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Reducing sedation for pediatric body MRI using accelerated and abbreviated imaging protocols

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Abstract Magnetic resonance imaging (MRI) is an established diagnostic imaging tool for investigating pediatric disease. MRI allows assessment of structure, function, and morphology in cardiovascular imaging, as well as tissue characterization in body imaging, without the use of ionizing radiation. For MRI in children, sedation and general anesthesia (GA) are often utilized to suppress patient motion, which can otherwise compromise image quality and diagnostic efficacy. However, evidence is emerging that use of sedation and GA in children might have long-term neurocognitive side effects, in addition to the short-term procedure-related risks. These concerns make risk–benefit assessment of sedation and GA more challenging. Therefore, reducing or eliminating the need for sedation and GA is an important goal of imaging innovation and research in pediatric MRI. In this review, the authors focus on technical and clinical approaches to reducing and eliminating the use of sedation in the pediatric population based on image acquisition acceleration and imaging protocols abbreviation. This paper covers important physiological and technical considerations for pediatric body MR imaging and discusses MRI techniques that offer the potential of recovering diagnostic-quality images from accelerated scans. In this review, the authors also introduce the concept of reporting elements for important indications for pediatric body MRI and use this as a basis for abbreviating the MR protocols. By employing appropriate accelerated and abbreviated approaches based on an understanding of the imaging needs and reporting elements for a given clinical indication, it is possible to reduce sedation and GA for pediatric chest, cardiovascular and abdominal MRI.

Keywords Body · Cardiovascular · Children · Compressed sensing · General anesthesia · Magnetic resonance imaging · Sedation

Introduction

Procedural sedation and general anesthesia (GA) are defined as the administration of sedative or dissociative agents, with or without analgesics, to induce a state that allows the child to tolerate unpleasant procedures while maintaining cardiorespiratory function. As a result of advances in development of MR-based imaging biomarkers and their expanding role in the diagnosis of various pediatric diseases, deep sedation or general endotracheal anesthesia for MR imaging in children is requested with increasing frequency. Infants and young children frequently have difficulty remaining still for the duration of the examination, leading to poor study quality and increasing the likelihood of diagnostic errors. Sedation is associated with a lower likelihood of diagnostic errors, fewer image-quality concerns and fewer incomplete reports [1]. Protocols for sedation are varied and depend on practice location and expertise of the practitioner. Chloral hydrate, pentobarbital and midazolam are effective for CT but are unfavorable for MRI sedation because they have no predictable onset, duration and reversal of sedative effects. Dexmedetomidine has been used for sedation in patients without cardiovascular risk factors and might have an

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improved safety profile when compared to opioid agents, but it is lighter and shorter-acting, which can lead to a higher rate of unsuccessful studies. Propofol is widely used for intravenous sedation for MRI because the duration of sedation can be titrated easily and its effects can be reversed promptly, but it can only be administered in the presence of anesthesiologists or pediatric intensivists because of the need for respiratory and cardiovascular support. Compared to sedation, GA is preferred in preterm or at-risk children because its safety and success are predictable, and GA is also often preferred for post-contrast imaging with breath-holds. Sedation is widely employed across the entire spectrum of MR imaging studies. In a recent unpublished survey of pediatric hospitals conducted by the pediatric committee of the Society of Cardiovascular Magnetic Resonance, 64% of children younger than 8 years needing cardiac MRI underwent GA, 23% underwent intravenous sedation, and only 13% had no sedation.

Risks associated with procedural sedation in children

Although sedation has a very favorable benefit–risk ratio in most children, it is not without risks, especially in small children with severe diseases and significant disabilities. The presence of an upper respiratory tract infection, a history of obstructive sleep apnea/snoring, obesity and older age are associated with increased probability of failed sedation [2]. Respiratory, cardiovascular and other events occurred at a rate of 534 per 10,000 anesthetic procedures using propofol, but without any long-lasting morbidity or mortality. The American Society of Anesthesiologists classification, anesthetic effect duration, and presence of airway abnormalities are independently associated with adverse events during anesthetic use. The risk of hypoxia is as high as 11% in children sedated with oral chloral hydrate and 17% in children sedated with intravenous pentobarbital [3]. Following sedation, delayed complications include prolonged drowsiness, paradoxical hyper-stimulation, gastrointestinal upset and motor imbalance. An increasing concern is the potential risk of neurotoxicity related to GA. For example, a recent study found that there was impairment of memory and recollection later in life in children who underwent GA in infancy, an effect that was independent of underlying disease or tissue injury [4]. Another recent study found an increased risk of being subsequently diagnosed with developmental and behavioral disorders in children who were enrolled in a state Medicaid program and who had surgery when they were younger than 3 years; their risk was 60% greater than that of a similar group of siblings who did not undergo surgery [5]. The debate surrounding the long-term neurological and cognitive side effects of sedation, however, is not settled. For example, in a prospective study by Davidson et al. [6], no cognitive impairment was observed in the GA group compared to the control group. Although additional studies are required to demonstrate a cause-and-effect relationship between the use of sedation in children and long-term cognitive dysfunction, it is prudent to keep the potential of long-term neurological and cognitive side effects in consideration.

Approaches to reducing sedation for pediatric MRI

The broad approaches to reducing the use of sedation and GA for diagnostic imaging in children were recently listed in a white paper on P4 (predictive, personalized, preventative, participatory) concepts of pediatric imaging research [7]:

1. Improve patient safety during sedation by innovations in transport, monitoring and use of non-neurotoxic medications.
2. Institute national evidence-based expert guidelines regulating use of sedation and anesthesia for diagnostic imaging in children.
3. Use distraction, noise-reduction and feed-and-wrap techniques to avoid sedation for short MRI and CT studies in small children.
4. Avoid general endotracheal anesthesia by converting protocols to sedated free-breathing acquisitions.
5. Develop advanced motion compensation and correction schemes for respiratory and cardiac motion, as well as gross patient motion.
6. Achieve protocol brevity by use of acceleration techniques that allow image recovery from partially filled k-space.
7. Achieve protocol brevity by use of a few targeted sequences that are proven to change management and influence outcomes.
8. Use of alternatives to MRI, such as ultrasound or non-sedated and free-breathing CT.

Modifying the choice of anesthetic agents in children and the use of distraction, noise-reduction and feed-and-wrap techniques for avoiding or reducing the need for sedation are powerful tools in the appropriate patient population and can be used in isolation or in conjunction with other approaches. This article focuses on achieving protocol brevity by use of newly developed acceleration techniques that significantly reduce scan time and the conversion of breath-held protocols to free-breathing acquisitions using motion-compensation schemes.

Technical and physiological considerations for accelerating MR image acquisition in children

MRI can noninvasively interrogate anatomy and function of different tissues or systems by employing pulse sequences, which are synchronized and precisely timed applications of radiofrequency pulses and gradient waveforms. Like its

application in the adult population, MRI in the pediatric population routinely includes traditional gradient and spin-echo pulse sequences to provide common tissue-contrast weighting (e.g., T1, T2, phase-contrast and diffusion). However, image acquisition in the pediatric population has additional considerations that become important when choosing acceleration techniques:

1. Higher heart rates in the pediatric population require higher temporal resolution. Likewise smaller anatomical features in the pediatric population demand higher spatial resolution. Although it is possible to use fixed spatial and temporal resolutions that are adequate across different sizes and heart rates, such a strategy unnecessarily prolongs the acquisition process for subjects who can be imaged at lower spatial or temporal resolutions. To reduce scan time, therefore, it is important to account for the large variations in body habitus and hemodynamics by employing MRI protocols that are optimized individually for each subject.
2. In addition to protocol optimization, appropriate phased-array coil selection is also important for imaging children. Many vendors only offer coil arrays designed for adults or offer a single choice of an integrated coil array for pediatric imaging, which may become suboptimal across different patient sizes, especially in neonates and infants. To fulfill various pediatric imaging needs, it is therefore a common practice to acquire coil arrays manufactured by third parties. Recently developed semi-flexible coils that seamlessly combine with the integrated coil arrays can provide more consistent performance across patient sizes [8].
3. Traditional gradient and spin-echo pulse sequences can be implemented in both 2-D multislice and 3-D modes. For 2-D imaging the slices are acquired sequentially, with each slice excited individually. Although the time needed to acquire each slice is very short, the total time to collect a stack of 2-D slices with isotropic resolution can be prohibitively long. Therefore it is a common practice to specify a non-zero spatial gap between adjacent slices and use anisotropic resolution where the through-plane resolution is worse than the in-plane resolution. Anisotropic voxels are undesirable in certain clinical circumstances, e.g., in children with congenital heart disease, where reformatting in different planes is required for visualization. In contrast, with 3-D MRI the entire volume is excited by a radiofrequency pulse and encoded using gradient combinations. Some of the benefits of 3-D imaging include: (a) Superior signal-to-noise ratio (SNR), (b) superior (and in some cases isotropic) through-plane resolution, (c) contiguous coverage without gaps, (d) shorter acquisition time compared to 2-D multislice imaging and (e) potential to achieve high acceleration with the high SNR and richer data structure. However 3-D techniques cannot match the in-plane resolution of 2-D techniques without prolonging the acquisition time. Also, 3-D techniques might suffer from loss of contrast-to-noise (CNR) ratio and can be more sensitive to motion. For instance, physiological motion (e.g., respiratory) typically impacts the entire volume being imaged. In contrast, artifacts from motion that occur during 2-D multislice imaging are generally restricted to only one or a few slices. Thus subject motion and related image artifacts are less of a concern in 2-D multislice methods.
4. In non-sedated patients, breath-held MRI acquisitions are often difficult to obtain in young children. In older children who understand breath-holding instructions, compliance and overall consistency can still be poor. Free-breathing acquisitions, along with prospective and retrospective cardiac gating techniques, are more favorable in pediatric patients and offer better inter-slice alignment.

Achieving protocol brevity by accelerating MRI data acquisition

Magnetic resonance imaging data acquisition takes place in the spatial frequency domain, called k-space. Conventional MRI relies on sequential coverage of Cartesian k-space, leading to poor data acquisition efficiency and long acquisition times. For imaging pediatric patients, long acquisition times equate to extended sedation. Here, we discuss some of the recent techniques developed to accelerate the MRI acquisition process for body imaging, including parallel imaging, partial Fourier, k-t acceleration, compressed sensing, non-Cartesian acquisition and simultaneous multislice acquisition. This section is not written to fully describe the underlying technical concepts of these techniques; it is a superficial overview that provides a high-level description of the available acceleration techniques. Table 1 summarizes the availability of these acceleration techniques on commercial platforms.

Parallel MRI

Parallel MRI is based on acquiring and processing data from multiple channels of a phased-array coil. Parallel MRI allows image recovery from undersampled k-space (depicted in Fig. 1) and thus can accelerate the acquisition process and is now a standard feature on all modern clinical scanners. Both GRAPPA (generalized autocalibrating partial parallel acquisition) [9] and SENSE (sensitivity encoding) [10] are well-established parallel imaging methods and are routinely used clinically to recover images from the undersampled data. SENSE operates in the image domain and provides an optimal (maximum likelihood) or near-optimal reconstruction when the

Table 1 Acceleration techniques and their availability on commercial platforms

Acceleration technique	Commercial availability	Notes
Parallel MRI	Siemens (GRAPPA, mSENSE), GE (ARC, ASSET), Philips (SENSE), Toshiba (SPEEDER), Hitachi (RAPID)	All major vendors provide SENSE-based, GRAPPA-based, or both reconstruction techniques
k-t SENSE/k-t GRAPPA	Philips (k-t SENSE)	
Keyhole	Siemens (TWIST), GE (TRICKS), Philips (4D–TRAK), Hitachi (TRAQ), and Toshiba (FREEZE FRAME)	Keyhole techniques are commonly used for time-resolved MR angiography
Radial sampling	Siemens (2-D Radial and StarVIBE), Philips	Typically employed in abdominal T1w scans
Spiral sampling	GE	Typically employed in 3D arterial spin labeling and cardiac scans
Compressed sensing	Siemens, GE (HyperSENSE)	
Prospective respiratory gating	All major vendors	
Respiratory compensation	GE (Respiratory Comp), Philips (PEAR), Toshiba (Respiratory Comp), Hitachi (PERRM)	
Respiratory motion-resolved imaging	Not offered	CS-based XD-GRASP is under active development by Siemens
Simultaneous multi-slice imaging	Siemens (CAIPIRINHA, SMS), GE (POMP, HyperBand), Philips (Multi-band), Hitachi (Dual-slice), Toshiba (QuadScan)	Most of these sequences are developed for brain imaging but are being adapted for other applications

ARC autocalibrating reconstruction for Cartesian imaging, *ASSET* array coil spatial sensitivity encoding technique, *CAIPIRINHA* controlled aliasing in parallel imaging results in higher acceleration, *GRAPPA* generalized autocalibrating partial parallel acquisition, *k-t* k-space domain and time domain, *mSENSE* modified sensitivity encoding, *PEAR* phase-encoded artifact reduction, *PERRM* phase-encode reordering to reduce motion, *POMP* phase-offset multi-planar, *RAPID* rapid acquisition through parallel imaging design, *SENSE* sensitivity encoding, *SMS* simultaneous multi-slice, *SPEEDER* Toshiba's parallel imaging technology, *TRAK* time-resolved angiography using keyhole, *TRAQ* time-resolved acquisition, *TRICKS* time-resolved imaging of contrast kinetics, *TWIST* time-resolved angiography with stochastic trajectories, *VIBE* volumetric interpolated breath-hold examination, *XD-GRASP* extra dimension golden-angle radial sparse parallel

coil sensitivity maps are accurately known. The fast computational speed of SENSE makes it is an attractive option for advanced iterative image-reconstruction methods. GRAPPA operates in the k-space domain and offers advantages in terms of its higher tolerance of reduced field of view (FOV), regions with low spin density, and subject motion [11]. Parallel MRI typically provides 2- to 3-fold acceleration, with higher acceleration rates leading to unacceptable noise amplification. Recently developed coils with high channel count or with semi-flexible design offer the promise of further acceleration using parallel MRI, with consistent performance across different patient sizes [8], but this is yet to be demonstrated in children.

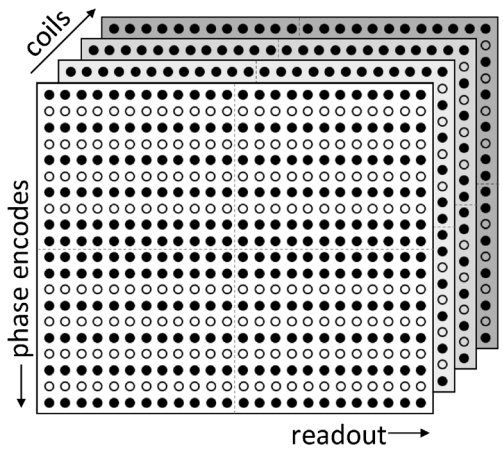

Fig. 1 Depiction of data sampling for parallel MRI. The filled circles represent acquired data while unfilled circles represent unacquired or missing data. The unacquired data are recovered by exploiting redundancy across coils

Partial Fourier

Partial Fourier is a commonly used strategy to accelerate data acquisition for MRI [12]. In partial Fourier imaging, the k-space is not fully sampled and a contiguous fraction of k-space is not acquired. Image recovery from partial Fourier data relies on exploiting conjugate symmetry of k-space (for real-valued images) or slowly varying phase (for complex-valued images). Because image phase for most MRI applications is not strictly slowly varying, partial Fourier can result in visible image degradation, especially when a significant fraction of k-space is not acquired. Partial Fourier can be performed either by reducing the number of phase encodes (Ny) or by enforcing partial (asymmetrical) echo readout (Fig. 2). The acquisition time is proportional to Ny, so reducing Ny can result in significant time reductions. In contrast, partial echo readout reduces the acquisition time by minimizing echo time (TE) and repetition time (TR). Because the TE/TR has a weak dependence on the readout duration (the data sampling

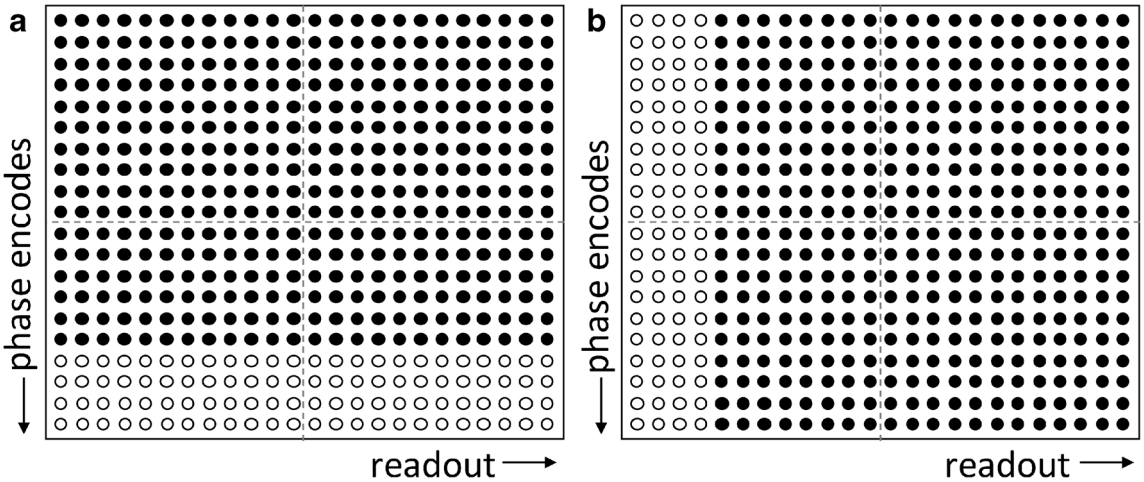

Fig. 2 Partial Fourier performed in the phase-encoding direction (**a**) and in the readout direction (**b**). The filled circles represent acquired data while unfilled circles represent unacquired or missing data

duration in each TR), the time savings provided by this strategy are typically modest. However reducing TE via partial echo readout can have advantages beyond acceleration. For example, reducing TE for phase-contrast MRI can reduce signal loss caused by turbulent flow [13]. Partial Fourier can also be used in conjunction with parallel MRI [14].

K-space and temporal dimension (k-t) acceleration

For dynamic applications, the MRI data are collected in the k-t domain, which is the union of k-space and the temporal dimension. The basic concept behind k-t methods is that the additional correlations along the temporal dimension can be exploited to enable image recovery at high acceleration rates. Compared to parallel MRI methods (e.g., SENSE or GRAPPA) that do not utilize temporal correlations and process each frame separately, the k-t methods leverage redundancies in both coil and temporal dimensions to achieve higher acceleration rates. However k-t methods exhibit temporal blurring, which gets progressively worse with the acceleration rate. Under the umbrella of k-t, a number of acceleration techniques have been developed. For example, for image-based recovery TSENSE (temporal SENSE) [15], k-t BLAST (broad-use linear acquisition speed-up technique)/SENSE [16] and k-t PCA (phase-contrast angiography) [17] have been proposed; for k-space-based recovery TGRAPPA (temporal GRAPPA) [18], k-t GRAPPA [19] and parallel MRI with extended and averaged GRAPPA kernels (PEAK-GRAPPA) [20] have been proposed. A number of view-sharing methods, which also qualify as k-t methods, have also been proposed, including keyhole [21], TWIST (time-resolved angiography with stochastic trajectories) [22] and TRICKS (time-resolved imaging of contrast kinetics) [23]. Some of the commonly used k-t methods are summarized in Table 2. These techniques are widely used in current pediatric applications to achieve time-resolved angiography at high heart rates commonly encountered in children but have not been exploited to reduce sedation rates. They have been used mostly as backup to conventional breath-held, rather than as free-standing angiographic acquisitions. This is mainly because of the lack of robust k-t-based free-breathing techniques that preserve spatial resolution and reduce temporal blurring for pediatric angiographic applications. The advent of compressed sensing techniques might offer a viable alternative to this clinical challenge.

Compressed sensing

Compressed sensing exploits image structure — in the form of sparsity — to facilitate recovery from highly undersampled data [24]. In the case of contrast-enhanced MR angiography, the underlying images are naturally sparse, i.e., a significant number of pixels or voxels have near-zero intensity coupled with a small number of pixels with high intensity from contrast-enhanced vasculature. For other applications where images are not naturally sparse, the sparsity is exposed by applying a sparsifying transform. Typically the application of compressed sensing for imaging has three major steps: (1) the image structure is exposed by applying a sparsifying transform under which most coefficients are zero or nearly zero, (2) random or pseudo-random undersampling is employed and (3) the image is recovered from the undersampled data by an iterative nonlinear method that enforces both data consistency and sparsity. The basic concept of compressed sensing is represented in Fig. 3. Compared to k-t methods, compressed sensing methods generate images with less temporal blurring and with suppressed undersampling

Table 2 Acceleration techniques that exploit redundancies across time

SENSE-based	TSENSE • It is similar to SENSE but uses fully sampled, time-averaged data to estimate coil sensitivity maps. • TSENSE eliminates the need for a separate calibration scan or fully sampled k-space center for each frame.	k-t BLAST/SENSE • It relies on the compact support in the x-f domain (x: space, f: temporal frequency). • It learns the distribution of the signal in the x-f domain using training data and then exploits this information to "unfold" the undersampled image.	k-t PCA • It is similar to k-t BLAST/SENSE but further improves the image quality by incorporating constraints on the temporal frequency at each pixel.
GRAPPA-based	TGRAPPA • It is similar to GRAPPA but uses fully sampled, time-averaged data to estimate GRAPPA kernels • TGRAPPA eliminates the need for a separate calibration scan or fully sampled k-space center for each frame.	k-t GRAPPA: • This extension of GRAPPA recovers missing k-space samples by performing interpolation in the k-t domain. • In contrast, GRAPPA does not utilize temporal dimension to perform interpolation.	PEAK-GRAPPA • It is similar to k-t GRAPPA but employs sampling in the k-t domain that is more uniformly distributed to support a stable interpolation.
View sharing	Keyhole • This technique was developed in 1990s and relies on explicitly sharing the outer parts of k-space across frames. • Only the central portion of the k-space is updated for each frame, leading to higher temporal resolution.	TWIST/TRICKS • TWIST and TRICKS divide the k-space into two or more concentric regions and sample these regions alternatively from frame to frame. • Images are recovered by data sharing across neighboring frames along with the application of SENSE/GRAPPA.	

These methods range from explicit data-sharing across frames (view sharing) to exploitation of temporal correlations using k-t methods

BLAST broad-use linear acquisition speed-up technique, *GRAPPA* generalized autocalibrating partial parallel acquisition, *k-t* k-space domain and time domain, *PCA* principal component analysis, *PEAK-GRAPPA* parallel MRI with extended and averaged GRAPPA kernels, *SENSE* sensitivity encoding, *TGRAPPA* temporal generalized autocalibrating partial parallel acquisition, *TRICKS* time-resolved imaging of contrast kinetics, *TSENSE* temporal sensitivity encoding, *TWIST* time-resolved angiography with stochastic trajectories

artifact. Dynamic applications can preferentially benefit from compressed sensing methods because of their ability in exploiting the rich spatial-temporal structure [25]. For dynamic applications, many compressed sensing methods carry the k-t prefix with their names but are distinct from the k-t methods mentioned in the previous section. Several compressed sensing methods have been proposed and applied to a wide range of MRI applications, including cardiovascular and abdominal imaging in pediatric patients (Fig. 4) [26, 27]. At high acceleration rates, compressed sensing reconstruction can lead to images that lack details and appear overly smooth. The clinical application of compressed sensing is challenged by long computational times and the potential need to manually tune parameters (e.g.,

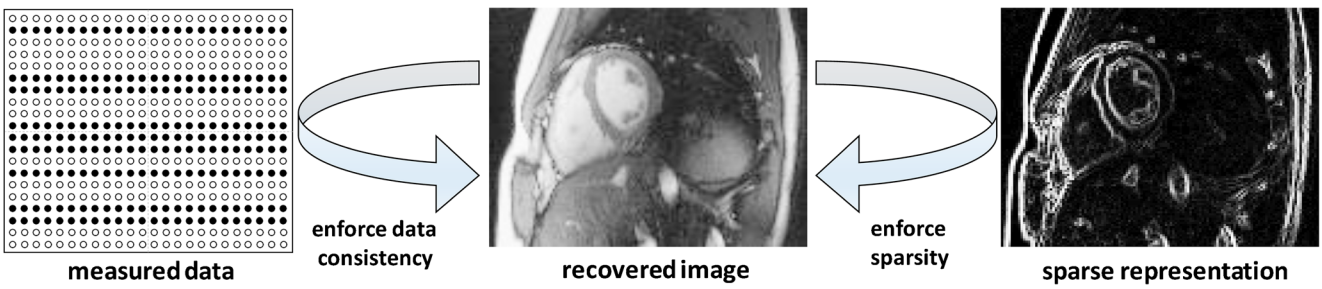

Fig. 3 Depiction of a typical compressed sensing method employed for MRI recovery. Under this approach, the image is iteratively recovered by enforcing both data consistency and sparsity constraints. Because most images are not sparse in their ambient domain, a sparsifying transform, e.g., total variation (shown on the right) or wavelet transform (not shown) is employed. The undersampling pattern (shown on the left) for compressed sensing method is preferred to be non-uniform

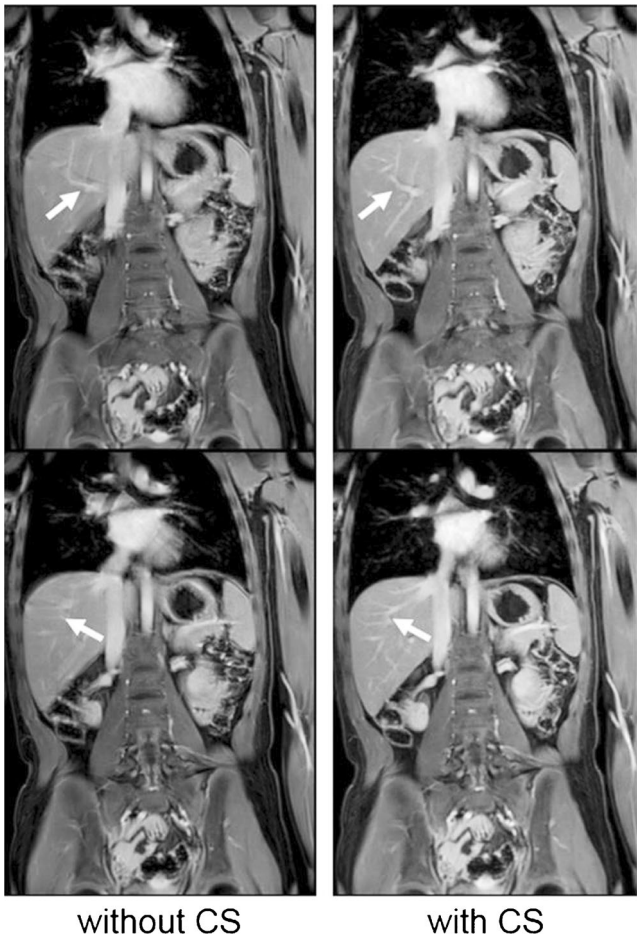

Fig. 4 Two representative coronal slices from a post-gadolinium T1-weighted fat-suppressed gradient echo acquisitions acquired at 3 T. The subject (a 12-year-old boy) was instructed to hold his breath during both acquisitions. Without compressed sensing (CS) the acquisition required 25 s (*left*). With compressed sensing the acquisition was shortened by 40%, requiring only 15 s (*right*). As a result of the shorter breath-hold, respiratory motion was minimized and hepatic vessels in particular are better visualized (*arrows*)

regularization weights). With recent advances in fast algorithms and parallel computing, compressed sensing is poised for routine clinical use in the next few years.

Non-Cartesian acquisition

For non-Cartesian trajectories, e.g., radial or spiral, the acquired samples are not restricted to a Cartesian grid. Such trajectories can reduce the acquisition time by enabling more efficient coverage of k-space. Because of their frequent sampling of the k-space center, such trajectories are not only more robust to motion artifacts but are also conducive to image-based respiratory gating (self-gating) [28]. Non-Cartesian trajectories can also be coupled with parallel MRI to further accelerate the acquisition process [29]. In addition, non-Cartesian sampling methods allow greater flexibility in designing incoherent sampling patterns and thus are well-suited for compressed sensing-based reconstruction [30]. Despite its promise, the use of non-Cartesian acquisition has been mostly limited to research settings. This is because most clinical scanners rely exclusively on Cartesian acquisitions for their ease of recovery, higher tolerance to system imperfections and off-resonance effects, and an extensive record of success. However, recent advances in the fields of parallel computing and fast-recovery algorithms promise to make non-Cartesian acquisition more competitive.

Simultaneous multislice imaging

Simultaneous multi-slice imaging allows simultaneous excitation and acquisition of multiple slices, improving the SNR and reducing acquisition time [31]. Because the superimposed slices belong to different spatial locations and are modulated by different coil sensitivity maps, they can be separated using SENSE- or GRAPPA-type techniques. By applying a slice-specific phase gradient in k-space, the superimposed slices can be shifted with respect to one another to further improve the separation process [32]. The concept of simultaneous multi-slice is illustrated in Fig. 5. Simultaneous multi-slice can be used for any arbitrary orientation of the imaging plane and can also be combined with radial sampling. Combination of simultaneous multi-slice and in-plane parallel MRI can potentially yield more acceleration than provided by each technique individually. Simultaneous multi-slice can be viewed as an intermediate between 2-D and 3-D imaging and can be applied to accelerate a wide range of MRI applications. For certain applications, the benefit of simultaneous multi-slice goes beyond reduced acquisition time. For example, for first-pass perfusion, simultaneous multi-slice can be superior to both 2-D and 3-D options [33]; unlike 3-D, simultaneous multi-slice has a shorter temporal footprint and thus is less sensitive to cardiac motion, and unlike 2-D, simultaneous multi-slice provides more extensive coverage of the myocardium. Figure 6 shows an example where simultaneous multi-slice is combined with in-plane parallel MRI and compressed sensing to provide high acceleration for cine imaging.

Achieving protocol brevity by improving gating efficiency

Acquisition of cardiovascular MRI data without motion-related artifacts is essential for reliable diagnostic imaging. Artifacts related to cardiac and respiratory motions can be minimized by using prospective or retrospective

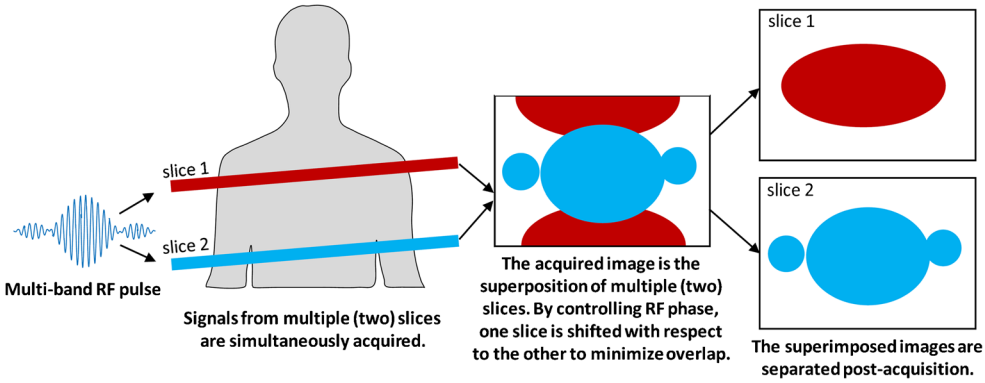

Fig. 5 Illustration of the simultaneous multislice imaging concept. A multiband radiofrequency pulse excites multiple slices (two in this case). The collected data contain signal from both slices. Utilizing the knowledge that slices are modulated by different sensitivity maps (from receive coils), the overlapped slices can be separated using a concept similar to that of parallel imaging. To facilitate post-acquisition separation, the slices are shifted (in the phase-encoding direction) with respect to each other; this is achieved by modulating the phase of the radiofrequency pulse

gating. In prospective gating, the data are accepted only when the cardiac and respiratory motions are in predefined windows. In retrospective gating, the data are collected continuously and accepted or rejected post-acquisition. Most commonly, electrocardiography (ECG) is used to provide information about the cardiac phase and internal (e.g., from diaphragmatic position using navigator echoes) or external (e.g., from respiratory bellows) signals are used to provide information about the respiratory motion. Recently, image-based (self-navigation) retrospective gating methods have also been proposed where the motion state is learned from the image itself. Figure 7 demonstrates how respiratory-triggered images avoid the blurring associated with free-breathing imaging [34].

For cardiovascular or abdominal imaging, the respiratory gating efficiency — typically 25–40% — has a direct impact on scan time. Several motion-compensation methods have been proposed to improve gating efficiency. For example, Han et al. [35] increased the gating efficiency to 45–58% for contrast-enhanced MR angiography by partially accepting data from the cardiac cycles that partially fall into the acceptable respiratory window. Recently, Dyverfeldt and Ebbers [36] compared different motion compensation strategies and demonstrated that weighted gating (employing multiple gating windows and reserving the most stringent window for central k-space) and gating with reordering (employing reordering such that central k-space is sampled during the end expiration) can significantly improve the gating efficiency. In addition to the techniques mentioned above, data-driven self-navigation methods have also been proposed [28]. These methods learn the respiratory phase from the measured MRI data and suppress or eliminate measurements based on the respiratory phase. More recently, several methods have been proposed to perform respiratory-motion-resolved imaging from continuous acquisition of data under free-breathing conditions. In contrast to other methods that try to suppress or compensate the respiratory motion, the respiratory-motion-resolved methods perform imaging along the additional dimension of respiration. By exploiting redundancies along the respiratory dimension — e.g., via compressed sensing — such methods can further improve the image quality [37]. These methods can be combined with golden-angle radial acquisition scheme, enabling cardiac and respiratory motion states extraction from the data and eliminating the need to use

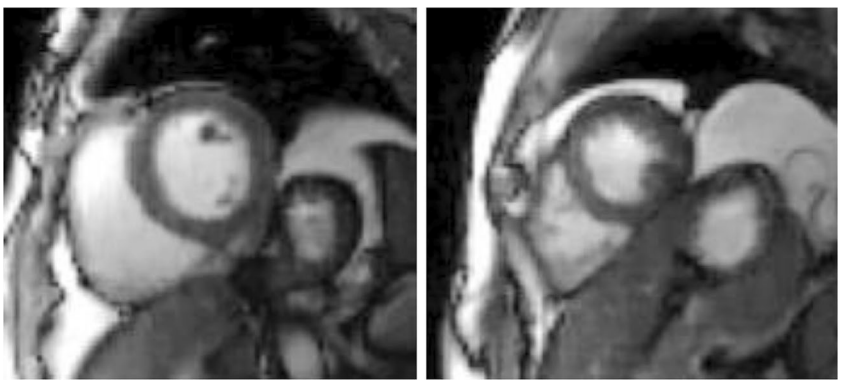

Fig. 6 Application of simultaneous multi-slice imaging to cardiac cine. Net acceleration rate of 12 is achieved by combining simultaneous multi-slice (two slices excited simultaneously) with in-plane parallel MRI and compressed-sensing-based recovery. The data were collected from a 38-year-old healthy male volunteer

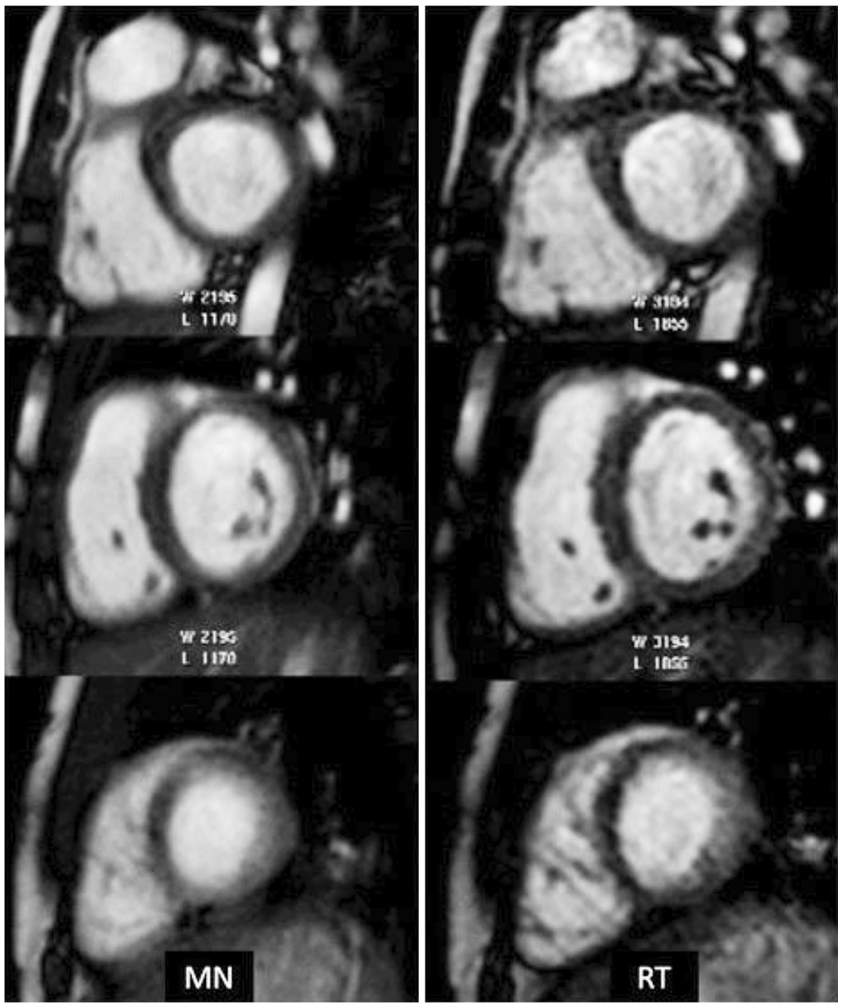

Fig. 7 Cardiac cine balanced steady-state free precession MR images obtained with multiple averages (*MN, left*) and respiratory triggering (*RT, right*). Notice the significant reduction in motion-related blurring of the respiratory-triggered images. The data were collected from a 14-year-old girl

ECG or navigator echoes. Because of an additional imaging dimension, however, the respiratory-motion-resolved methods are computationally intensive. Although these methods are not yet routinely used clinically, the preliminary results have been promising for cardiovascular and abdominal applications [38, 39].

Achieving protocol brevity by abbreviating MR imaging protocols

Most pediatric body MR studies require 45–90 min of scanning time [40]. In younger children and in children with cognitive impairment, some form of sedation is generally used to minimize motion-related artifacts. In addition to the need for general endotracheal anesthesia to facilitate longer sedation duration and breath-holding, such long exams have other significant disadvantages such as lower probability of completion, increased cost, decreased magnet utilization and poor examination turnaround times, and greater need for specialized supervision. Protocol optimization and brevity is desired to minimize these disadvantages. While optimization pertains to answering specific imaging questions, protocol brevity could be a result of both optimization as well as utilizing technological advancements that help to accelerate image acquisition and minimize motion-related artifacts.

Using targeted sequences to abbreviate imaging protocols

The key to abbreviating MR protocols lies in the use of a few targeted sequences that are proven to change management and influence outcomes. The ideal protocol answers the clinical question at hand and targets the pre-study differential diagnosis. Most pediatric body MR studies aim to fulfill one or more of the following objectives: (1) determine morphology, severity and extent of local disease process, (2) perform tissue characterization to improve specificity, (3) determine functional and biological features and (4) screen for associated conditions or systemic involvement. The sequences that might be chosen for each objective are quite extensive, and the degree of difficulty varies with the region being scanned, the imaging target, and the size and age of the patient. Routine use of redundant data collection using multiplanar imaging (for example, three-plane T2, or three-plane post-contrast T1) might

increase the duration of the scan without providing enhanced diagnostic efficacy.

General principles that guide targeted and abbreviated protocol development are: (1) target study to the imaging question and pre-study differential (see next section on reporting elements), (2) prioritize sequences yielding imaging findings that influence therapeutic decision-making, (3) optimize technical parameters to achieve balance between coverage, signal noise and spatial resolution, (4) obtain multiple imaging planes only for critical findings and (5) check study before terminating an abbreviated study, especially if the child is sedated. Familiarity with imaging findings that influence therapeutic decision-making is required to know what sequences should be prioritized and what sequences are expendable.

Using reporting elements to prioritize sequences and abbreviate protocols

Expert consensus statements from relevant scientific communities exist for cardiovascular and body MR imaging for various pediatric disease processes [40]. They help to standardize image acquisition and reporting within an institution and between institutions. More important, they allow delineation of reporting elements: the key qualitative and quantitative findings that are shown to influence management or outcome for a given condition. Adult MR practice leads the way in emphasizing structured radiology reporting that incorporates standardized reporting elements and lexicon, as illustrated by breast imaging with BI-RADS (Breast Imaging Reporting and Data System) and focal liver lesion characterization with LI-RADS (Liver Imaging Reporting and Data System). This has, in turn, led to the development of abbreviated MR imaging protocols that cater efficiently to the reporting elements [41, 42]. A similar approach to standardizing reporting elements for common pediatric indications for body MRI is expected to be helpful for developing standardized targeted protocols.

The key reporting elements for anomalous aortic origin of the coronary artery include the type of ostial morphology, location of coronary ostia, presence and length of intramurality, course through commissure or column, and coronary dominance. Well-performed navigator respiratory-gated 3-D steady-state free precession (SSFP) coronary MR angiography is the only MR sequence needed to answer these questions and could result in a protocol that is less than 10 min, optimally performed on a 3T scanner. Similarly, the reporting elements for another cause of sudden cardiac death in children, hypertrophic cardiomyopathy, are maximal thickness of the left ventricular wall; distribution of left ventricular hypertrophy; presence and severity of left-ventricular outflow tract obstruction; presence of systolic anterior motion of mitral valve; ventricular volumes, function and mass; status of the proximal coronaries; and presence and distribution of myocardial late gadolinium enhancement. All these questions can be answered with the following four sequences in 20 min: cine SSFP short-axis phase-contrast imaging left-ventricular outflow tract, 3-D SSFP coronary MR angiography, and short-axis late gadolinium enhancement. With the likely availability of accelerated 3-D imaging in the near future, this protocol might be further reduced to three free-breathing 3-D acquisitions using 4-D flow [43], 3-D SSFP coronary MR angiography [44] and 3-D myocardial late gadolinium enhancement [45], using respiratory navigator or self-navigation for respiratory-motion compensation, and compressing sensing for acceleration. An abbreviated protocol for vascular ring evaluation might be limited to an axial black-blood sequence to assess the severity of airway compromise, and free-breathing gadolinium-enhanced 3-D MR angiography to assess the presence and type of vascular ring. Protocol brevity can also be achieved using society guidelines in the setting of MRI for repaired tetralogy of Fallot, the most common indication for pediatric cardiac MRI [46]. Figure 8 shows both conventional and abbreviated MRI protocol flowcharts to attain clinically needed diagnostic information in repaired tetralogy of Fallot.

Follow-up imaging is especially amenable to abbreviated imaging protocols. For example, the initial evaluation of a child with a diffuse vascular malformation might include sequences to assess morphology, extent and planes of involvement of the vascular malformation, presence of high-flow versus low-flow components, tissue characterization of the lymphatic, venous or arterial components, and distinction from a benign or malignant neoplasm, and screening for associated conditions. However the follow-up studies might be limited to the assessment of the residual lesion with a single 3-D sequence (T2, SSFP or MR angiography) to plan follow-up treatment because the remaining information is redundant. This could be performed without sedation in most children.

The challenge of gross motion on unsedated pediatric studies

The focus of this paper is on correcting for physiological motion and using accelerated or abbreviated sequences that reduce the chance of encountering bulk motion. However it is inconceivable that any attempt

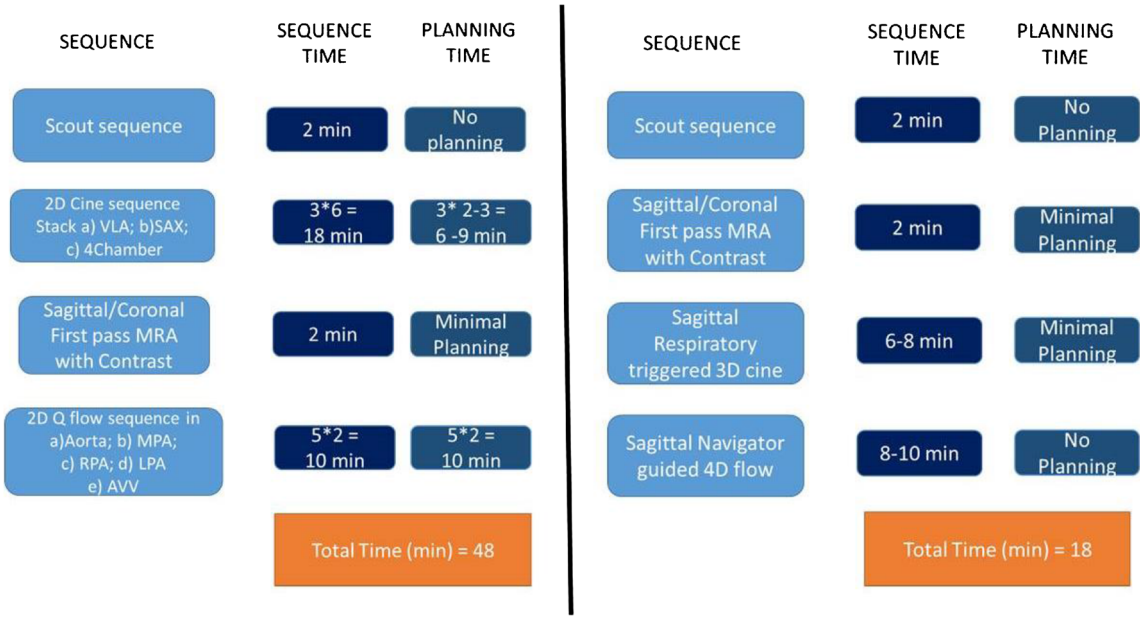

Fig. 8 The conventional protocol and a recently proposed abbreviated protocol (right) are shown. The conventional protocol (left) needs significant planning prior to acquisition of the cine and flow sequences, while the abbreviated protocol has minimal planning requirements (all sequences are non-oblique axial, sagittal or coronal acquisitions). Note: The scout sequence and the first-pass MR angiography sequence are the same between the protocols. *AVV* atrioventricular valves, *4CH* four chamber, *MPA/LPA/RPA* main/left/right pulmonary artery, *SAX* short axis, *VLA* vertical long axis

to move toward unsedated imaging in younger children would be successful without solutions to manage bulk motion. The unpredictable nature of bulk motion in children makes resolution particularly difficult. A few sequences are available with demonstrated success in some populations including fast sequences such as single-shot fast spin echo [47] and BLADE/PROPELLER [48]. The former is effective for rapid morphological imaging in uncooperative patients and is a staple of fetal imaging and brain imaging for shunt malfunction. PROPELLER stands for periodically rotated overlapping parallel lines with enhanced reconstruction and is known by different names based on the vendor (GE Healthcare, Waukesha, WI: PROPELLER; Siemens Healthcare, Erlangen, Germany: BLADE; Philips Healthcare, Best, the Netherlands: MultiVane). It utilizes a hybrid trajectory of radial and Cartesian sampling using rotating blades with multiple phase-encoding lines, and it oversamples the center of k-space, corrects for in-plane rotation and translation, and rejects data based on estimates of through-plane motion. In common practice, 8–32 lines (blades) are acquired in a single shot. The trajectory angle is then incremented and a second set of blades is acquired. The process continues until the rotating blades provide even coverage of the k-space. Further decrease in the impact of motion can be achieved through multiple-signal averaging. For BLADE/PROPELLER sampling, oversampling of the center of k-space provides redundancy of information so that the data from each new set of blades can be compared to the data from the previous sets of blades and can be corrected (or even completely discarded) based on data consistency. This technique works well for periodic motion like respiration or for rigid in-pane translation. However, in our experience it fails to provide satisfactory results in children with unpredictable three-dimensional motion, and there is a need for novel tools with three-dimensional correction of motion that are adapted to the characteristics and needs of the pediatric population.

Conclusion

Magnetic resonance imaging is an integral part of clinical care for pediatric patients. As a result of long scan times and limited compliance from pediatric patients, MRI is commonly performed under sedation or GA. In response to the growing evidence of potential sedation and GA risks, there is an unmet need to eliminate or reduce sedation and GA for pediatric MRI exams while maintaining the quality and quantity of information generated for addressing the clinical questions. Two effective mechanisms to reduce sedation include accelerating MRI scan by utilizing recent advances in acquisition and processing techniques and optimizing MRI protocols by eliminating or reducing redundant scans. Newly developed acceleration techniques, including k-t methods, compressed sensing, and simultaneous multislice acquisition, when coupled

with targeted MRI protocols, can fulfill the promise of brief, free-breathing examinations and reduce or potentially eliminate the need for sedation or GA for common pediatric indications.

Compliance with ethical standards

Conflicts of interest None

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