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3D T1-weighted contrast-enhanced brain MRI in children using a fat-suppressed golden angle radial acquisition: an alternative to Cartesian inversion-recovery imaging

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ABSTRACT

Background: T1-weighted post-contrast MRI is essential in brain protocols. We demonstrate the feasibility and utility of a 3D non-Cartesian radial acquisition in children.

Purpose: To compare bulk motion artifacts, image quality, and lesion conspicuity in 3D T1-weighted post-contrast brain MRI between a new fat-suppressed radial gradient-echo and a traditional non-fat-suppressed inversion-recovery Cartesian gradient-echo sequence.

Material and methods: Images from 53 patients acquired at 3 Tesla were compared. Three radiologists rated the images in three categories, including the presence of bulk motion and whether it impacted diagnosis, whether one sequence was preferred over the other in overall image quality and conspicuity of vascular structures and lesions, and whether diagnosis was possible if only the new fat-suppressed radial acquisition was obtained.

Results: The Fleiss' kappa for inter-rater agreement was 0.67 for bulk motion and 0.54 for sequence preference. Of the 53 cases, 56% were identified to have significant motion on conventional imaging, while only 13% had motion artifacts on the radial acquisition ($p < 0.05$). There were no cases where motion was seen on the radial acquisition but not on conventional imaging. Both sequences were equally preferred in 87% of the cases. All radiologists agreed that the radial approach had lower gray-white matter contrast than the conventional inversion-recovery method, but preferred the former for making diagnosis in uncooperative patients.

Conclusion: We demonstrate the potential utility of a fat-suppressed 3D T1-weighted post-contrast brain gradient-echo sequence in children. The technique is useful in non-sedate pediatric imaging due to its reduced sensitivity to bulk motion.

1. Introduction

MRI techniques that are designed to have reduced sensitivity to bulk patient motion are attractive and of high-value in clinical practice. In pediatric imaging, such benefits are helpful especially in uncooperative patients or when patients are unable communicate with the technologist and follow instructions to hold still [1,2]. Motion-insensitive scans minimize the need for repeat scans and also potentially remove the need for sedation and general anesthesia in a sub-population of children who can undergo an awake MRI exam [3–5].

In Gadolinium-contrast-enhanced whole-brain MRI, a 3D T1-weighted volumetric post-contrast scan is one of the most commonly used pulse sequences to visualize pathology [6–11]. Historically, the non-fat-suppressed 3D Magnetization Prepared Rapidly Acquired Gradient Echo (MPRAGE) method with Cartesian encoding has been the clinical workhorse pulse sequence. On average, a MPRAGE sequence with whole-brain coverage and 1 mm isotropic voxels typically requires 5–6 min of scan time. For children undergoing non-sedate MRI exams, this duration can be quite long to lie still. Consequent head motion, albeit inadvertent, can be a frequent occurrence. Confident visualization of enhancing lesions is desirable in these post-contrast scan and they are often compared to a similar pre-contrast MPRAGE scan. Therefore, reduced sensitivity and improved immunity to bulk motion is crucial in post-contrast imaging. In recent years, rapid gradient-echo pulse sequences [12] and their fat-suppressed non-Cartesian radial variants [13] have been introduced as alternatives in post-contrast 3D

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T1-weighted brain MRI. Despite similar or slightly shorter scan times, radial scans have reduced motion sensitivity and have been demonstrated to preserve diagnostic image quality in comparison to MPRAGE. In radial acquisitions, the inherent oversampling of central k-space and increased immunity to bulk motion [5] has been exploited in uncooperative patients [14].

In late 2017, our tertiary pediatric referral hospital obtained a fat-suppressed non-Cartesian 3D radial gradient-echo acquisition and associated image reconstruction capability. Therefore, the purpose of this study was to evaluate a fat-suppressed 3D golden-angle radial "stack of stars" gradient echo scan (i.e., **RAVE** - **RA**dial **V**olumetric **E**ncoding) and to compare its results with our clinical practice's conventional 3D MPRAGE pulse sequence in post-contrast T1-weighted brain imaging at 3 Tesla. Over the past few years, the RAVE pulse sequence has already been demonstrated successfully in body applications to facilitate robust free-breathing T1-weighted imaging [15–20]. A recent 2018 report has comprehensively described its comparison to MPRAGE brain imaging in 65 children at 1.5 Tesla [13], concluding that RAVE is a viable alternative to MPRAGE in restless children while preserving diagnostic image quality. Other groups have also reported the use of RAVE in head and spine MRI [21–23].

Herein, we hypothesize that 3D RAVE can potentially serve as a practical alternative sequence to traditional 3D Cartesian-encoded MPRAGE in post-contrast brain imaging at 3 Tesla, similar to the objective by Park et al. [13]. We specifically evaluate RAVE in the context of pediatric brain imaging, where frequent bulk motion and consequent artifacts can frequently hamper diagnostic image quality.

2. Material and methods

This retrospective and HIPAA-compliant MRI study was approved by our institution's research and ethics board as a minimum-risk quality-improvement project with a waiver of informed consent/assent. Data from fifty-three consecutive patients (31 boys, 22 girls age range: 0.1–19.4 years, average age: 12.4 ± 4.9 years) were reviewed. All patients were referred for MRI for clinically indicated reasons. MRI data were acquired with patients in a supine position and head first on a 3 Tesla scanner (Siemens Magnetom Prisma®, software version VE11C, Siemens Healthineers, Erlangen, Germany), using either a 20- or a 64-channel head coil array.

The fat-suppressed 3D RAVE sequence was operated within the safety limits of specific absorption ratio for routine brain imaging. The addition of RAVE to the end of our institution's clinical brain MRI exam with contrast was approved by the Radiology Department. The RAVE non-Cartesian radial pulse sequence utilized in this work is a work-in-progress 3D T1-weighted spoiled gradient echo method, and is a commercially available product from Siemens Healthineers as StarVIBE (also commonly referred to as Radial VIBE). Fat-suppression, herein obtained with a frequency-selective approach, is needed in non-Cartesian data reconstruction to avoid off-resonance blurring from fat's chemical shift and provides RAVE additional tissue contrast around the skull. Whereas in Cartesian imaging chemical-shift artifacts manifest principally along the frequency encoding axis, in non-Cartesian radial trajectories, the artifact propagate and smear in a circular fashion. Fig. 1 illustrates the k-space filling of RAVE. Within each phase-encoded slice, data are acquired along radial spokes during successive repetitions of the sequence. Consecutive spokes within each slice are rotated in-plane by a golden-angle of 111.25 degrees to maximize in-plane k-space coverage with minimal redundancy. As a benefit of the golden-angle increment, no spokes are repeated.

Table 1 summarizes the relevant pulse sequences parameters used in this work. MPRAGE acquisition parameters were not altered from our hospital's routine practice, and parameters for the 3D RAVE sequence were adjusted to provide approximately equal volumetric coverage in a similar amount of scan time as the MPRAGE (approximately 5:30 for RAVE versus 6:10 for MPRAGE). Note that the MPRAGE is acquired by default in the sagittal direction and utilizes two-fold GRAPPA parallel imaging acceleration with 0.9 mm in-plane resolution, while the RAVE scan is acquired in the axial plane without parallel imaging and with 1 mm in-plane resolution in its current form. Note also that the two sequences are fundamentally different in their repetition time, echo time, inversion time, receiver bandwidth, and fat suppression settings, leading to intrinsic differences in signal-to-noise ratio and tissue contrast. Both sequences were performed after standard single-dose Gadolinium-contrast administration (Gadavist®, Bayer, Whippany, New Jersey). The MPRAGE sequence was always acquired first immediately after contrast administration to preserve our institution's standard-of-care protocol, followed by RAVE as the final scan of the exam. On occasion, a routine axial T1-weighted spin-echo sequence that is part of our standard protocol, with a scan time of 4–5 min, was performed after the MPRAGE and prior to the RAVE sequences at the discretion of the attending neuroradiologist. Patients were not given any additional instructions to hold still between MPRAGE and RAVE acquisitions, but were told by the technologist and nurse to expect the Gadolinium contrast injection.

Images from both MPRAGE and RAVE were reconstructed online using the Siemens ICE framework and sent to the local PACS system for diagnostic interpretation. The data were assessed independently by three attending pediatric neuroradiologists, in a retrospective manner, with approximately 25, 12, and 2 years of post-fellowship experience. The data were not blinded, as differences in gray-white matter signal between the MPRAGE and RAVE sequences revealed their identity (i.e., the RAVE does not have inversion recovery magnetization preparation and is fat-suppressed). Raters were asked three questions. First, was there any noticeable presence of bulk motion and related artifacts in each image set, and if yes, whether the degree of artifact was mild, moderate, or severe in its impact on diagnostic image quality. The second question was concerned with conspicuity of lesions and vascular enhancement and raters were asked whether they preferred MPRAGE or RAVE or both equally in visualizing contrast-enhancing anatomy and pathology. The third question asked whether the same diagnosis in each patient could be reached if RAVE was acquired instead of MPRAGE (i.e., if MPRAGE was unavailable)?

The STATA statistical software package (Version 13, College Station, Texas) was used. The Mann-Whitney *U* test was used to compare MPRAGE and RAVE scores to determine which sequence was superior in the first category concerning bulk motion. We used the Wilcoxon rank-sum test in the second question to see if scores differed statistically from "equal" to imply a preference for either MPRAGE or RAVE. A non-significant result here would imply equal preference. A p-value of 0.05 was chosen to reflect statistical significance. Fleiss' Kappa coefficient for multiple inter-rater agreement was also computed for each score category.

3. Results

Fig. 2 (motion) and Fig. 3 (sequence preference) summarize the scores from the image ratings. The Fleiss' kappa statistic for the three radiologists as a group were 0.67 ± 0.08 (95% confidence interval (CI): 0.52–0.83) for the question on bulk motion and 0.54 ± 0.06 (95% CI: 0.41–0.66) for the second rating concerning sequence preference. There was unanimous agreement amongst the three neuroradiologists that in all cases, the same diagnosis could be reached if RAVE was acquired in place of MPRAGE.

Of the 53 cases, 56% were identified to have significant bulk motion on MPRAGE, manifesting primary in typical ghosting and ringing artifacts along the phase encoding direction. Only 13% of the cases had bulk motion artifacts on the radial acquisition ($p < 0.05$). There were no cases where bulk motion was seen on the radial acquisition but not on the MPRAGE. Of these identified cases and pooling across the scores, 8% of the cases that had motion artifacts identified on RAVE were rated as "mild", while 5% were deemed "moderate". In the latter, bulk

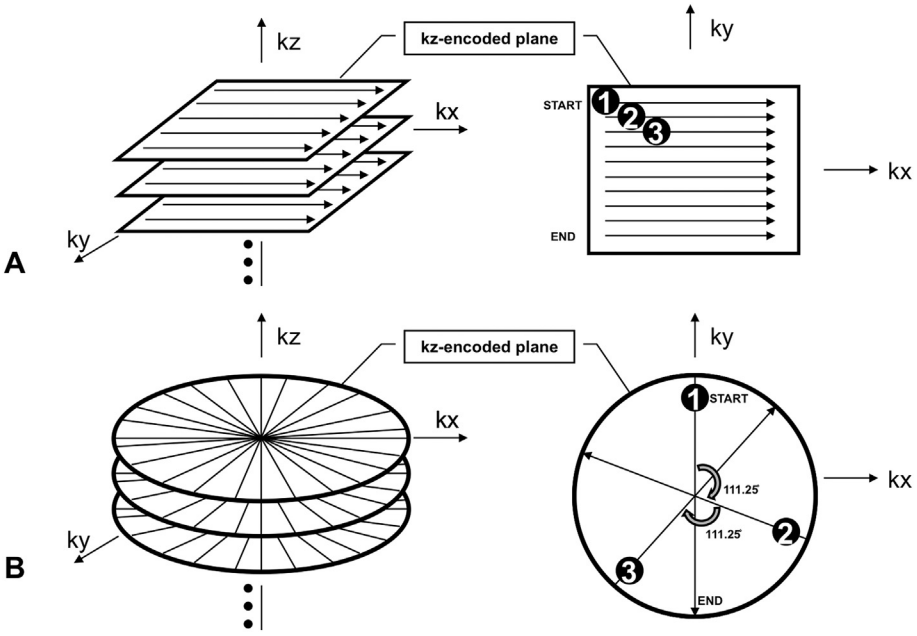

Fig. 1. Illustration of 3D k-space comparing conventional (A) Cartesian and (B) radial "stack of stars" radial trajectory for RAVE. In Cartesian encoding, all data fall on a rectilinear grid. Typically, consecutive echoes are filled in a sequential pattern. In RAVE, uniform Cartesian-grid sampling is maintained along the slice phase encoding direction (kz). However, within each kz-encoded plane, consecutive views are rotated by an angle of 111.25 degrees. For this implementation, a particular spoke is acquired for all kz partitions first before proceeding to the next golden-angle spoke.

Table 1
Summary of pertinent MPRAGE and RAVE pulse sequence parameters.

Parameter	3D MPRAGE	3D RAVE
Acquired orientation	Sagittal	Axial
Base sequence	Inversion-recovery gradient-echo	Spoiled gradient echo
Voxel size in-plane (mm)	0.9	1.0
Field-of-view (mm)	220	220
Matrix size	256	256
Number of slices in acquisition	160	170
Slice thickness (mm)	1 mm	1 mm
Slice oversampling	10%	10%
Repetition time TR (ms)	4 (for gradient echo) 2300 (for IR cycle)	3.1
Echo time TE (ms)	2.3	1.6
Inversion time TI (ms)	900	n/a
Fat suppression	None	Frequency-selective
Partial echo/partial Fourier	No	No
Bandwidth/pixel (Hz)	200	810
Spokes per slice	n/a	700
Parallel imaging	GRAPPA × 2	None
Number of signal averages	1	1
Excitation flip angle	8 degrees	15 degrees
Approximate scan time for given parameters (min:sec)	6:10	5:30

motion causing significant radial streaking artifacts across the axial brain images was the primary complaint. In comparison, a greater percentage of the cases had "mild" motion and related artifacts identified on MPRAGE (46%), and 10% of the cases were rated "moderate" artifact impact on diagnostic quality. In neither RAVE nor MPRAGE were there any cases with a "severe" rating.

In 46 of the 53 cases, Rater 2 and Rater 3 did not show a preference for either RAVE or MPRAGE. Rater 1, with > 25 years of clinical experience, showed no preference in 48 cases. In three cases, RAVE was unanimously preferred by all three radiologists. In two additional cases, RAVE was preferred by at least two of the three radiologists. In the four cases where MPRAGE was preferred, only one case was scored similarly by two radiologists. There were no cases where one radiologist preferred RAVE, while one or both remaining raters preferred MPRAGE, and vice versa. In cases where RAVE was preferred, the primary reason was the absence of coherent ghost-like motion-induced artifacts.

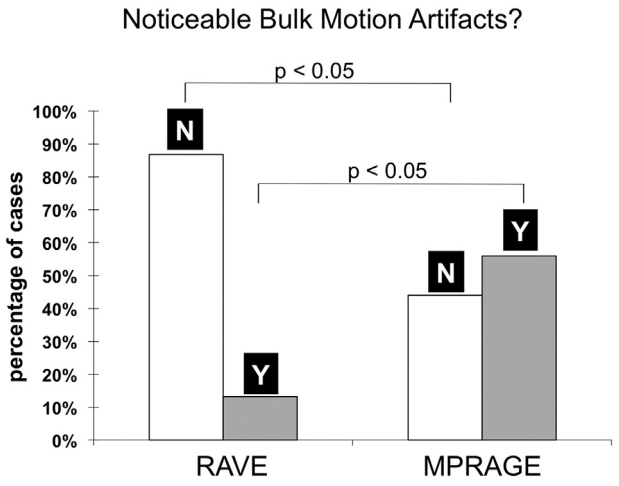

Fig. 2. Summary of scores for evaluating the presence of bulk motion in MPRAGE and RAVE.

Conversely, in cases where MPRAGE was preferred, the predominant reason was superior gray-white matter tissue contrast and better contrast-enhancement. The Wilcoxon rank-sum test was not statistically significant for this category, therefore implying equal preference to either pulse sequence.

Figs. 4, 5, 6, and 7 illustrate representative examples from several patients, highlighting the overall lack of bulk motion-induced artifacts and comparable contrast-enhancement properties of the RAVE data.

4. Discussion

The goal of this work was to determine whether 3D RAVE can potentially serve as an alternative sequence to our institution's existing MPRAGE acquisition in post-contrast brain imaging, primarily with the aim to improve robustness against bulk motion in uncooperative pediatric patients. The large proportion of cases where RAVE and MPRAGE were equivalent in diagnostic preference supports this notion. Poor diagnostic image quality due to bulk motion and related artifacts is a common pitfall of post-contrast MPRAGE imaging in children, where patients are often unable to remain still for 4–5 min. This is

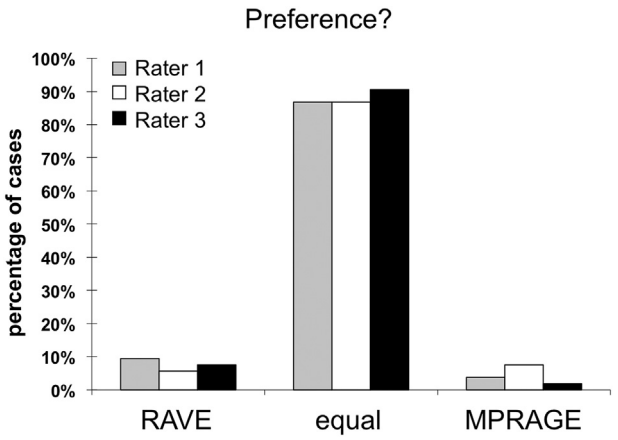

Fig. 3. Summary of scores from three independent radiologist evaluations for sequence preference in visualizing contrast-enhancing vascular structures and pathological lesions. In > 90% of the cases, there's equal preference for both sequences. In the few cases where RAVE was preferred, significant motion impacted the diagnostic image quality of the MPRAGE counterpart. Conversely, in cases where MPRAGE was preferred, the primary reason was superior contrast-enhancement and tissue signal contrast in the MPRAGE.

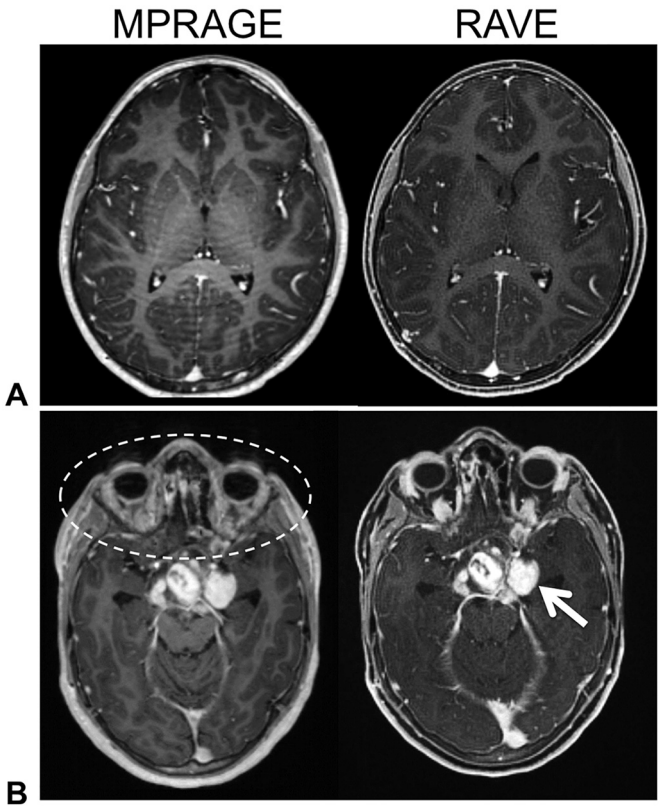

Fig. 4. Representative images from (A) a 12 y boy and (B) a 13 y old girl with a solid and cystic suprasellar mass (arrow). Both cases were obtained without sedation. In the MPRAGE scans, note significant ringing artifacts due to head motion in (A) as well as blurring effects due to eye motion (dashed oval) in (B). Corresponding RAVE scans do not exhibit any noticeable motion artifacts, while maintaining lesion conspicuity of the suprasellar mass.

exacerbated by the fact that a post-contrast MPRAGE scan does not typically occur until 25–30 min after the beginning of a brain MRI exam, when all pre-contrast imaging (e.g. pre-contrast MPRAGE, diffusion imaging, T2, T2 FLAIR, susceptibility weighted imaging) have been completed. A repeat MPRAGE scan may be requested if the artifacts in the initial scan are severe. In pediatric imaging, the additional

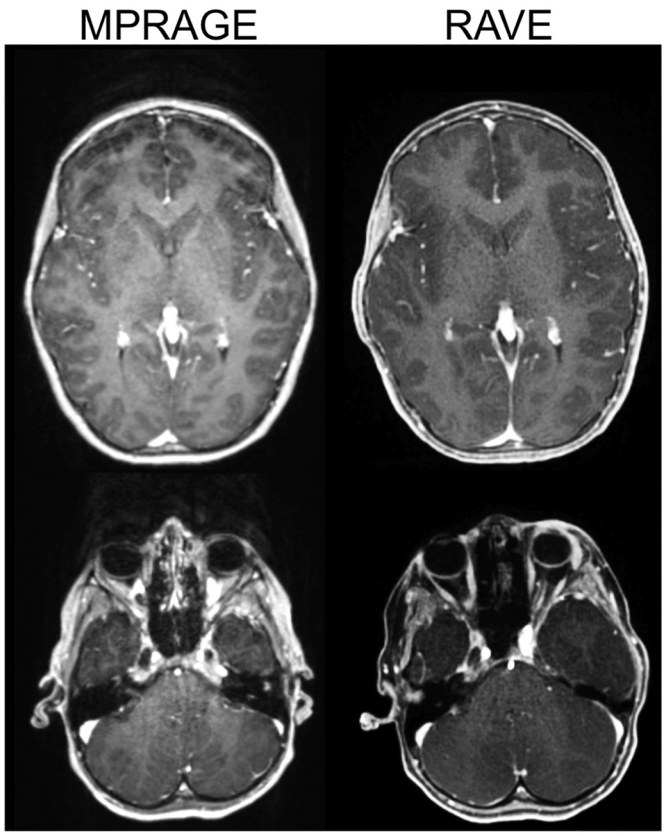

Fig. 5. Two representative slices from an 11 y male who underwent MRI simulator training with Child Life Specialists to convert from an originally scheduled sedate exam to one without sedation. Motion-related blurring can be seen in the frontal lobe and around the orbits in MPRAGE. They are reduced in the RAVE scan.

time of a repeat scan can lead to anxiety and discomfort. The repeat MPRAGE scan may also not necessarily yield an improvement in diagnostic image quality. RAVE provides an alternative and confident "first-time-right" post-contrast 3D T1-weighted whole-brain approach with robustness against motion.

In this work in predominantly children and adolescents undergoing non-sedated MRI, we have demonstrated the utility of 3D RAVE to consistently provide diagnostic quality data, with no need for a repeat RAVE scan due to motion artifacts or poor image quality, despite having a similar scan duration as our conventional MPRAGE sequence. The RAVE pulse sequence was easily adopted by our Radiology Department's MR technologists with minimal additional training. In our current experience with brain imaging and typical field-of-views of 200–250 mm, given the < 1 mm spatial resolution, a minimum of 600 radial spokes per slice is needed to avoid streaking artifacts across the image that are visually distracting to the reading neuroradiologist. As an outcome of this pilot study, the RAVE technique is now a selectable choice in our post-contrast brain protocols when a restless or uncooperative patient is encountered. In this scenario, it is the default choice for post-contrast T1-weighted imaging in lieu of MPRAGE, despite the decreased tissue contrast between gray and white matter and reduced signal-to-noise ratio. The technique is particularly useful in patients prone to head (and body) movement, which can be identified by the technologist during the pre-contrast portion of the exam. In these situations, the technologist can opt to run the RAVE sequence post-contrast as the first choice. At the outset of this study, our objective was not to necessarily demonstrate superiority of RAVE over MPRAGE. In patients where motion is absent, our neuroradiologists still find the conventional MPRAGE sequence more desirable, as it provides greater

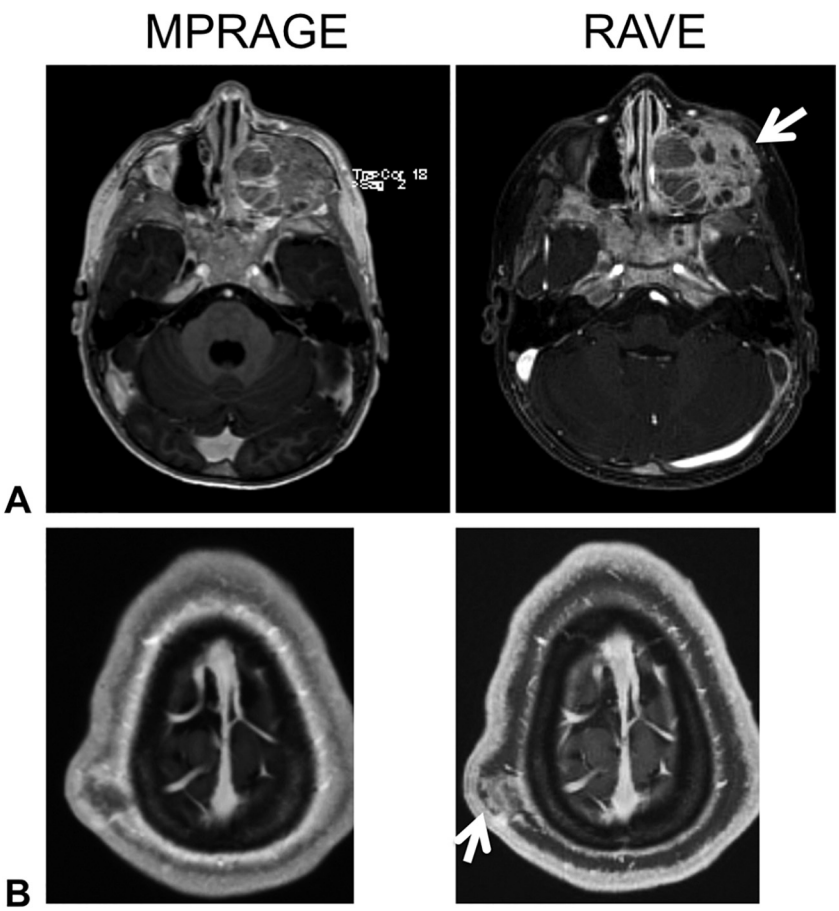

Fig. 6. Representative images from (A) a 17 y boy with metastatic neuroblastoma and (B) a 4 y boy with a scalp neurofibroma. In both instances, the enhancing pathology is better visualized in RAVE with fat suppression (arrows).

T1-weighted tissue contrast, and can be compared to a similar pre-contrast MPRAGE scan. The results from this study at 3 Tesla complement existing literature and most notably a recent pediatric study performed at 1.5 Tesla by Park et al. [13]. In that study, the investigators reported in 65 pediatric patients that the radial acquisition had fewer motion and pulsation artifacts than in MPRAGE.

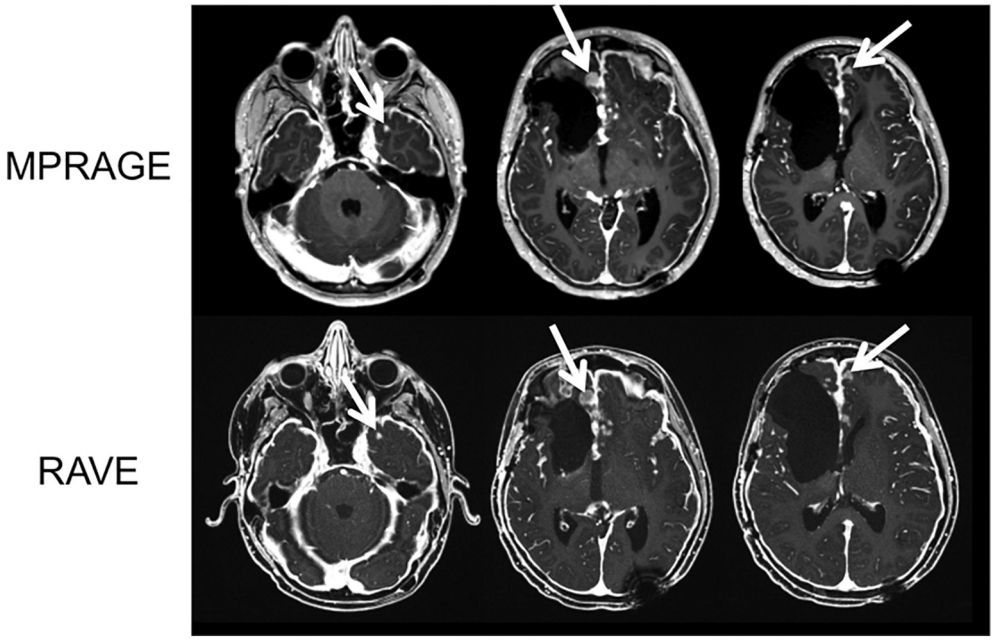

Fig. 7. Representative images from a 13 y boy with multiple metastatic nodules (arrows), all of which are clearly seen with equal conspicuity in MPRAGE and RAVE scans.

Furthermore, in 25 patients with severe motion artifacts, data from the radial acquisition scored higher in image quality and lesion conspicuity ($p < 0.001$).

We note several limitations in this study. First, we did not compare a fat-suppressed MPRAGE pulse sequence with our fat-suppressed RAVE technique. Although such a sequence has been proposed in the past [24], it has not been demonstrated in brain applications. A fat-suppressed MPRAGE sequence was not available on our 3 Tesla systems at the time of this study, and a frequency-selective *water*-excitation MPRAGE sequence was the closest alternative after consultation with scientists from the manufacturer. However, adding water-excitation to our conventional MPRAGE protocol increased scan time slightly and it was ultimately not favored by our neuroradiology group. Conversely, we did not compare a non-fat-suppressed RAVE protocol to conventional non-fat-suppressed MPRAGE. Since fat-suppression is critical in non-Cartesian imaging reconstruction to minimize chemical-shift artifacts that manifest in multiple directions, the only option to obtain a non-fat-suppressed RAVE image without fat-related blurring would have been to first perform a multi-echo chemical-shift-encoded radial acquisition, separately reconstruct the water-only and fat-only components, and retrospectively synthesize an in-phase-mimicking data set by adding the water-only and fat-only data. While we currently have a working dual- and multi-echo Dixon-based RAVE sequence, it requires offline data reconstruction and processing [19,25], and it is not yet optimized for streamlined clinical workflow and PACS integration. As a future direction of work, the diagnostic utility of RAVE and MPRAGE should be evaluated in the context of lesion conspicuity independent of the presence or absence of fat-suppression.

Second, we also did not compare pre-contrast 3D RAVE against MPRAGE as the former was not coupled in the current study to a magnetization preparation (i.e., inversion recovery) module and therefore lacked the desirable white-matter to gray-matter tissue contrast. In its current form, the RAVE gradient-echo sequence is not suitable for pre-contrast T1-weighted evaluation of brain morphometry. Inversion recovery radial gradient echo pulse sequences have been demonstrated in the past in cardiac imaging [26], and an application to brain imaging would have significantly strengthened the present study. We also feel it would add significant clinical value to pediatric MRI protocols and are pursuing pre-contrast inversion-recovery RAVE as a direction of future work. Consequently due to this limitation we could not easily blind the data during the evaluation process, as it was not difficult for each radiologist to identify MPRAGE from RAVE based on the underlying tissue gray-white matter signal contrast.

Third, although our sample size is relatively small, we do not anticipate an increase in sample size to significantly alter the study's findings. However, the overall rating categories used in this work were qualitative and subjective. In the current age range studied from newborn to 19 years, we did not notice any preference for RAVE for subset of patients based on age group. A future study targeting an age group where patient irritability, uncooperativeness, and motion are most likely to be encountered will be beneficial. Fourth, we did not utilize parallel imaging or compressed sensing acceleration with our existing implementation of RAVE. In this study, the RAVE sequence had a scan time that was approximately 10% shorter than that of the MPRAGE while providing similar spatial resolution and volumetric coverage. Integration of parallel imaging and compressed sensing with RAVE can potentially further shorten its scan time in comparison to MPRAGE, an avenue that can be pursued to additionally increase RAVE's robustness to motion in pediatric imaging. Data acceleration can also minimize the increase in scan time when RAVE is coupled to magnetization preparation. However, significant upgrades in computational hardware are needed to keep image reconstruction times down to clinically manageable times.

Fifth, we did not alter the order with which MPRAGE and RAVE was acquired after contrast administration in order to not interfere with clinical workflow. To preserve standard-of-care practice, we always implemented MPRAGE first. Randomizing the scan order could have potentially minimized bias in the study. It is plausible that the MPRAGE sequence may have been more susceptible to motion as a child may involuntarily shiver or shudder in response to the stimulus from the first-passage of the contrast agent. In the current study, there were no reports of patient discomfort from contrast agent administration or leakage at the site of injection. Lastly, one characteristic of RAVE that should be explored in brain imaging to further improve diagnostic image quality is to selectively exclude portions of the radial k-space during data acquisition that becomes corrupted by motion during the scan [27]. Subsequently, the scan continues until sufficiently valid and non-corrupted data is acquired for reconstruction.

5. Conclusions

In conclusion, RAVE has provided our neuroradiology practice with a more confident “first-time-right” post-contrast protocol with the potential to reduce the need for repeat scans. Our preliminary experience has demonstrated that the radial fat-suppressed T1-weighted 3D gradient-echo pulse sequence is adequate for clinical use, and that as an alternate to MPRAGE, it can yield diagnostically useful images with immunity to bulk motion, especially in pediatric patients who are uncooperative and where head motion is anticipated.

Conflict of interest declaration

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