Comparison of Readout-Segmented Echo-Planar Imaging (EPI) and Single-Shot EPI in Clinical Application of Diffusion-Weighted Imaging of the Pediatric Brain

Kristen W. Yeom1
Samantha J. Holdsworth2
Anh T. Van2
Michael Iv1
Stefan Skare3
Robert M. Lober4
Roland Bammer2

OBJECTIVE. Readout-segmented echo-planar imaging (EPI) has been suggested as an alternative to single-shot EPI for diffusion-weighted imaging (DWI) with reduced distortion. However, clinical comparisons of readout-segmented EPI and EPI DWI are limited by unmatched imaging parameters and reconstruction procedures. Our goal was to compare the clinical utility of generalized autocalibrating partial parallel acquisition (GRAPPA)-accelerated readout-segmented EPI DWI with GRAPPA-accelerated EPI DWI for visualization of the pediatric brain in regions prone to distortion, such as the orbit, skull base, and posterior fossa.

SUBJECTS AND METHODS. Thirty consecutive patients (mean age, 7.8 years) presenting with orbital, skull base, and posterior fossa neuropathologic abnormalities were scanned at 3 T. Images were obtained using GRAPPA-accelerated readout-segmented EPI and GRAPPA-accelerated EPI with an identical scanning time, acceleration factor, target resolution, and image postprocessing procedure. The two datasets were independently reviewed by two blinded neuroradiologists. Imaging studies were evaluated for resolution, signal-to-noise ratio (SNR), contrast, distortion, lesion conspicuity, and diagnostic confidence and graded using a 7-point Likert scale (1, nondiagnostic; 7, outstanding).

RESULTS. There was good reader agreement in the scores (κ = 0.66; 95% CI, 0.54–0.78). The mean scores for EPI and readout-segmented EPI, respectively, were as follows: resolution, 5.0 and 6.0; SNR, 5.5 and 3.0; contrast, 3.7 and 3.2; distortion, 4.8 and 6.0; lesion conspicuity, 4.6 and 5.1; and diagnostic confidence, 4.7 and 5.4. Readout-segmented EPI was superior in resolution, distortion reduction, lesion conspicuity, and diagnostic confidence, whereas EPI scored better in SNR and contrast. Readout-segmented EPI was considered the better sequence overall in 85% of the cases.

CONCLUSION. This study shows the benefits of improved resolution and reduced distortion of readout-segmented EPI in evaluating the orbit, skull base, and posterior fossa, sites of common neuropathologic abnormalities in children.

Diffusion-weighted imaging (DWI) is used to evaluate microscopic water motion within tissue and has been shown to be useful for assessing various brain lesions, including ischemia, abscess, toxic metabolic diseases, and tumors. DWI also may have a role in therapeutic monitoring and in establishing prognosis in some of these diseases [1–4]. Given its clinical impact, DWI is considered by many radiologists to be an essential MRI sequence for diagnostic brain imaging.

Mainly because of its speed, single-shot echo-planar imaging (EPI) is the sequence typically used to acquire clinical DW images. Unfortunately, EP images suffer from susceptibility artifacts that manifest as geometric distortion, signal dropout, and image blurring. These artifacts can be problematic if evaluating the orbit, skull base, or posterior fossa, which are common locations of neuropathologic abnormalities in children. For example, when evaluating a dermoid or epidermoid mass of the orbit or the frontonasal bone, susceptibility differences between the tissues in this region (i.e., frontonasal bone, air-filled nasal cavity, and glabellar soft tissue) often limit the diagnostic quality of single-shot EP images. Other examples of pediatric lesions occurring in these sites where DWI might be useful include retinoblastoma, orbital and skull base neuroblastomas and rhabdomyosarcomas, Langerhans cell histiocytosis, congenital lymphatic and vascular malformations, optic glioma, brainstem and cerebellar tumors, and others.
Distortion in EPI is driven by the temporal separation between subsequent odd and even echoes within the EPI readout train. One way to reduce distortion in EPI is, therefore, the use of parallel imaging with either generalized autocalibrating partial parallel acquisition (GRAPPA) [5–7] or sensitivity-encoding (SENSE) [8, 9]. GRAPPA and SENSE speed up the traversal of k-space; however, image distortion in parallel imaging–enhanced EPI DWI remains problematic particularly at high field strengths and for high-resolution imaging.

Another way to reduce distortion in DWI is to speed k-space traversal through the use of alternate trajectories. These methods include but are not limited to navigated multishot EPI sequences [10]; interleaved spiral sequences [11]; and fast spin-echo (FSE)–based sequences such as periodically rotated overlapping parallel lines with enhanced reconstruction (PROPELLER) [12], short-axis PROPELLER EPI [13], and readout-segmented EPI [14, 15].

Readout-segmented EPI is a particularly promising candidate for pediatric imaging because it has been shown to be relatively robust to motion [16] without the significant scanning time and specific absorption rate penalties posed by PROPELLER FSE sequences. The EPI and readout-segmented EPI k-space trajectories are shown in Figure 1. In readout-segmented EPI, several adjacent segments or “blinds” are acquired, and geometric distortion is reduced compared with EPI by a factor proportional to the blind width.

Previously, we compared our in-house–built GRAPPA-accelerated readout-segmented EPI DWI sequence and tailored reconstruction with a vendor-supplied SENSE-accelerated EPI DWI sequence and showed that readout-segmented EP images were of significantly higher quality [17]. However, in part because of the inflexibility of the vendor-supplied software, there were three limitations acknowledged in that study: The target resolution and acceleration factor were not matched; the scanning times of the two sequences were not matched; and there were considerable differences in the image reconstruction, including phase correction, ghost correction, partial-Fourier reconstruction, and parallel imaging calibration.

The purpose of this study was therefore to compare and assess the clinical utility of the two following DWI sequences for imaging the pediatric brain in regions prone to susceptibility-induced geometric distortion such as the orbit, skull base, and posterior fossa: scanning time–matched GRAPPA-accelerated readout-segmented EPI and GRAPPA-accelerated EPI. Here, the two imaging sequences were performed with an identical scanning time, acceleration factor, and target resolution and the same fundamental image postprocessing procedure was used.

Subjects and Methods

Subjects

Thirty consecutive pediatric patients presenting for 3-T MRI assessment of neuropathologic abnormalities in the orbit, skull base, or posterior fossa were prospectively enrolled at our children’s hospital. Subjects included 16 females and 14 males, with a mean age of 7.8 years (range, 16 days–22 years). The types of orbital, skull base, or posterior fossa pathologic abnormalities evaluated in these patients are listed in Table 1. All examinations were performed after institutional review board approval and written informed consent from each subject’s parent, as well as consent from the patient when appropriate, had been obtained.

MRI

GRAPPA-accelerated readout-segmented EPI and GRAPPA-accelerated EPI DW images were acquired of each patient on a 3-T system (DVMR 750, GE Healthcare) using an eight-channel head coil and a high-performance gradient system (gradient strength, 50 mT/m; slew rate, 200 mT/m/s).

The following parameters were used for both sequences: FOV, 20 cm; acquisition matrix, 180 × 180; acceleration factor, 3; slice thickness, 4 mm; TR, 3 s; partial-Fourier encoding with 18 overscans (i.e., partial ky Fourier imaging factor, 0.6); one b = 0 and three diffusion directions with b = 1000 s/mm² (Stejskal Tanner diffusion preparation with x, y, z diffusion encoding). The scanning times for both readout-segmented EPI and EPI were matched for a total scanning time of 2 minutes 30 seconds. Readout-segmented EPI used three blinds of width 64 points in k-space (blind overlap of 6), and EPI used 3 averages (NEX). After slew rate limitations are taken into account, a blind width of 64 for readout-segmented EPI achieves a 55% reduction in distortion compared with EPI. The minimum TE achievable for readout-segmented EPI and EPI was 56 and 63 ms, respectively. Note that in readout-segmented EPI, an extra navigator blind was acquired for phase correction to address conflicting phase error differences due to the random motion that occurs between blinds [15].

The partial-Fourier EPI and readout-segmented EPI data were both phase corrected using a triangular-window approach [12] with a radius of 0.5 before partial-Fourier reconstruction using projection onto convex sets [18, 19]. A more detailed description of the postprocessing for readout-segmented EPI (also applicable to EPI albeit without the gridding procedure) is described elsewhere [9].

Imaging Evaluation

A board-certified pediatric neuroradiologist with a certificate of added qualification and a board-certified second-year neuroradiology fellow independently evaluated the readout-segmented EPI and EPI isotropic DW images of 30 patients. Each reader independently evaluated the readout-segmented EPI and EPI studies alongside the vendor-provided product DWI studies, which served as a standard reference, and was blinded to the type of sequence.

The images were assessed for the following parameters: resolution, signal-to-noise ratio (SNR), contrast, distortion, lesion conspicuity, and diagnostic confidence. Resolution, SNR, and contrast took into account the overall imaging quality for...
visualizing the brain: Resolution assessed the ability to see small structures (e.g., mammillary bodies, cerebellar folia, and fissures); SNR referred to general perceived SNR of the whole brain; and contrast referred to overall gray–white matter contrast. Distortion was assessed at susceptible sites (e.g., skull base, orbit, posterior fossa) including the site of disease. Lesion conspicuity referred to contrast between the lesion and the background tissue. The following 7-point Likert scale was used to assess the imaging parameters: 1, non-diagnostic; 2, poor; 3, acceptable; 4, standard; 5, above average; 6, good; and 7, outstanding. Each neuroradiologist weighed all six measures of image quality to select which sequence was the best overall, the “winner.”

All statistical analyses were performed with Matlab (version 7.8.0, MathWorks). Reader agreement was assessed using a linearly weighted kappa statistic. Tests for differences in ratings between EPI and readout-segmented EPI were performed using a two-tailed Wilcoxon signed-rank test.

**Results**

Both readers were in excellent agreement in their preference for imaging sequence (κ = 0.86; 95% CI, 0.61–1.12). The readers were in good agreement in their scores (κ = 0.66; 95% CI, 0.54–0.78).

The averaged scores of the two radiologists for resolution, SNR, contrast, distortion, lesion conspicuity, and diagnostic confidence calculated across the 30 patients are shown in Figure 2. The mean scores of both reviewers for EPI and readout-segmented EPI, respectively, were as follows: resolution, 5.0 and 6.0; SNR, 5.5 and 3.0; contrast, 3.7 and 3.2; distortion, 4.8 and 6.0; lesion conspicuity, 4.6 and 5.1; and diagnostic confidence, 4.7 and 5.4.
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Readout-segmented EPI was superior to EPI in reducing distortion ($p < 0.001$), scoring higher than EPI in all cases except in one case in which the score was tied. Readout-segmented EPI was also superior to EPI with regard to resolution ($p < 0.001$). However, EPI was superior to readout-segmented EPI in both SNR ($p < 0.001$) and contrast ($p = 0.031$). Readout-segmented EPI also scored higher with regard to lesion conspicuity ($p = 0.011$) and diagnostic confidence ($p = 0.001$). When all these measures were considered, readout-segmented EPI was considered the winner overall in 85% of the cases. Despite the better image contrast and SNR of EPI, the better geometric fidelity and higher perceived resolution of readout-segmented EPI had a higher impact for overall diagnostic confidence and lesion detection. Readout-segmented EPI was particularly useful for evaluating lesions dominated by susceptibility and distortion artifacts in locations such as the orbit, posterior fossa, or skull base (Figs. 3–6). For example, in Figures 3 and 4, the orbital lesions and the details of the orbital structures (including the optic nerve, extraocular muscles, and globe) are well depicted on readout-segmented EPI, whereas they appear distorted on EPI. In another example, a hemorrhagic collection and an air-containing ventricle of a postoperative patient appear more distorted on EPI than on readout-segmented EPI (Fig. 5). Also note the more intricate detail of the encephalomalacia and debris within the abscess cavity on readout-segmented EPI in Figure 6. In the five instances in which EPI was preferred, the lesion primarily resided or originated in the brain parenchyma (Fig. 7).

**Discussion**

Previously, investigators showed that readout-segmented EPI outperformed EPI in all measures of imaging quality [17]. However, important limitations of that prior study were
Readout-segmented EPI was particularly useful for evaluating lesions occurring in regions dominated by susceptibility and distortion artifacts such as lesions in the orbit, posterior fossa, or skull base (Figs. 3–6). Readout-segmented EPI was also superior in assessing the postoperative brain (Fig. 5) and lesions that exacerbate distortion, such as abscess (Fig. 6).

In this study, note also that motion correction between blinds was not implemented for readout-segmented EPI and that motion correction was not used between volumes for EPI. Despite the fact that motion correction was not used, the data did not appear to be visually affected by motion. In addition, despite the blind overlap of only 6 pixels, the phase-correction approach was sufficient to correct for motion-induced phase errors without introducing detrimental gaps in k-space. As a multishot approach, this relative motion insensitivity to brain motion shows great promise for the routine use of readout-segmented EPI in a pediatric setting.

A limitation of readout-segmented EPI was found in cases in which the lesion arose contiguous to the brain parenchyma (Fig. 7). In the 15% of cases in which EPI was the overall winner, the lesion margin against the adjacent brain was less distinct on readout-segmented EPI than on EPI and was thus graded down for lesion conspicuity. This difference was deemed primarily to be the result of the higher SNR and greater contrast of EPI.

The higher SNR of EPI is expected given the higher scan time efficiency of EPI, which is attributable to the more efficient k-space coverage and the absence of an additional navigator. Although readout-segmented EPI is faster than other methods used in a pediatric setting for reducing distortion in DWI, such as PROPELLER FSE, readout-segmented EPI is slower than single-shot EPI by an amount that is proportional to the number of blinds used. One may argue that to fully leverage the better distortion and resolution properties of readout-

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**Fig. 4**—Marked distortion artifact seen on echo-planar imaging (EPI) is not visible on readout-segmented EPI of 6-year-old boy (patient 15 in Table 1) with optic pathway glioma. A and B, Marked distortion artifact seen at anterior tumor margin and in orbit (arrows, A) on EP image (A) is significantly reduced on readout-segmented EP image (B).

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**Fig. 5**—Postoperative changes on echo-planar imaging (EPI) and readout-segmented EPI of 10-year-old girl (patient 14 in Table 1) who had undergone resection of right middle cranial fossa glioblastoma. A, On EP image, postoperative changes result in marked distortion and poor delineation of right extraaxial collection and hemorrhage (white arrow). Also note distorted left frontal horn (black arrow) due to presence of intraventricular air. B, Image quality is improved on readout-segmented EPI. Collection and hemorrhage (arrow) are easier to see than on A and left frontal horn has more anatomic configuration. C, Fast spin-echo image.
segmented EPI in a clinical setting, one must simply scan longer.

The superior tissue contrast of EPI was also expected in this study; however, its impact in a clinical setting was unexpected. In readout-segmented EPI, the shorter readout time per blind results in a shorter effective TE. At first glance this property of readout-segmented EPI would seem to be advantageous because shorter TEs result in a higher SNR assuming that all other imaging parameters remain fixed. However, in this setting, the shorter TE of readout-segmented EPI resulted in reduced T2 contrast on the DW images—which effectively obscured the barrier between lesions and normal tissue. This additional T2 contrast on EPI DWI (otherwise known as T2 shine-through) is a controversial topic because it mixes contrast driven by proton self-diffusion with T2 contrast. However, in this study this effect shows a potential advantage in evaluating lesions with T2 high intensity occurring within or contiguous with the brain parenchyma.

Note that one may consider increasing the TE of readout-segmented EPI to increase the T2 contrast; however, this change is likely to come at a detrimental cost to SNR. Another more obvious solution is to use full-Fourier encoding for readout-segmented EPI [20] to increase the TE. Although the use of partial-Fourier encoding, as used in this work, benefits EPI by keeping the TE at a reasonable length, the TE of readout-segmented EPI can be increased through the use of full-Fourier encoding with very little loss in SNR efficiency compared with its partial-Fourier alternative (Holdsworth SJ, et al., presented at the 2011 annual meeting of the International Society for Magnetic Resonance in Medicine). Thus, further work will be conducted that explores the use of full-Fourier encoding to improve lesion contrast for readout-segmented EPI.

In conclusion, this study confirms the benefits of readout-segmented EPI in evaluating lesions in the orbit, skull base, and posterior fossa.
where neuropathologic abnormalities are common in children. Although not prospectively studied, it appears that the additional contrast generated by longer TEs, such as used for EPI versus readout-segmented EPI, may improve lesion conspicuity and outweigh the distortion benefit of readout-segmented EPI in certain clinical circumstances. Therefore, a more careful assessment of the impact of TE and T2 shine-through on lesion conspicuity is warranted.

References