RESOLVE: A Powerful Tool for Imaging the Pediatric Spine

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Introduction

Diffusion-weighted imaging (DWI) is one of the most powerful imaging tools available to radiologists today. DWI of the brain revolutionized neuroimaging when it was introduced in the mid-1990s. Until recently, clinically useful DWI of the spine has not been possible using standard single shot EPI techniques due to susceptibility artifacts and the need for higher spatial resolution. The novel 2D-navigator-corrected readout-segmented EPI sequence known as RESOLVE (REadout Segmentation Of Long Variable Echo trains) can obtain images with higher spatial resolution and reduced distortion of the spine related to susceptibility, pulsations, respiration, and motion [1]. This is especially helpful when imaging children where the small size of their spine/cord, prominent CSF and arterial pulsations, and higher pulse and respiratory rates compared to adults can pose significant limitations on the quality of the images obtained. Motion artifacts that notoriously plague every facet of pediatric imaging are also reduced with RESOLVE. RESOLVE is proving to be a valuable sequence for the evaluation of numerous pathological states of the pediatric spine.

Sequence description

RESOLVE [1, 2] is a multi-shot, diffusion-weighted sequence, which is based on the readout-segmented echo-planar imaging (rs-EPI) sampling scheme [3]. The sequence incorporates a 2D non-linear correction for motion-induced phase errors [4] and supports iPAT using GRAPPA [5]. The rs-EPI method only samples a subset of raw data points in the readout direction, making it possible to use a very short EPI echo spacing with a typical value of 360 µs. This is significantly shorter than the echo spacing used for single-shot EPI (ss-EPI), which reduces the level of susceptibility and blurring.

1 Pulse diagram for the RESOLVE sequence. The figure shows radiofrequency (RF) pulses and magnetic field gradient pulses for diffusion-encoding (Gx) and for spatial encoding along slice (Gz), readout (Gr) and phase-encoding (Gp) directions. The gradients with the † symbol have an amplitude that is varied at each spin excitation to control an offset in the k direction, so that a different readout segment is sampled by the imaging echo at each shot. In contrast, the navigator echo always samples a fixed 2D region at the centre of k-space.
Many of the primary CNS tumors that metastasize to the spine have a hypercellular tumor matrix. Primitive neuro-ectodermal tumors (PNETs) consist of small, round cells with scanty cytoplasm and have an extremely high cellular density with a high nuclear-to-cytoplasmic index. The total water content of these tumors is low, and their densely packed cellular nature results in restricted diffusion. The physical characteristics of these tumors render them sensitive to detection by DWI. Due to their high grade and often high degree of necrosis, they may not exhibit enhancement on conventional imaging sequences that currently are the standard imaging method for detection of drop metastasis.

Medulloblastoma, a PNET, is the second most common neoplasm of the CNS in children and has pathologic features that make it optimal for

In general, multi-shot, diffusion-weighted sequences are susceptible to image artifacts that arise from motion during the diffusion preparation, resulting in shot-to-shot phase errors. Navigator phase correction [6, 7] can address this problem by sampling data from the center of k-space at each shot; these data are then used to monitor and correct the phase variation between shots. CSF pulsation around the brain and spinal cord causes non-rigid-body motion, resulting in a 2D non-linear phase variation in image space, which requires 2D navigator data to perform a correction [4]. The rs-EPI sampling scheme is particularly well-suited to this type of correction because, unlike the more commonly used interleaved EPI sequence, the Nyquist sampling condition is fulfilled at each shot and there are no aliased signal contributions in the image domain to interfere with the phase correction procedure.

As shown in figure 1, following a spin excitation and diffusion preparation, the RESOLVE sequence uses two EPI readouts to acquire data from two spin echoes respectively at each shot. The first spin echo is used to sample a region of k-space, known as a readout segment, in which contiguous data samples are collected for all phase-encoding (k_y) points and for a subset of readout (k_x) points. A variable pre-phase gradient is applied along the readout (x) axis before the EPI readout to control an offset along k_x, so that a different readout segment is sampled at each shot. As shown in the k-space trajectory in figure 2, data from multiple readout segments are combined to provide full k-space coverage; typical protocols require 5, 7 or 9 shots to acquire the full data set, depending on the spatial resolution. The second spin echo shown in figure 1 is used to sample the central readout segment, providing 2D reference data from the center of k-space, which are used to perform a non-linear phase correction.

To further reduce the effect of motion-induced phase errors, the RESOLVE sequence uses a reacquisition scheme [8], which has been adapted to the case of a 2D navigator [9]. This ensures that readout segments with severe phase errors, which cannot be removed by the 2D navigator correction, are discarded and replaced by reacquired data.

Currently useful applications:
1. Tumor
   a. Intradural
      i. Drop metastases

DWI of the brain has revolutionized the sensitivity of MR in diagnosis, staging, and follow-up of children with central nervous system (CNS) tumors [10]. Likewise DWI of the spine is demonstrating the ability to reveal spinal disease that may not be visible on conventional MR sequences in children with primary brain tumors [11] (Figs. 3–5). Many of the primary CNS tumors that metastasize to the spine have a hypercellular tumor matrix. Primitive neuro-ectodermal tumors (PNETs) consist of small, round cells with scanty cytoplasm and have an extremely high cellular density with a high nuclear-to-cytoplasmic index. The total water content of these tumors is low, and their densely packed cellular nature results in restricted diffusion. The physical characteristics of these tumors render them sensitive to detection by DWI. Due to their high grade and often high degree of necrosis, they may not exhibit enhancement on conventional imaging sequences that currently are the standard imaging method for detection of drop metastasis. Medulloblastoma, a PNET, is the second most common neoplasm of the CNS in children and has pathologic features that make it optimal for

![Diagram showing the k-space sampling scheme used for the imaging echo in the RESOLVE sequence. In this example, a five shot acquisition is used which divides k-space into five segments along the readout direction. Within each shot, an EPI readout is used to sample all phase-encoding (k_y) points and a subset of readout (k_x) points. The second (navigator) echo is always used to sample the central readout segment, providing 2D reference data from the center of k-space, which are used to perform a non-linear phase correction.](image-url)
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2-year-old girl* with ataxia and vomiting found to have a large posterior fossa tumor that restricted diffusion and demonstrated minimal enhancement, consistent with an atypical rhabdoid teratoid tumor (ATRT). Initial MRI scan of the spine: Sagittal T1 post-contrast (3A), ADC map (3B), isotropic DWI (3C), sagittal T2 (3D), and axial T1 post-contrast image at the level of interest (3E) demonstrate the lack of any abnormal signal or enhancement (3A, D, E) at the location of the nodular diffusion abnormality at the dorsal aspect of the thoracic cord (3B, C).

4

Follow up scan two months later. Sagittal T1 post-contrast (4A), ADC map (4B), isotropic DWI (4C), sagittal T2 (4D), and axial T1 post-contrast image at the level of interest (4E) demonstrate interval increase in the size of the previously visualized nodular diffusion abnormality, now also seen on the T2 image as well. Another nodular diffusion abnormality along the ventral aspect of the lower thoracic cord is now clearly visible. Note the continued lack of conspicuity on the T1 post-contrast images (4A, E).

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Images of the thoracolumbar spine from initial scan (5A–D) and follow-up scan two months later (5E–H). Initially negative T1 post-contrast (5A) and T2 image (5B) with possible tiny, nodular diffusion abnormality along the distal cauda equina on isotropic DWI (5C) and ADC map (5D). Follow-up T1 post-contrast image demonstrates enhancement within the distal thecal sac (5E); T2 image demonstrates nodularity along the cauda equina and within the distal thecal sac (5F); isotropic DWI (5G) and ADC map (5H) demonstrate nodular and clumpy areas of restricted diffusion consistent with drop metastases.
evaluation with DWI. Other CNS tumors that can restrict diffusion and spread to the spine include other PNETs such as atypical teratoid rhabdoid tumor (ATRT), as well as ependymoma, glioblastoma multiforme, germinoma, and choroid plexus carcinoma.

ii. Primary cord tumor

Just as in the brain, DWI is helpful in narrowing the differential diagnosis of primary spinal tumors (Fig. 6). Diffusion tensor imaging (DTI) can be used to visualize ordered white matter tracts of the spinal cord in an effort to further characterize a mass. It is helpful to determine whether the lesion displaces the tracts or infiltrates between them. Identification of white matter tracts can ultimately assist in surgical planning as well [12].

iii. Epidermoid

Restricted diffusion within a solitary intradural cyst is essentially pathognomonic for an epidermoid cyst (Fig. 7). The restricted diffusion within these cysts is related to their squamous epithelial contents. Epidermoids are often congenital and can be related to tethered cords, a common indication for spine MRI in children. Arachnoid cysts and epidermoid cysts can be easily differentiated with DWI [13].

2-year-old boy* with limping and back pain. Sagittal T1 post-contrast (6A) and axial T2 images (6B) demonstrate an intramedullary mass involving the conus medullaris. There is mild enhancement of the lesion, and the mass is iso- to hyperintense on T2. ADC map (6C) reveals isointensity of the mass with the normal cord, corresponding to an iso- to hyperintense appearance on the isotropic DWI image (6D). This excludes a densely cellular lesion such as PNET, and is consistent with a lower grade lesion such as a diffuse leptomeningeal neuroepithelial tumor (DLNT) as in this case.

10-year-old girl with back pain and asymmetric reflexes. Sagittal T1 post-contrast (7A), sagittal T2 (7B), axial T2 with fat saturation (7C) demonstrate a round, non-enhancing, T2 hyperintense, cystic-appearing lesion at the tip of the conus medullaris. Hypointensity on the ADC map (7D) and hyperintensity on the isotropic DWI image (7E) are classic for an epidermoid cyst.
b. Extradural  
i. Vertebral/paravertebral/ metastatic tumors

As previously discussed, spine DWI is particularly well-suited to pediatric oncologic imaging due to the high frequency of densely cellular tumors that occur in children. These tumors can be found both intra- and extradurally within the spine. Pediatric extradural tumors that lend themselves to DWI detection include neuroblastoma, leukemia, lymphoma, rhabdomyosarcoma, and Ewing sarcoma (Fig. 8). The unifying pathologic feature of these tumors is that they are comprised of small, round, blue cells. In the case of primary vertebral Ewing sarcoma, DWI not only assists with tumor detection but also in differentiation from other vertebral lesions that can have a similar appearance on conventional imaging sequences such as eosinophilic granuloma and chordoma (Fig. 9).

Diffusion-weighted imaging can also be a useful tool for distinguishing acute benign osteoporotic from malignant vertebral compression fractures. Increased water motion is typically present in post-traumatic benign compression fractures resulting in low or iso-intense signal on DWI and high ADC values on ADC maps [14]. In contrast, pathologic compression fractures related to densely cellular tumors such as lymphoma have restricted diffusion with hyperintensity on DWI and hypointensity on ADC maps [15] (Fig. 10).

2. Infarction

DWI is a powerful tool in the identification of spinal cord infarction, sometimes revealing restricted diffusion in the cord even before changes on the T1 or T2-weighted images develop [16]. Spinal cord infarctions in children are rare, but can occur in such settings as spinal arteriovenous malformations (AVMs) and fibrocartilaginous emboli. The latter are caused by retrograde migration of nucleus pulposis from the intervertebral disk into the spinal microcirculation [17]. This is usually caused by a minor physical trauma or a physical effort in conjunction with Valsalva [16]. Acute spinal cord infarcts present with severe pain followed by a rapidly progressive paraplegia/tetraplegia and loss of reflexes. MR images reveal cord swelling, increased T2 signal, and

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6-year-old boy with intermittent fevers, bilateral leg pain, and abdominal mass. Sagittal T1 post-contrast with fat saturation (8A), sagittal T2 (8B), axial T1 post-contrast with fat-saturation (8C), axial T2 with fat-saturation (8D), sagittal ADC map (8E) and isotropic DWI (8F) images demonstrate a large paraspinial mass invading the central spinal canal. Restricted diffusion within the mass is consistent with neuroblastoma. Note the epidural involvement at the dorsal aspect of T5, well delineated on the isotropic DWI sequence. Extensive metastatic disease involving the vertebral bodies is also apparent.
8-year-old boy with ataxia. Sagittal pre-contrast T1 (9A) and post-contrast T1 with fat saturation (9B), sagittal and axial T2 with fat saturation (9C, D), sagittal ADC (9E), isotropic DWI (9F), and color FA (fractional anisotropy) map (9G) reveal a large, enhancing epidural mass involving the T6 vertebral body producing cord compression. Restricted diffusion in the mass (9E, F) is typical for Ewing sarcoma.

10-year-old boy with back pain. Sagittal pre-contrast T1 (10A), post-contrast T1 with fat saturation (10B), sagittal and axial T2 with fat saturation (10C, D), ADC map (10E) and isotropic DWI (10F) images demonstrate multilevel compression fractures with enhancement of the involved vertebral bodies, low signal on ADC maps, and marked hyperintensity on DWI. Findings are consistent with leukemia/lymphoma. Chronic relapsing multifocal osteomyelitis is one differential consideration.

17-year-old girl with acute onset of neck pain followed by flaccid tetraparesis. Sagittal pre- and post-contrast T1 (11A, B) and sagittal and axial T2 (11C, D) images demonstrate intrinsic T2 hyperintensity within the cord from the level of the cervicomedullary junction to the level of C4. There is corresponding hypointensity with minimal enhancement on T1. Sagittal ADC map (11E) demonstrates marked hypointensity within the cord at these levels, and isotropic DWI image (11F) demonstrates hyperintensity consistent with acute cord infarction.
markedly restricted diffusion [18] (Fig. 11). Spinal cord infarcts secondary to fibrocartilaginous emboli can demonstrate loss of expected T2-hyperintensity in the disk and loss of disk height.

DWI can aid in the differentiation of acute infarction from inflammatory conditions such as transverse myelitis, a condition not uncommon in children. While restricted diffusion can be seen with transverse myelitis once vasogenic edema becomes cytotoxic, the ADC values are typically not as low as those seen with acute infarction. Further studies are needed to evaluate these differences.

3. Infection

Infection involving the spine is frequently encountered in children. Osteomyelitis, diskitis, and epidural abscesses are common ailments, caused by hematological seeding of bacteria and often manifested with fever, pain, and/or limp. Abscesses can be surgical emergencies due to their potential for cord compression that requires emergent surgical intervention before permanent cord damage ensues. Prompt and accurate imaging detection is critical, and can be assisted by the use of spine DWI. Both osseous and epidural/intradural abscesses restrict diffusion, appearing markedly hyperintense on isotropic trace images and dark on ADC maps [19]. Polymorphonuclear leukocytes and necrotic debris in abscesses restricts water motion, a characteristic that can help differentiate abscesses from simple or mildly proteinaceous fluid collections. Abscess formation is often more conspicuous on DWI than on conventional images. DWI can also identify the extent of the abscess and assist in identifying multifocal disease that may not otherwise be apparent (Fig. 12).

Future directions

DWI shows promise in the evaluation of numerous pathological states of the pediatric spine. More research is needed in regards to demyelinating disease such as multiple sclerosis and spinal cord trauma such as SCIWORA (Spinal Cord Injury Without Radiographic Abnormality) in an effort to improve lesion detection and contribute to a prompt and accurate prognosis.

Several technical developments could further improve the quality of spine DWI images, specifically the use of coils with larger numbers of elements (which has improved diffusion imaging of the brain in recent years) and the use of multi-band to improve the efficiency of the image acquisition [20, 21]. Work also needs to be done to determine the optimum b-values for spine imaging as a range of values has been used in the literature.

As RESOLVE becomes more readily available in the community, it should serve to revolutionize spine imaging just as DWI did when it was introduced into routine MR imaging of the brain. DWI of the brain is currently standard-of-care in MR imaging, and we expect that DWI of the spine will become part of the standard of care for spine imaging in the near future.

Conclusions

RESOLVE DWI is a powerful imaging tool for evaluation of spinal pathology. Images presented in this article demonstrate that this technique is exquisitely helpful in the work-up of numerous pathological conditions of the spine affecting children, including tumor, infarction, and infection.

*Siemens Disclaimer: MR scanning has not been established as safe for imaging fetuses and infants less than two years of age. The responsible physician must evaluate the benefits of the MR examination compared to those of other imaging procedures.
References

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