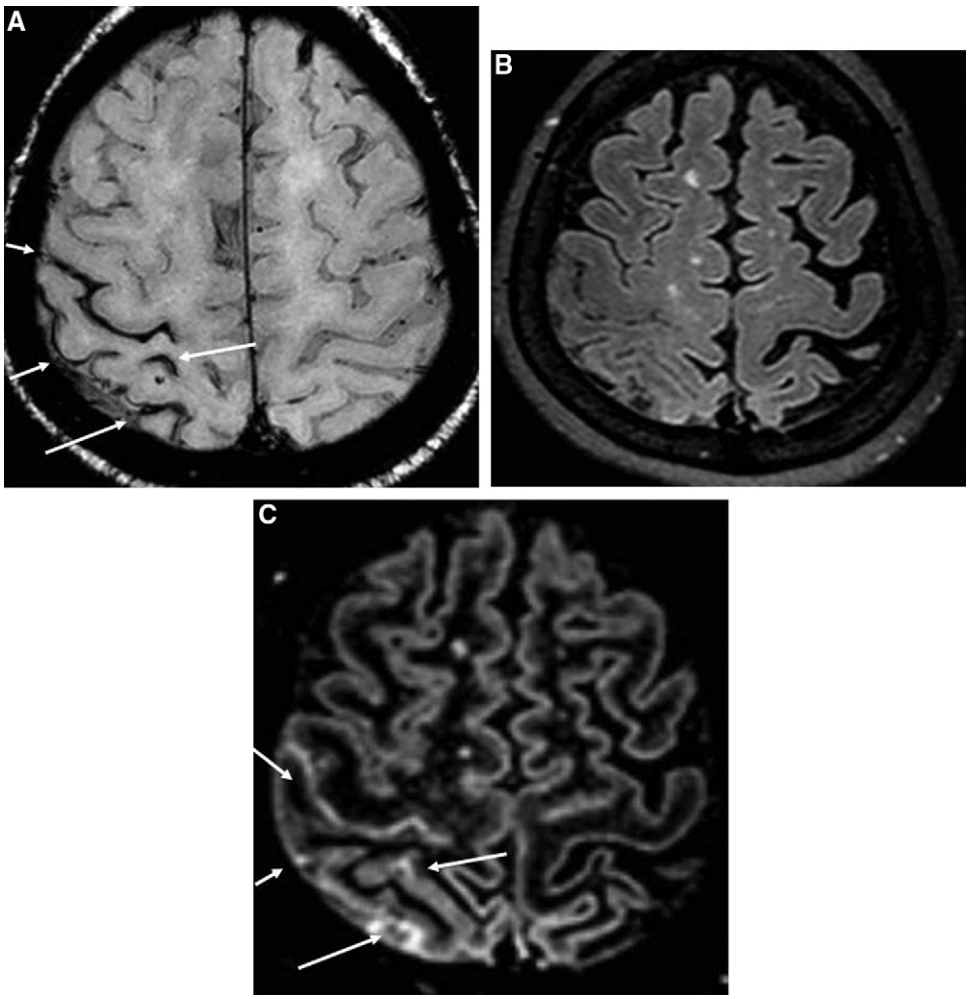

Fig. 9. A 64-year-old woman with chronic SAH (2 months after onset). A. SWI images showing chronic SAH or superficial siderosis (arrows). B. Sulcal hyperintensity is not apparent on the 3D FLAIR image. C. 3D DIR showing sulcal hyperintensity (arrows).

signals in patients with partial epilepsy [59,66]. Morimoto et al. [4] described that 3D DIR imaging can detect seizure focus laterality in the temporal lobe of patients with epilepsy based on ATLAS laterality, with significantly higher concordance with the final clinical diagnosis than that by 2D T2-weighted images, 3D T2-weighted images, 2D FLAIR, or 3D FLAIR at 3T.

Brain tumors

3D DIR imaging provides high contrast between a tumor and the adjacent normal-appearing cortex [26]. Thereby, it facilitates the determination of the extent of abnormal tissue before surgery for refractory epilepsy, especially because neuroglial tumors might be associated with areas of cortical dysplasia that might contribute to epileptogenesis [58]. Harris et al. [6] reported that pre-contrast or post-contrast 3D DIR images might provide information additional to that provided by 2D FLAIR images because 2D FLAIR images tend to overestimate lesion volume and tend to have a lower lesion contrast-to-noise ratio than 3D DIR images.

Subarachnoid hemorrhage

FLAIR is more sensitive than CT in the detection of subarachnoid hemorrhage (SAH) at both acute and subacute stages [67,68]. 3D DIR imaging also reveals acute and subacute SAH as sulcal hyperintensity. Reportedly, the 3D DIR sequence is more sensitive for detecting subacute SAH than CT, 2D and 3D FLAIR, 2D T2* and SWI sequences (Fig. 8) [8]. 3D DIR imaging might improve the detection of SAH by:

- reducing vascular and CSF flow-related artifacts;
- enhancing SAH-to-background contrast;
- improving spatial resolution [8].

Chronic SAH, which is presumed to be superficial siderosis, is visible using SWI (Fig. 9). 3D DIR might be better for identifying chronic SAH than 3D FLAIR imaging (Fig. 9).

Meningitis

Diagnosis of meningitis is based on the clinical features and CSF analysis. Compared with contrast-enhanced (CE) T1-weighted imaging, CE-FLAIR imaging reportedly has superior specificity

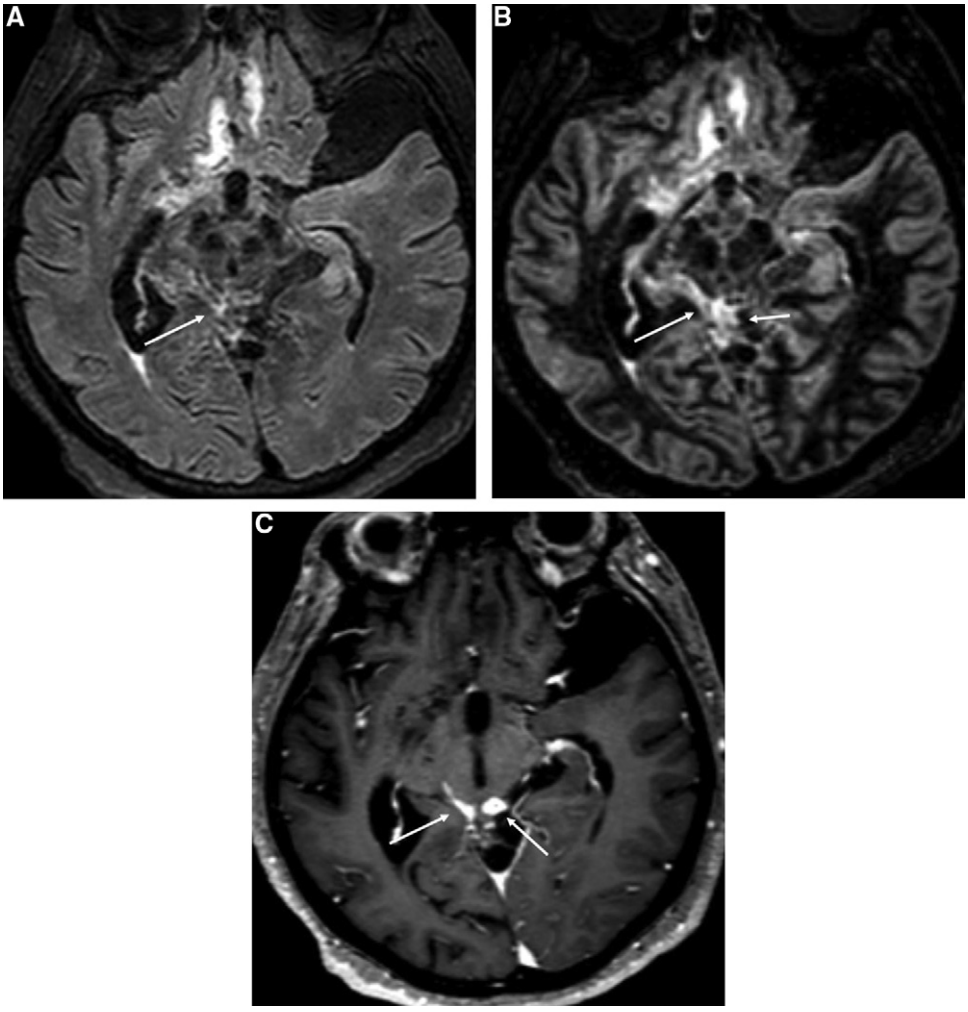

Fig. 10. A 67-year-old woman with tuberculous meningitis examined using 3D FLAIR, 3D DIR, and contrast-enhanced 3D T1-weighted MR imaging. (A) 3D FLAIR, (B) 3D DIR and (C) contrast-enhanced 3D T1-weighted MR images showing tuberculous meningitis. Without contrast medium, 3D DIR imaging can detect leptomeningeal lesions more clearly than 3D FLAIR imaging (arrows A–C).

and similar sensitivity in detecting inflammatory leptomeningeal lesions [69]. Non-CE 3D DIR imaging may reveal subtle leptomeningeal lesions (Fig. 10).

Optic nerve lesions

Optic neuritis (ON), the inflammatory demyelination of the optic nerve, is strongly associated with an increased risk of developing MS or neuromyelitis optica (NMO). Among patients with ON, MRI is useful to predict those who will develop MS [70]. The length and position of the affected optic nerve segment might also provide prognostic information [71]. Some investigators have reported the added value of fat saturation for imaging optic nerves using short tau inversion recovery (STIR) and 3D FLAIR T2-weighted imaging, which include both fat and water suppression [72,73]. Recently, Hodel et al. [7] reported that the 3D DIR sequence is more sensitive and specific than the 2D STIR FLAIR sequence in detecting ON, suggesting that the 3D DIR sequence is more useful in patients with suspected ON (Fig. 11). This sensitivity and specificity are probably attributable to the high spatial resolution inherent to the 3D DIR imaging, which reduces CSF flow-related artefacts and which improves image contrast [7]. 3D DIR imaging is particularly useful to identify intracranial optic tract lesions because of freedom from CSF inflow artifacts (Fig. 12). The optic nerve DIR hyperintense signal length might be a biomarker for retinal axonal loss; it would be applied in routine investigations and in the evaluation of new anti-inflammatory or neuroprotective drugs [74]. A report of one study described that a hyperintense signal was frequently observed in at least one optic nerve segment on the 3D DIR sequence in visually asymptomatic patients with MS, whereas a hypointense signal was observed in optic nerve segments in a comparison group [32].

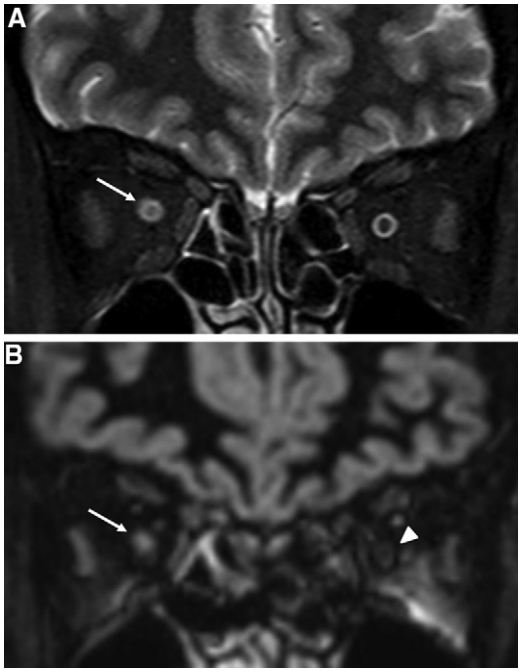

Fig. 11. A 44-year-old woman with NMO examined using coronal 3D DIR and 2D STIR imaging. (A) Coronal 2D STIR and (B) 3D DIR images showing right optic neuritis. The high signal of right optic neuritis is more clearly visible on the 3D DIR image than on the 2D STIR image (arrows A and B). It is noteworthy that the signals of the left normal optic nerve and adjacent fluid are sufficiently suppressed on the 3D DIR image (arrowhead B).

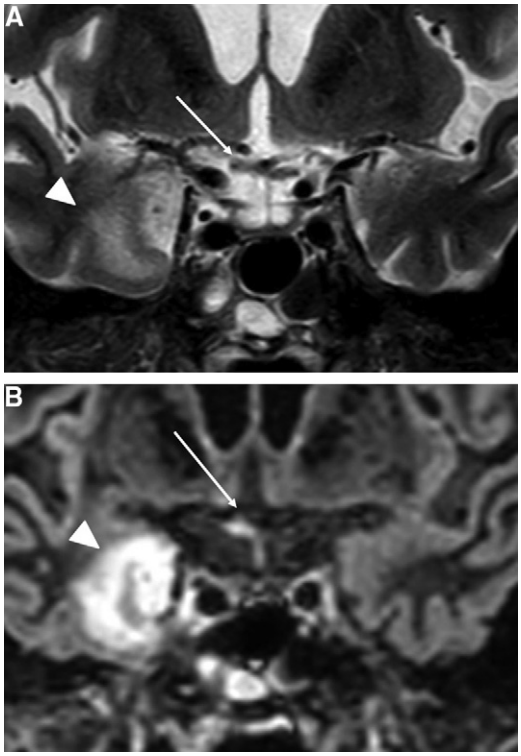

Fig. 12. A 78-year-old woman presented with right visual impairment examined using coronal 3D DIR and 2D STIR imaging. After surgery, she received heavy ion radiotherapy for epipharyngeal cancer. A. The 2D STIR image shows no definite high signal in the optic chiasm (arrow A). B. Coronal 3D DIR image showing radiation induced optic neuropathy. A coronal section through the optic chiasm shows high signal intensity at the right side of the optic chiasm (arrow B). Radiation necrosis is visible in the right temporal lobe (arrowheads A and B).

Conclusion

Compared to other MR techniques, 3D DIR imaging provides superior lesion conspicuity and topography (cortical or subcortical lesion) discernibility in various CNS diseases. Wider use of 3D DIR imaging is anticipated in clinical settings although imaging time of this technique is relatively long.

Disclosure of interest

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