Improving the Robustness of Clinical T1-Weighted MRI Using Radial VIBE

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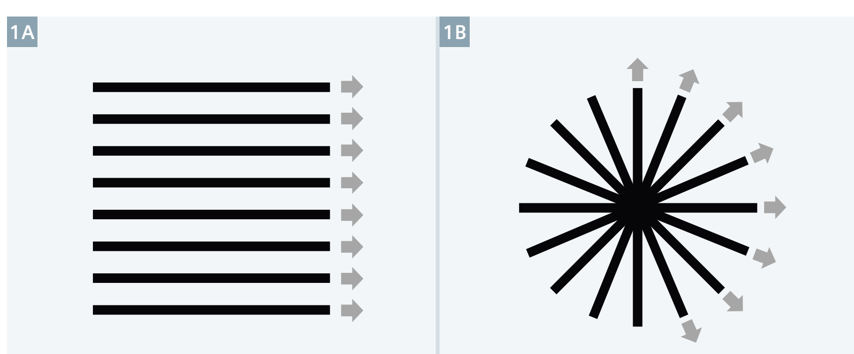
Introduction

Despite the tremendous developments that MR imaging has made over the last decades, one of the major limitations of conventional MRI is its pronounced sensitivity to motion, which requires strict immobility of the patient during the data acquisition. In clinical practice, however, suppression of motion is often not possible. As a consequence, MR images frequently show motion artifacts that appear as shifted object copies, which are well-known as 'ghosting' artifacts and which, depending on the artifact strength, can potentially obscure important diagnostic information. Ghosting artifacts pose a particular problem for abdominopelvic exams that need to be performed during suspended respiration. Because many patients struggle to adequately hold breath during the scan, the number of exams with suboptimal image quality is relatively high. This has impaired the acceptance of MRI as an imaging modality of choice in many abdominopelvic indications. Other widely utilized MRI applications such as head and neck imaging are also often affected by motion-induced ghosting artifacts, e.g., if patients are anxious, or if wthey cannot suppress swallowing or coughing during the exam.

Radial *k*-space acquisition scheme

The high sensitivity to motion results from the data-sampling strategy used in conventional MR imaging to spatially resolve the object. Conventional sequences acquire the data space (*k*-space) using a sampling scheme along parallel lines (Fig. 1A), which is usually referred to as 'Cartesian' sampling. The acquired parallel lines differ by a fixed difference in the signal phase, which is why the scheme is also called 'phase encoding' principle. However, if the object moves during the exam, phase offsets are created that disturb the phase-encoding scheme. In a simplified view, it can be thought of as jittering of the sampled lines, which causes gaps in the *k*-space coverage and results in aliasing artifacts along the phase-encoding direction from improper data sampling. Hence, the Cartesian geometry is inherently prone to motion-induced phase distortions. Even if navigation or triggering techniques are used to minimize phase inconsistencies within the acquired data, a certain amount of residual ghosting artifacts is almost always present.

The situation can be improved when changing the *k*-space acquisition to a different sampling geometry. One promising alternative is the 'radial' sampling scheme, which acquires the data along rotated spokes (Fig. 1B). Due to the overlap of the spokes in the center, gaps in the *k*-space coverage cannot occur if individual spokes are 'jittered' and, therefore, appearance of ghosting artifacts is not possible with this scheme. Furthermore, the overlap has a motion-averaging effect. Data inconsistencies can instead lead to 'streak' artifacts. However, in most cases the streaks have only a mild effect on the image quality, and they can easily be identified as artifacts due to their characteristic visual appearance (e.g., Fig. 3B). Because the artifacts appear mainly as 'texture' added to the underlying object, the likelihood that lesions get obscured is significantly lower than for the more dominant Cartesian ghosting artifacts.



1 **(1A)** Conventional 'Cartesian' MRI sampling scheme along parallel lines, and **(1B)** radial sampling scheme along rotated spokes that overlap in the center of *k*-space.

Interestingly, although the advantages for clinical applications seem clear and although the idea of radial sampling has been known since the early days of MRI, the technique has not been widely employed in clinical practice so far. Radial sampling was first described by Lauterbur in his seminal MRI paper from 1973 [1]. However, because practical implementation required coping with a number of technical complexities, it was soon replaced by the Cartesian acquisition scheme which could be more easily and more robustly implemented on early MRI systems. These technical complexities include a more sophisticated image reconstruction, higher required homogeneity of the magnetic field, and the need for much more accurate and precise generation of time-varying gradient fields. Consequently, radial sampling has only been used sporadically in research projects while clinically established techniques are currently almost exclusively based on the Cartesian scheme.

Over the last several years, however, it has become possible to resolve the majority of issues that prevented a practical application of radial sampling, in part through improvements of the MR hardware designs and in part through new algorithmic developments. Therefore, it is now for the first time feasible to utilize radial acquisitions routinely on unmodified clinical MRI systems, with sufficient reliability and robustness for clinical applications and with image quality comparable to that of the conventional Cartesian scans.

Radial VIBE sequence

The Radial VIBE sequence* is the first available works-in-progress sequence for Siemens MR systems that integrates these developments for volumetric acquisitions and provides radial *k*-space sampling in a fully seamless way, aiming at achieving higher robustness to motion and flow effects in daily practice. It is based on the conventional product VIBE sequence, which is an optimized T1-weighted 3D gradient echo sequence (3D FLASH) with various fat-saturation options. Radial sampling has been implemented using a 3D 'stack-of-stars' approach, which acquires the k_x-k_y plane along radial spokes and the k_z dimension

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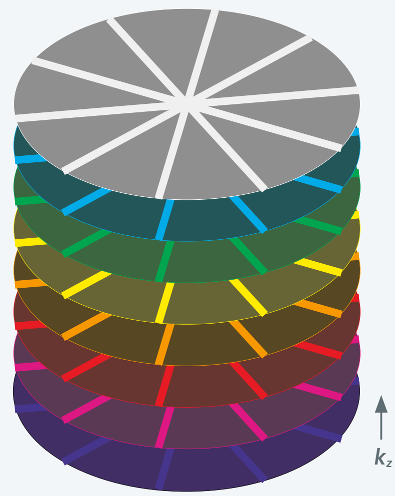

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Stack-of-stars trajectory as implemented by Radial VIBE, which employs radial *k*-space sampling in the k_x-k_y plane and Cartesian sampling along k_z.

with conventional sampling, resulting in cylindrical *k*-space coverage (see Fig. 2). This trajectory design enables use of time-efficient fat-saturation methods, such as Quick FatSat or SPAIR, with minimal artifact strength, which is important as radial scans should be performed with fat suppression for most applications. Although Cartesian acquisition steps are employed along the k_z dimension, a high degree of motion robustness is achieved due to the use of an incoherent temporal acquisition order. The Radial VIBE sequence can be used on the full range of Siemens MR systems, including systems from the B-line generation (e.g., MAGNETOM Avanto, Trio, Verio) and D-line generation (e.g., MAGNETOM Skyra, Aera), and it can also be used on the Biograph mMR MR-PET system as well as Siemens' 7T** systems. Because the sequence does not require any modification of the MR hardware or reconstruction system, it can be deployed to installed systems and used clinically for fat-saturated T1-weighted exams as a motion-robust alternative to 3D GRE, VIBE, MPRAGE, or 2D TSE sequences.

* Radial VIBE is a prototype for StarVIBE. StarVIBE is now 510k released and is available for 1.5T MAGNETOM Aera and 3T MAGNETOM Skyra. Radial VIBE is work in progress.

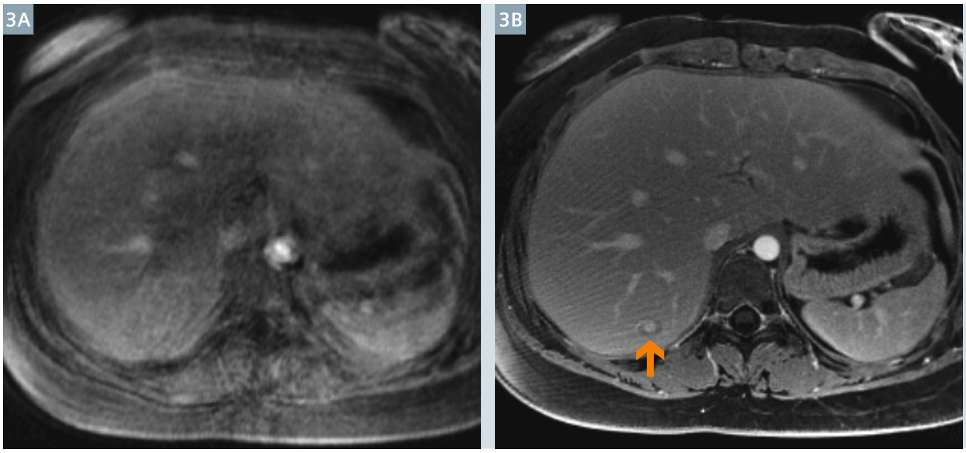
** The product is under development and not commercially available yet. Its future availability cannot be ensured. This research system is not cleared, approved or licensed in any jurisdiction for patient examinations. This research system is not labelled according to applicable medical device law and therefore may only be used for volunteer or patient examinations in the context of clinical studies according to applicable law.

Clinical applications and results

Over the last two years, the sequence has been tested extensively at NYU Langone Medical Center to evaluate the achievable image quality across various MR systems in daily routine applications. Radial VIBE scans were added to clinical protocols under IRB approval in more than 5000 patient exams and compared to established reference protocols. Several clinical studies have been performed or are ongoing that investigate the improvement in diagnostic accuracy resulting from the absence of ghosting artifacts.

Free-breathing abdominal imaging

A key application of the Radial VIBE sequence is imaging of the abdomen and/or pelvis before and after injection of a contrast medium, which is conventionally performed during suspended respiration. With Radial VIBE, it is possible to acquire the data during continued shallow breathing, which therefore can be the preferred exam strategy for patients who are unable to sustain the normally



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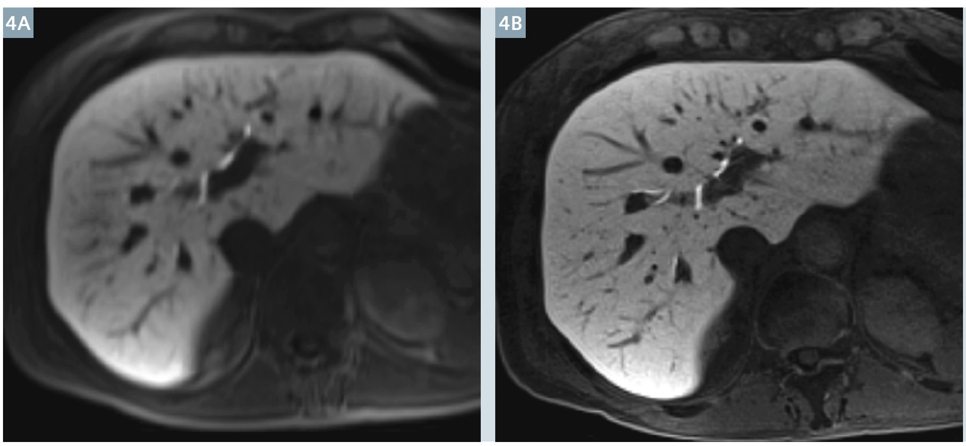
(3A) Conventional VIBE exam of a patient failing to hold breath during the acquisition and **(3B)** Radial VIBE acquisition during free breathing. Radial VIBE provides significantly higher image quality and reveals a lesion in the liver (arrow) not seen on the conventional scan



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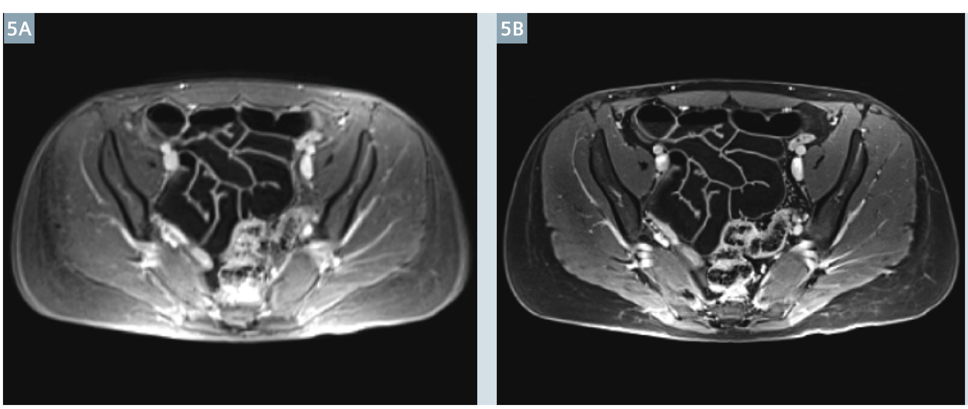
(4A) Conventional breath-hold VIBE exam of a patient 20 min after injection of Gadoxetate Disodium. **(4B)** Because Radial VIBE exams can be performed during continued respiration, data can be acquired over longer time, resulting in clearly improved resolution (here 1.0 mm isotropic).



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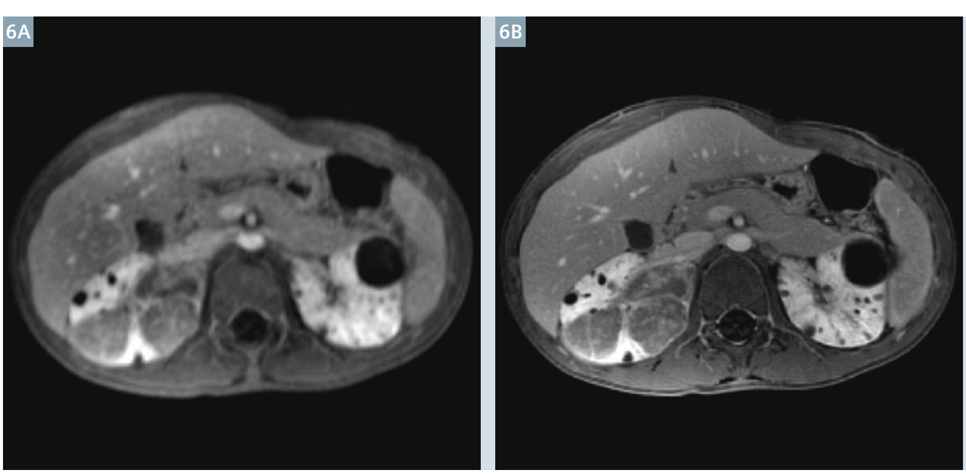
MR enterography using **(5A)** conventional VIBE and **(5B)** Radial VIBE acquisition. The higher motion robustness achieved with Radial VIBE leads to sharper images and improved resolution.



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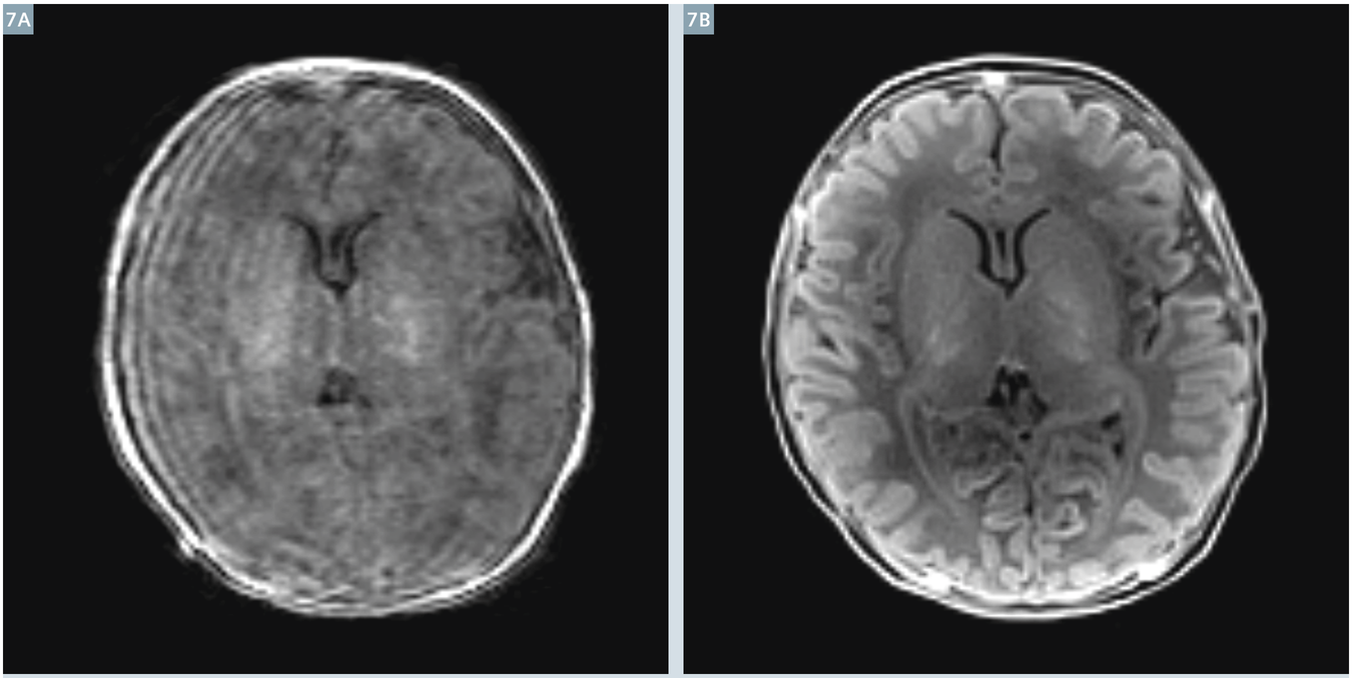
Abdominopelvic exam of a sedated pediatric patient with Tuberous Sclerosis. **(6A)** Because suspending respiration is not possible under deep sedation, conventional exams are affected by respiration artifacts. **(6B)** Radial VIBE provides significantly sharper images with improved spatial resolution, as visible from the small cysts in the kidneys.



7 Brain exam of a 4-day-old* patient using **(7A)** conventional MPRAGE and **(7B)** Radial VIBE sequence. Due to vigorous patient activity, the MPRAGE scan is affected by strong ghosting artifacts, while Radial VIBE provides diagnostic image quality.

*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.

required breath-hold time, such as elderly or severely sick patients. A blinded-reader study by Chandarana et al. demonstrated that the average image quality obtained with free-breathing radial acquisition is comparable to conventional breath-hold exams and significantly better than free-breathing exams with Cartesian acquisition [2]. As an example, figure 3 compares a free-breathing Radial VIBE exam to a conventional Cartesian exam of a patient with insufficient breath-hold capability. The Radial VIBE image is affected by a certain amount of streak artifacts but clearly depicts a lesion in the right lobe of the liver, which is fully obscured in the Cartesian scan.

High-resolution abdominopelvic imaging

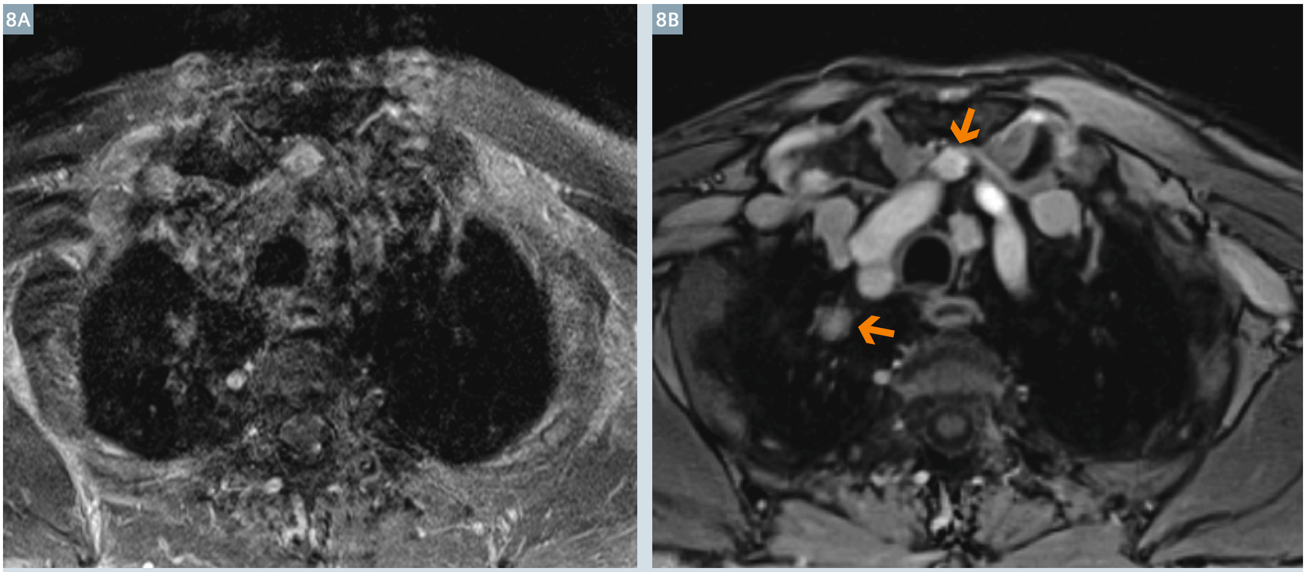
The ability to acquire data during continued respiration also has advantages for the examination of patients with proper breath-hold capacity. With conventional Cartesian sequences, the achievable spatial resolution in abdominopelvic exams is limited by the amount of *k*-space data obtainable within typical breath-hold durations of less than 20 sec. Because Radial VIBE eliminates the need for breath holding, it is possible to sample data over several minutes and, thus, to increase the spatial resolution by a significant factor. Figure 4 demonstrates this possibility for an isotropic 1 mm high-resolution scan of the liver 20 min after injection of Gadoxetate Disodium, which provides clearly sharper visualization of the biliary duct compared to the corresponding Cartesian protocol. In figure 5, the achievable resolution improvement is shown for the case of MR enterography, which is another good candidate for Radial VIBE due to the higher overall robustness to the bowel motion.

Pediatric imaging

During the clinical evaluation phase, Radial VIBE demonstrated particular value for the application in pediatric* patients. Pediatric exams are often conducted under general anesthesia or deep sedation, which makes active breath holding impossible. Therefore, conventional abdominopelvic scans are in most cases affected by respiration artifacts that impair the achievable effective resolution and diagnostic accuracy. Due to the inherent motion robustness, much sharper and crisper images are obtained with Radial VIBE, as evident from the depiction of small cysts in the kidneys of a patient with Tuberous Sclerosis shown in figure 6. A retrospective blinded-reader study of our case collection revealed that 8% of all lesions were only identified with Radial VIBE but missed in the corresponding Cartesian reference exams [3].

In young neonatal patients, sedation is usually avoided due to the higher risk of potential adverse effects. Imaging these patients is challenging because they often move spontaneously in the scanner. Also in this patient cohort Radial VIBE provides improved image quality and reliability, which is demonstrated in figure 7 for a brain exam of a 4-day-old patient, in this case compared to a Cartesian MPRAGE protocol.

*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.



8 Examination of the neck and upper chest using **(8A)** a conventional 2D TSE sequence and **(8B)** Radial VIBE. Because of the respiration and strong blood flow, the TSE scan shows drastic artifacts. Two suspicious lesions are more clearly visible on the Radial VIBE exam (arrows).

Imaging of the neck and upper chest

Although imaging of the head and neck region appears less critical at first glance, severe motion-related artifacts occur quite often in routine exams. Conventional neck protocols usually include slice-selective T1-weighted TSE sequences, which are especially sensitive to motion and flow. If patients are unable to suppress swallowing or coughing during the acquisition, images are rendered non-diagnostic. Furthermore, adequate examination of the upper chest region is often not possible because of drastic artifacts from respiration and strong blood flow in the proximity of the heart. Radial VIBE exams are a promising alternative for this application and are largely unaffected by swallowing, minor head movements, or flow, which is illustrated in figure 8. The sequence also maintains a convincing sensitivity to chest lesions in the presence of respiratory motion [4]. Because Radial VIBE scans are immune to ghosting artifacts, exams can be performed with high isotropic spatial resolution, which allows for retrospective reconstruction in multiple planes (MPRs). In this way, it is possible to substitute multiple conventional slice-selective protocols in varying orientation with a single Radial VIBE high-resolution scan. A representative example is shown in figure 9.

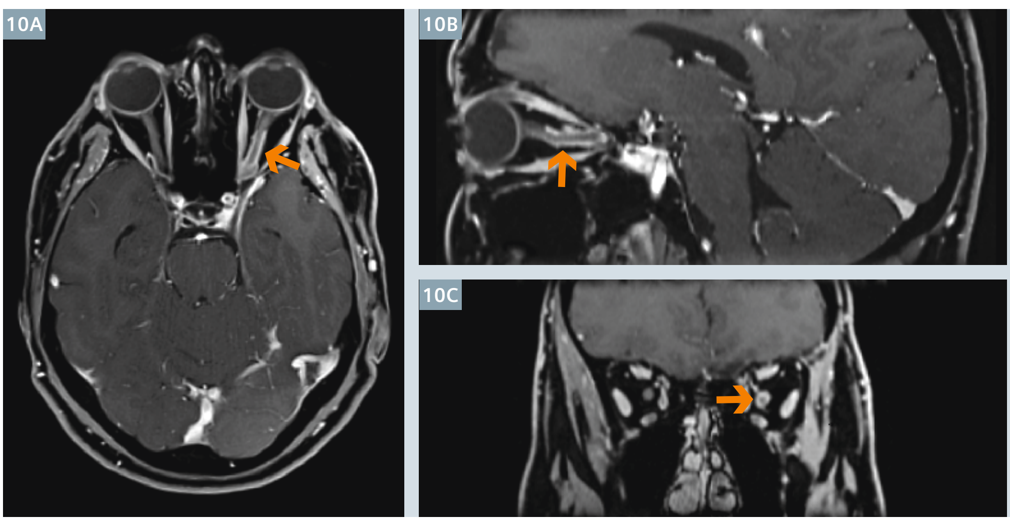
Imaging of the orbits, inner auditory canal, and full brain

Finally, the sequence also offers improved sharpness and clarity for the examination of the orbits. When patients move the eyes or change the position of the eyelids during the exam, conventional protocols show a band of strong ghosting artifacts along the phase-encoding direction, which can make identifying pathologies a difficult task. Radial VIBE provides cleaner depiction of the optic nerves and improved suppression of intra- and extraconal fat [5]. Flow effects from surrounding larger blood vessels can lead to mild streak patterns but are less prominent than for most Cartesian protocols and can be additionally attenuated with the use of parallel saturation bands. The possibility to create high-resolution MPRs is another advantage of using Radial VIBE for this application, which is demonstrated in figure 10 for a patient with optic nerve sheath meningioma. In a similar way, the sequence can be applied for examinations of the inner auditory canal (IAC) or the full brain, in which a particularly high sharpness of vessel structures is achieved.

Conclusion

The large number of successful patient exams of various body parts conducted with Radial VIBE over the last two years demonstrates that radial sampling is now robust and reliable for routine use on standard clinical MR systems. Due to the higher resistance to patient motion and the absence of ghosting artifacts, improved image quality can be obtained in applications where motion-induced image artifacts are a common problem. In particular, the Radial VIBE sequence enables exams of the abdomen and upper chest during continued shallow respiration, which can be a significant advantage for patients that struggle to adequately hold breath. Furthermore, the sequence enables reconfiguring exam protocols towards higher spatial resolution and allows consolidating redundant acquisitions into MPR-capable isotropic scans. Because the sequence works robustly on existing MRI hardware, Radial VIBE has the potential to find broad application as motion-robust T1-weighted sequence alternative and will complement the spectrum of clinically established imaging protocols.

9 Neck exam using transversal Radial VIBE acquisition with 1 mm isotropic resolution. Due to the robustness to swallowing and minor head motion, high quality 3D scans are possible that can be reconstructed in multiple planes (MPR). This enables consolidating redundant 2D protocols with varying scan orientation.



10 Multiplanar reconstructions of a transversal Radial VIBE exam with 0.8 mm resolution. The sequence achieves good fat suppression and provides sharp depiction of the optic nerves without artifacts from eye motion. An abnormal contrast enhancement of the left optic nerve is clearly visible (arrows), which is indicative of an optic nerve sheath meningioma.

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