Diffusion weighted MR imaging in non-infarct lesions of the brain

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Abstract

Diffusion weighted imaging (DWI) is a relatively new method in which the images are formed by the contrast produced by the random microscopic motion of water molecules in different tissues. Although DWI has been tried for different organ systems, it has been found its primary use in the central nervous system. The most widely used clinical application is in the detection of hyperacute infarcts and the differentiation of acute or subacute infarction from chronic infarction. Recently DWI has been applied to various other cerebral diseases. In this pictorial paper the authors demonstrated different DWI patterns of non-infarct lesions of the brain which are hyperintense in the diffusion trace image, such as infectious, neoplastic and demyelinating diseases, encephalopathies – including hypoxic–ischemic, hypertensive, eclamptic, toxic, metabolic and mitochondrial encephalopathies – leukodystrophies, vasculitis and vasculopathies, hemorrhage and trauma.

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Keywords: Brain; Magnetic resonance; Diffusion-weighted; Apparent diffusion coefficient

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1. Introduction

Diffusion weighted imaging (DWI) is based on the sensitivity of MR to microscopic mobility of water molecules within tissues. DWI consists of a DW image, also called the diffusion trace, and an apparent diffusion coefficient (ADC) map. DW image is a T2-weighted echoplanar background image attenuated by the rate of apparent diffusion. DW image, together with qualitative and quantitative assessment of the ADC map has been widely used in the diagnosis of acute cerebral infarction, owing to the reliable distinction of cytotoxic and vasogenic edema [1]. Edema is a non-specific reaction of brain parenchyme to different factors which can, to some extent, be differentiated by DWI. Cytotoxic edema – characterized by abnormal cellular uptake of

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water and myelin edema – characterized by intramyelinic accumulation of vacuolated or free water – have high signal intensity on the diffusion trace, with decreased ADC as a result of isotropically restricted water diffusion. On the other hand vasogenic edema, caused by increased permeability of the blood–brain barrier, and interstitial edema, caused by subependymal water diffusion in acute hydrocephalus have intermediate signal on the DW image with increased ADC [2].

Diffusion tensor imaging (DTI) which is not the main scope of this paper, is an extension of DWI that provides additional information about brain tissue structure by measuring functional anisotropy, or the directional component of water diffusion. DTI has recently been used in white matter injury, demyelinating diseases, as well as in some cases of neoplasms [3,4].

Because of the heavily T2 weighting of the DW image, lesions with long T2 relaxation times have artifactual high signal, called the T2 shine-through effect, mimicking restricted diffusion. This artifact may be overcome by means of higher b values or by the ADC map which does not have shine-through effect [5].

DWI has very recently been described and suggested in the differential diagnosis of various non-infarct lesions of the brain, as well. In this pictorial paper, the authors briefly reviewed the non-infarct lesions, which are hyperintense on the diffusion trace image, with specific concern to the pathophysiologic changes – such as high viscosity, high cellularity, vacuolization, compartmentalization of water, etc. – effecting water diffusion, thus changing the ADC (Table 1) (the DW images throughout the paper is of $b = 1000$).

2. Infections

Brain abscesses are cystic lesions with a thick, rim-shaped contrast enhancing capsule, surrounded by massive vasogenic edema. This appearance on conventional MR images with similar clinical findings can sometimes not be differentiated from cystic necrotic tumors, differential diagnosis of which is crucial for the necessity of prompt treatment. On the DW image, brain abscesses show very high signal associated with decreased ADC (Fig. 1). The limited diffusion in abscesses are attributed to the high viscosity of the proteinaceous fluid and hypercellularity of the pus consisting of bacteria and inflammatory cells [2,6–8].

Fig. 1. Cerebral abscess: 65 years old, male. (a) FLAIR (TR/TE/TI:9060/138/2500), (b) postcontrast T1-weighted images. A right temporal lobe abscess with a thick rim enhancing capsule, surrounded by massive edema. On the DW image (c) the lesion has high signal with partially decreased ADC (d). Diagnosis was confirmed by surgery.
Herpes simplex encephalitis is one of the most common viral infections. T2-hyperintense lesions with typical temporal and frontal localization with petechial hemorrhage are characteristic findings. Conventional MR imaging and clinical findings might be non-specific, necessitating the proof of evidence of viral DNA by polymerase chain reaction in the cerebrospinal fluid. DW image shows high signal in the lesions with usually decreased ADC values representing cytotoxic edema and rarely higher ADC values representing vasogenic edema \[9,10\] (Fig. 2). Areas of cytotoxic edema correspond to a worse outcome compared to areas of vasogenic edema \[9\].

Creutzfeld-Jakob disease is one of several spongiform encephalopathies. Characteristic findings are rapidly progressive dementia, myoclonus and periodic sharp-wave complexes on electroencephalography. MR imaging is helpful in differentiating the two forms of the disease \[11\]. The sporadic type is characterized by bilateral symmetric hyperintensity in the putamen and head of caudate nucleus on T2-weighted and FLAIR images are characteristic, sometimes associated with bilateral thalamic or cerebral cortical involvement \[11,12\]. Symmetrical high signal of the pulvinar thalami, known as “the pulvinar sign” is characteristic for the variant type. Although thalamic high signal may be seen in both types, it is less pronounced than in the caudate and putamen in the sporadic type, whereas it is the most prominent sign in the variant type \[11\]. Diffusion trace image shows high signal with decreased ADC (Fig. 3). The restricted diffusion can be attributed to the compartmentalization of water molecules within the clustered vacuoles in the gray matter \[2,13\]. Persistence of high signal on the DW image is helpful in differentiating from infarct \[11\]. In addition to DWI, MR spectroscopy is also helpful in the diagnosis, but definite diagnosis is by brain biopsy or autopsy.

3. Neoplastic lesions

3.1. Primary tumors

Brain neoplasms show variable signal on the DW image and the ADC map. Tumors with higher cellularity or higher grade show increased signal on the DW image and a marked reduction in ADC values \[8,14\]. In addition to the hypercellularity which causes increased intracellular water, the low ADC values are also related to the decreased extracellular fluid \[2\]. Low grade gliomas, because of their low cellularity, have a significantly
higher ADC values compared to high grade gliomas and lymphomas [5,14]. Measurement of ADC values should be done from the maximally restricted diffusion areas, because histologically the actual grade of the tumor is determined from the areas with the highest grade [14] (Fig. 4). Conjoint evaluation of conventional MR sequences and DWI are of great importance in atypical cases (Fig. 5). In a study of 275 patients with brain tumors, Yamasaki et al. [5] reported suggesting results of ADC values in the differentiation of dysembryoplastic neuroepithelial tumors, malignant lymphomas versus glioblastomas and metastatic tumors, and ependymomas versus primitive neuroectodermal tumors. Similarly, Rumboldt et al. [15] reported statistically significant differences between pilocytic astrocytoma, ependymoma and medulloblastoma, with 100% specific cut-off ADC values for differentiating juvenile pilocytic astrocytoma and medulloblastoma.

Lymphomas are highly cellular tumors DWI of which is controversial. Typical MR findings are slightly hyperintense lesions compared to normal brain tissue on T2-weighted images usually in the cerebral hemispheres, basal ganglia and thalamus, with...
Fig. 5. High grade glial tumor and gliomatosis cerebri: 58 years old, female. FLAIR (TR/TE/TI: 9060/138/2500) image (a) shows areas of tumoral infiltration with contrast enhancement (b, TR/TE: 510/10) in the left cingulate gyrus and bilateral basal ganglia, showing high signal on DWI (c) with increased ADC (d) (diagnosis was confirmed by surgery).

ring-shaped or diffuse enhancement [14,16] (Fig. 6). Cerebral lymphomas without contrast enhancement are regarded as cerebral manifestation of a systemic disease, namely angiotropic large cell lymphoma or intravascular lymphomatosis [16,17]. Küker et al. [16] have found that DWI was helpful in differentiating primary central nervous system lymphomas from angiotropic large cell lymphoma which is frequently accompanied by diffusion abnormalities due to brain ischemia. In a study with seven central nervous system T-cell lymphomas, three patients showed hyperintensity and four patients showed isointensity in the DW image and ADC maps [18]. In some other studies it has been reported that ADC values of the primary central nervous system lymphomas were lower than other intracerebral tumors, close to acute infarct [5,14,16].

3.2. Metastases

Metastases show variable signal (generally iso- or hypointense, occasionally hyperintense) in the DWI [8]. Rarely high signal intensity in the DW image with decreased ADC may be seen, due to mostly the hypercellularity of the lesion [2,8], extracellular methemoglobin [8] or sometimes increased protein concentration in the form of highly viscous mucin in cystic metastases [8,19]. In case of multiple lesions in the setting of a known primary malignancy, metastatic tumors are not a diagnostic challenge. However, in case of solitary metastasis, with no known primary malignancy, differentiation is difficult. DWI is not helpful in differentiating such metastasis from markedly enhancing high grade gliomas [5,14].

Epidermoid cysts are rare congenital lesions arising from the inclusion of ectodermal tissue into the neural tube. Cerebellopontine angle is the most common location. Typical MR imaging findings are well-defined, lobulated masses, slightly hyperintense or isointense to the cerebrospinal fluid on T1- and T2-weighted images with no internal contrast enhancement. On proton density and FLAIR images, the lesions are slightly hyperintense to the cerebrospinal fluid. The lesions show high signal on the DW image with mixed signal on the ADC map (Fig. 7). Initial studies have attributed the high signal in DWI to the increased cellularity and restricted diffusion of water.
molecules due to high viscosity of the fluid containing kerato-hyalin and cholesterol crystals [2,20]. However, recent reports suggest that this is due to the T2 shine through effect [8,21]. DWI is not only helpful in differentiating epidermoids from arachnoid cysts, but also differentiating residual or recurrent tumor from cerebrospinal fluid-filled cavities in the postoperative patient [22,23].

4. Encephalopathies

4.1. Hypoxic–ischemic encephalopathy

Hypoxic ischemic encephalopathy (HIE) is a general term describing the infarct-like lesions as a result of ischemia, anoxia or hypoglycemia, presenting with restricted diffusion representing cytotoxic edema (Fig. 8). It may be due to cardiac arrest, severe hypotension or hypertension, trauma and neonatal ischemia [2]. Perinatal hypoxic ischemia causes structural and functional damage to the brain of the neonate, commonly effecting the basal ganglia, thalami and white matter, usually sparing the cerebellum. ADC in neonates is 30–50% higher compared with adults, because normal neonatal white matter is less myelinated and structured and contains more water. Directly after a severe ischemic insult, ADC in neonates decreases [3,24]. Moderate ischemic lesions may have normal or increased ADC, due to their small size and surrounding extracellular edema [24].

4.2. Posterior reversible leukoencephalopathy syndromes

Hypertensive encephalopathy is characterized by T2-hyperintense foci predominantly within the cortex and subcortical white matter of the occipital lobes on MR imaging. Due to the pathogenesis consisting of increased blood–brain barrier permeability, microhemorrhages and endothelial cell damage, both vasogenic and cytotoxic edema may be seen. Areas of cytotoxic edema, mainly located in the border-zone arterial regions, are irreversible lesions with persistent abnormalities on follow-up FLAIR images [25,26] (Fig. 9).

Eclampsia is characterized by well-defined findings of preeclampsia complicated with seizures. The typical MR findings are cortical and subcortical hyperintense lesions mainly in the posterior cerebral areas, on T2-weighted and FLAIR images, with evidence of cytotoxic edema in DWI [25].

4.2.1. Toxic encephalopathy

Immune-suppressive drugs such as cyclosporine, interferon alfa and tacrolimus, immunoglobuline therapy and methotrexate may cause transient encephalopathy [2,27–30].
Cyclosporin induced encephalopathy presents with vasopasm and T2-hyperintense lesions with restricted diffusion in the cerebral cortex and watershed regions, due to areas of both vasogenic and cytotoxic edema [27]. Immunoglobulin therapy may cause acute encephalopathy with restricted diffusion due to cytotoxic edema [30]. Methotrexate induced leukoencephalopathy is usually a chronic process. However, acute reversible neurotoxicity has recently been reported. In these cases there are T2-hyperintense lesions particularly in the centrum semiovale with restricted diffusion with high signal in diffusion images and low signal in the ADC map. These
areas representing cytotoxic edema could be either reversible or irreversible [28,29].

Uremic encephalopathy in patients with chronic renal failure demonstrates high signal in the DW image with increased ADC in the basal ganglia and white matter attributable to vasogenic edema [24,31].

4.3. Wernicke encephalopathy

Wernicke encephalopathy is a disorder resulting from thiamine deficiency. Typical MR imaging findings are hyperintense lesions surrounding the third ventricle, mamillary body, aqueduct and thalami on the T2-weighted, FLAIR and DW images, attributable to both cytotoxic and vasogenic edema [32].

5. Leukodystrophies

Leukodystrophies are genetic diseases, most commonly of metabolic origin, which disturb normal myelination of the white matter. On conventional MR imaging myelin edema, as well as myelin loss and gliosis are characterized by high signal on T2-weighted images. DWI differentiates between vasogenic edema and myelin edema, the latter showing restricted diffusion with low ADC. Myelin edema presents with high signal, whereas demyelinated white matter and gliosis presents with low signal on the DW image [33]. Among leukodystrophies high grade myelin edema is encountered in Krabbe disease, Canavan disease (Fig. 10), maple syrup urine disease; low grade or no myelin edema is encountered in mucopolysaccharidoses, GM gangliosidoses, van der Knaap disease, phenylketonuria, adrenomyeloneuropathy and medium grade myelin edema is found in metachromatic leukodystrophy, adrenoleukodystrophy [33].

Characteristic MR findings of Canavan disease are diffuse white matter abnormalities with bilateral globus pallidus involvement. Atypical cases have been reported with selective involvement of the U-fibers [34] and bilateral involvement of the caudate nuclei, putamen, thalami and dentate nucleus [35]. DWI demonstrates restricted diffusion with low ADC due to intramyelinic edema, vacuole formation, myelin loss and spongiform degeneration of the white matter.

Phenylketonuria patients with increased serum phenylalanine present with high signal on T2-weighted and FLAIR images with restricted diffusion in the posterior deep white matter attributed to cytotoxic edema [36].
Fig. 10. Atypical Canavan disease: 5 years old, male. T2-weighted turbo spinecho image (TR/TE: 3986/99) shows high signal on bilateral basal ganglia (a). DWI (b) shows high signal, associated with decreased ADC (c). Single voxel proton MR spectroscopy (TR/TE: 1500/135) reveals the characteristic N-acetylaspartate peak (d) (diagnosis was confirmed by laboratory tests) [35].

Restricted diffusion due to intramyelinic edema corresponding to the high signal intensity areas in the white matter and perirolandic areas was reported in tyrosinemia [37].

In mitochondrial encephalopathy syndromes such as Kearns Sayre syndrome, mitochondrial encephalopathy with lactic acidosis and stroke-like episodes (MELAS) and Leigh syndrome, typical MR findings with T2-hyperintense lesions were reported. Recently DWI findings in Kearns Sayre and MELAS have been reported attributed to cytotoxic and vasogenic edema and vacuolization involving status spongiosus [38,39].

6. Demyelinating diseases

Multiple sclerosis is the most common demyelinating disease. DWI, diffusion-tensor imaging and MR spectroscopy may improve lesion detection with standard T2-weighted techniques. On DWI acute lesions may show increased ADC due to vasogenic edema, and myelin destruction with axonal preservation; or decreased ADC due to intramyelinic edema [2,40]. Chronic MS plaques do not show diffusion restriction [2] (Fig. 11).

6.1. Osmotic myelinolysis

Osmotic myelinolysis is characterized by regions of demyelination throughout brain, most commonly in the pons. Extrapontine myelinolysis is most commonly seen in the basal ganglia, thalami and gray-white matter junctions. Characteristic MR findings of central pontine myelinolysis are symmetric T2-hyperintense lesions involving the basilar pons sparing the peripheral areas of pons and descending corticospinal tracts. DWI shows areas of increased ADC similar to MS lesions. However, depending on the age of the lesions, not only degree of ADC elevation may vary [41], but also lesions with decreased ADC may be seen [42] (Fig. 12).

7. Epilepsy

Seizures induce cellular swelling and fluctuations in the extracellular water. Typical postictal MR imaging findings are unilateral high signal in the cortical or limbic structures particularly in the hippocampus on T2-weighted images. Detectable MR spectroscopic findings have also been documented. In DWI
Fig. 11. Multiple sclerosis: 31 years old, female. FLAIR (TR/TE/TI: 9060/138/2500) (a) and postcontrast (b, TR/TE: 510/10) images show hyperintense active demyelinating lesions with contrast enhancement in the right supratentorial periatral white matter with high signal on DWI (c) and ADC (d) (clinical diagnosis).

Fig. 12. Osmotic myelinolysis: 56 years old, female with hyponatremia. Hyperintense lesions in the pons and thalami (not shown) on FLAIR (TR/TE/TI: 8000/110/2500) (a) and DWI (b) with slightly increased ADC (c).
Fig. 13. Postictal edema in a 41 years old male patient secondary to a seizure attack due to the tumor on the left temporal lobe. FLAIR (TR/TE/TI: 8000/110/2500) (a) and DW (b) images show high signal areas on bilateral hippocampal gyri.

Fig. 14. Behçet’s disease: 38 years old, female. FLAIR (TR/TE/TI: 8000/110/2500) image (a) shows hyperintense lesion in the brain stem with extension to the basal ganglia on the left (b), with partially restricted diffusion in the diffusion trace (c) and the ADC map (d) at the level of the brain stem.
first signs of cytotoxic edema are usually followed by signs of vasogenic edema in the postictal period [43] (Fig. 13).

8. Vasculitis and vasculopathies

Behcet’s disease is an inflammatory multisystem disease. The central nervous system involvement causes lesions secondary to vasculitis, mainly with venular involvement, and dural sinus thrombosis. MR imaging findings are T2-hyperintense lesions with contrast enhancement, most commonly in the brain stem. On DWI the lesions are either iso- or hyperintense with high ADC. The pattern with high signal on both diffusion and ADC images is attributable to vasogenic edema due to the disrupted blood–brain barrier associated with acute inflammatory response [44] (Fig. 14).

Systemic lupus erythematosus is another cause of cerebral vasculopathy which affects the arterioles and capillaries. On DWI lesions representing both infarcts and vasogenic edema can be seen [45].

9. Hemorrhage

Spontaneous intracerebral hemorrhage is most frequently seen in the form of deep hemorrhage secondary to hypertension. Non-enhanced CT is still the technique of diagnostic choice, while MR imaging gives additional information about the stage of the hemorrhage depending on the signal intensity of the blood products typically changing over time. Recently DWI has been used to differentiate hemorrhage from infarction in hyperacute stroke and to identify perihematomatoma ischemia or edema [46] (Fig. 15). In DWI the core of an acute hematoma is hyperintense with decreased ADC. However, T2-shine-through and T2 black-out effects and susceptibility artifacts from blood products contribute to the appearance on DW image and ADC values. Therefore, DWI should be read with great caution in hemorrhagic lesions [47]. Conjunct use of DWI with T2- and T2*-weighted images is mandatory [8]. In the follow-up of patients with external capsular hemorrhage, striatal or thalamic diffusion abnormalities have been reported due to secondary transneuronal degeneration mimicking a new onset infarction [48].

10. Trauma

MR imaging findings in posttraumatic patients are T2-hyperintense lesions due to diffuse axonal injury at gray-white matter junctions, in the white matter and in the brain stem. T2*-weighted imaging improves detection of hemorrhagic lesions [49]. DWI can depict shearing injuries not visualized with FLAIR, T2-weighted fast spin echo and T2*-weighted gradient echo sequences [50]. Lesions with decreased ADC may be related to trauma-induced brain ischemia, on the other hand lesions with increased ADC represents increased amount of extracellular water [51] (Fig. 16).
Fig. 16. Diffuse axonal injury: 35 years old, male patient, had a motorcycle accident. FLAIR (TR/TE/TI: 9060/138/2500) (a) and T2-weighted gradient echo (b, TR/TE: 800/30) images show foci of axonal injury in the corpus callosum and frontal subcortical white matter, hemorrhagic in the former. Lesions have high signal on the DW image (c) and high ADC (d). Note that DWI discloses more lesions on the frontal lobe which is not seen on the FLAIR image.

11. Conclusion

Beside the widespread use in acute cerebral infarction, DWI is helpful in various other lesions of the brain not only in the differential diagnosis, but also in predicting the prognosis, depending on the diffusion pattern, mainly due to the type of edema. In recent studies, it has been reported that there might be cytotoxic or vasogenic – or sometimes both type of – edema in the same patient or in different patients having the same disease [2,9,10,24]. Generally, lesions with decreased ADC, representing cytotoxic edema, suggest a worse prognosis and are more likely to be irreversible as reported in herpes encephalitis, HIE and hypertensive encephalopathy [9,10,25,26]. However, it has also been reported that lesions with cytotoxic edema may sometimes be reversible [28,29]. Therefore, DWI remains a valuable tool in non-infarct lesions of the brain, however the controversial findings should be kept in mind.

References


