Musculoskeletal and Body MRI in Children

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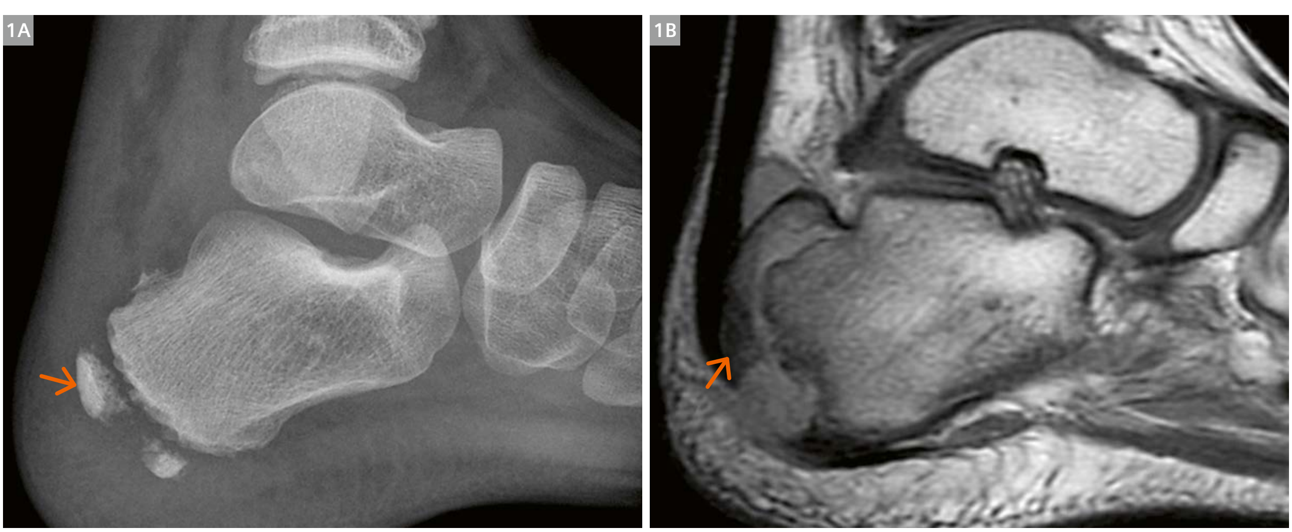
MRI imaging in pediatric patients is as much about the process as it is about the result. While high-quality images are the ultimate goal, for children an imaging study is a success if diagnostic images are obtained while minimizing the risk to the patient, which includes reducing the risk of anesthesia [1–2]. There are many ways to improve spatial resolution and gain signal-to-noise ratio (SNR) in MRI, though most strategies cost time. In clinical practice there are limitations on patient cooperation and magnet utilization that require a practical approach to imaging. While working with children is enormously satisfying, there are also challenges that come with pediatric imaging which require minimizing exam times, eliminating labor-intensive breath-holding instructions, and imaging through motion (respiratory and gross motion). Motion is a major obstacle when it comes to imaging young children. In many instances, the difference between a non-diagnostic exam and a successful exam may simply require reducing sequence time by half. While this used to require unacceptable compromise in image quality, this is no longer true. With increased field strength magnets (i.e. 3T), appropriate selection of multichannel phased array coils, and parallel imaging techniques, scan times have decreased considerably from where they started. With a few additional strategies it is not only possible, but more than likely that a complete exam can be performed in a young child[1] without sedation. Advanced protocol planning, sequence prioritization, real-time exam monitoring, and skilled patient handling are also critical elements of a successful MRI examination in a young child.

A fundamental principle in imaging pediatric patients is to limit sequences to only those that are necessary, acquiring the most high yield sequences first. Patient cooperation is limited and young patients often have tolerance for two or three sequences. Radiologists should assume the most critical diagnostic information must be obtained in the first ten minutes of an exam. If those first sequences are diagnostic, the patient will be spared a follow-up exam under anesthesia. MRI is increasingly being used to screen patients with certain symptoms for presence or absence of disease, such as fracture detection in limping toddlers, evaluation for infection in children with fever of unknown origin, or appendicitis screening in patients with right lower quadrant pain. MRI may be the best means of detecting fractures in certain locations when the bones have not yet ossified (Fig. 1), and for localizing disease when patients are unable to verbalize symptoms.

[1]*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. Note: This disclaimer does not represent the opinion of the authors.*



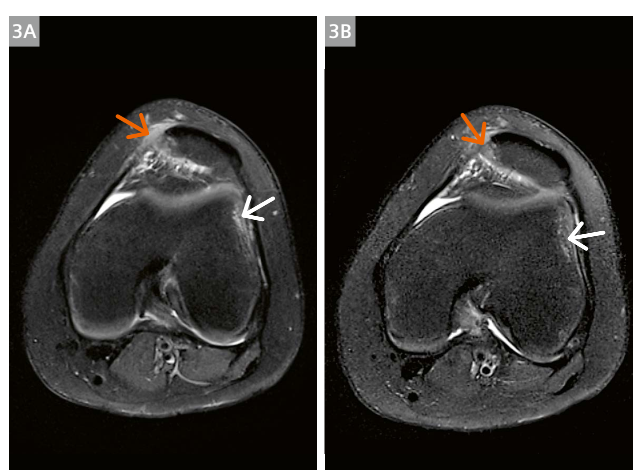
1 6-year-old female with calcaneal apophyseal fracture **(1A)** Lateral radiograph of the ankle reveals a normal-appearing apophysis (orange arrow). **(1B)** Sagittal PD-weighted TSE sequence reveals avulsion of the calcaneal apophysis, not appreciated on radiographs secondary to the lack of ossification.

It is more important to acquire images quickly to allow actionable diagnosis, rather than spending additional time enhancing imaging quality at the expense of patient cooperation.

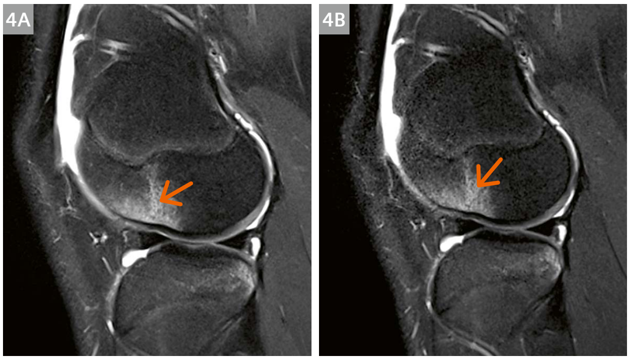
Monitoring MRI examinations in real-time allows for adjustment of imaging parameters as the study unfolds [3]. As toddlers are often unable to articulate the location and nature of their symptoms, imaging requires looking far and wide initially and focusing down on an abnormality once identified. Setting up an MRI in a toddler with an unexplained limp, for example, often requires using one or more body matrix coils (depending on the child) to perform initial sequences with a large field of view (FOV) from the pelvis to the feet (Fig. 2). These sequences can be performed quickly, with need for additional sequences determined by the presence or absence of abnormal findings. Without real-time radiologist supervision, these protocol modifications would not be possible and the examination may need to be repeated.

While vigilant exam monitoring, careful protocoling, and adept patient handling are critical to successful imaging of children, these efforts may still fall short of the goal without additional sequence advancements. Accelerated acquisitions and motion robust sequences are, therefore, particularly valuable in pediatric imaging. Acceleration techniques allow for substantial reductions in imaging times so that they may be tolerated by young patients; in our experience this generally means shorter than two minutes per sequence. In pediatric musculoskeletal imaging, MRI protocols rely heavily on turbo spin-echo (TSE) sequences which include proton density (PD), intermediate weighted (IW), and T2-weighted images. Accelerated TSE acquisitions can be obtained through *k*-space undersampling in parallel imaging [4]; however a reduction or acceleration factor of R comes with a reduction of $1/\sqrt{R}$ in (SNR). In addition, SNR is also reduced by the noise amplification factor, or the *g*-factor (geometry factor) penalty that varies by the location in an image depending on the number of aliased replicates per voxel based on coil sensitivities [5]. The *g*-factor penalty depends on the receive coil design and coverage, and the geometry of imaging and can vary between 1 and 2 across the image. Simultaneous multi-slice (SMS) is another technique to accelerate imaging that excites multiple spatially distributed slices simultaneously by using a multi-band radiofrequency pulse and techniques to control aliasing and reduce the *g*-factor penalty [5–11]. Data obtained from receive coils from simultaneously excited slices are separated to reconstruct images. When parallel imaging and SMS are both applied, imaging times can be reduced 4- to 8-fold over traditional methods. In our routine knee MRI protocol we compared an accelerated T2-weighted TSE sequence using a parallel imaging iPAT factor of 2 with an SMS factor of 2 to achieve 4-fold acceleration against our traditional sequence without the SMS acceleration (Figs. 3, 4). We found both the SMS TSE and the TSE were equivalent in identifying pertinent imaging findings [12]. Compared to the traditional sequence, the SMS accelerated sequence is nearly twice as fast (Table 1). Further reduction in imaging time can be gained by increasing the SMS factor, with incremental cost to SNR. In our patient population we found that 4-fold acceleration is sufficient for most patients, and additional acceleration can be reserved for patients who are extremely nervous or fidgety, given the modest reduction in SNR.

2 2-year-old female with limp. Coronal T1 **(2A)** and STIR **(2B)** sequences through the entire pelvis and lower extremities were performed using a body matrix coil as an initial screen to identify areas of pathology. No abnormality was identified.



3 11-year-old female with patellar dislocation. **(3A)** Axial T2-weighted TSE image with fat suppression and **(3B)** corresponding axial T2-weighted SMS TSE image demonstrates a tear of the medial retinaculum (orange arrow) and a bone contusion at the lateral femoral condyle (white arrow).



4 14-year-old boy with lateral femoral contusion (orange arrow) undergoing MRI. **(4A)** Sagittal T2-weighted TSE sequence and **(4B)** corresponding sagittal T2-weighted SMS TSE sequence for comparison.

The 3D TSE volumetric SPACE (Sampling Perfection with Application optimized Contrasts using different flip angle Evolution) acquisition is integral for imaging of large joints (knee and ankle) in children [13–18]. The three-dimensional, high-spatial resolution, isotropic images can be reconstructed into any imaging plane from a single volumetric data set, making it helpful for identifying subtle cartilage defects or ligamentous injuries. The imaging time, however, is relatively long which makes it particularly vulnerable to motion. The standard PD-weighted SPACE sequence in the knee protocol at our institution is 7 minutes and 40 seconds. Parallel imaging techniques can be applied to the acquisition but may cause aliasing artifacts and increase noise. CAIPIRINHA "Controlled Aliasing in Parallel Imaging Results in Higher Acceleration" [19] is a parallel imaging strategy that uses *k*-space sampling patterns designed to reduce aliasing and overlap on reconstructed images. While aliasing artifacts are still present, they are shifted to the corners of the image space.

Parameters	T2-weighted TSE	T2-weighted SMS TSE
Plane	Sagittal	Sagittal
Acquistion time (min:sec)	2:45	1:50
TR (ms)	4500	3000
TE (ms)	53	53
Echo train length	34	33
Matrix	384	384
Parallel imaging acceleration factor and reconstruction	2 (GRAPPA)	2 (GRAPPA)
FOV (mm)	140	140
Voxel dimension (mm)	0.4 x 0.4 x 3.0	0.4 x 0.4 x 3.0

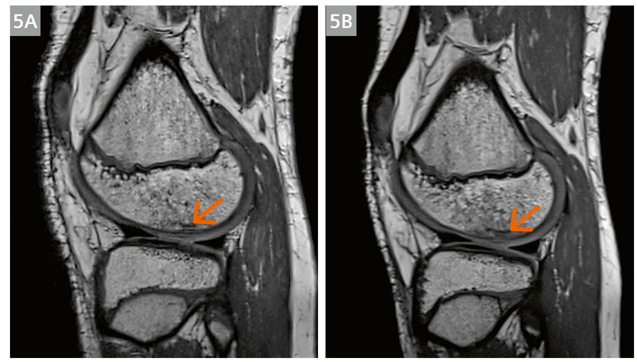
Table 1: MRI parameters for T2-weighted TSE sequence versus T2-weighted SMS TSE sequence in the knee.

Parameters	PD-weighted 3D SPACE	PD-weighted 3D CAIPIRINHA SPACE
Plane	Sagittal	Sagittal
Acquistion time (min:sec)	7:40	4.00
TR (ms)	1000	1000
TE (ms)	49	49
Echo train length	41	41
Flip angle (°)	120	120 (variable)
Matrix	320 x 320 x 240	320 x 320 x 240t
Parallel imaging acceleration factor and reconstruction	2 (GRAPPA)	2 (GRAPPA)
FOV (mm)	162 x 249	162 x 249
Voxel dimension (mm)	0.54 x 0.54 x 1	0.54 x 0.54 x 1

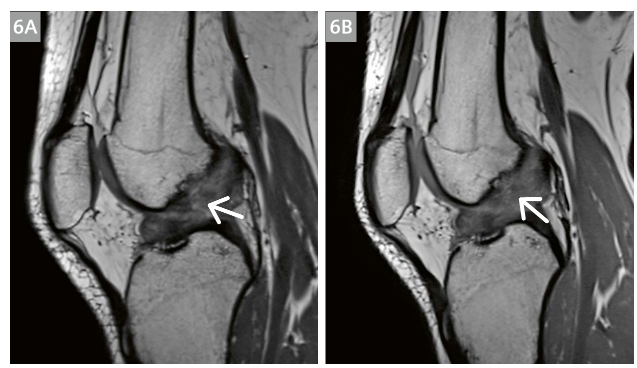
Table 2: MRI parameters for Proton Density (PD)-weighted 3D SPACE sequence versus PD-weighted 3D CAIPIRINHA SPACE sequence in the knee.

Combined CAIPIRINHA and SPACE allows for 4-fold acceleration through undersampling in both the phase and partition encoding directions [14]. We compared the standard PD-weighted SPACE sequence in the knee with the CAIPIRINHA PD-weighed SPACE sequence (Table 2). Applying CAIPIRINHA to SPACE reduced our scan time from 7:40 minutes to 4:00 minutes without compromise in image quality (Figs. 5, 6). We reserve this sequence for slightly older patients (above the age of 8) who are able to cooperate for the 4 minute long acquisitions. In the younger patients, 2D sequences are still generally preferred. Anticipated pathologies in our youngest patients do not typically require such fine spatial resolution, and these patients reap greatest benefit from short acquisitions that require periodic opportunities for breaks.

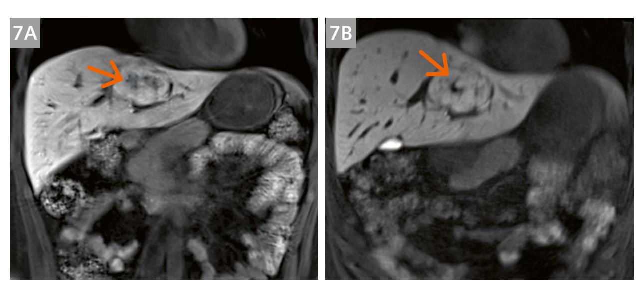
Motion robust imaging alternatives are highly valuable in pediatric patients, particularly for abdominal and pelvic imaging [20]. Examinations that require breath-held sequences often require the child to be anesthetized and intubated to allow for periods of suspended respiration. With the aim of reducing need for anesthesia and/or the depth of anesthesia, free-breathing imaging capabilities are imperative. In the abdomen, 3D volumetric interpolated breath-hold examination (VIBE) imaging offers the most robust approach to acquiring T1-weighted imaging. VIBE allows for high spatial resolution with relatively fast imaging acquisitions of the entire abdomen [21, 22]. Depending on parameter selection, it is possible to acquire images through the entire field of view in approximately 20 seconds in a cooperative patient. Even adult patients may have difficulty breath-holding for a 20 second sequence [23], and children are even less likely to manage this. Cartesian VIBE obtained during free-breathing produces motion artifact within the image (Fig. 7) which limits the diagnostic quality of the sequence [24, 25]. T1-weighted images can be acquired with respiratory navigation, though this is less developed than navigated T2-weighted sequences, and image quality is inferior to the conventional breath-hold sequences [26–28]. Additionally, navigated T1-weighted imaging is not possible with fat suppression, which limits its utility for post-contrast imaging. A modified version of the VIBE sequence is a radial VIBE sequence that uses rectilinear sampling in the *z*-direction and radial sampling in the *xy* plane [24]. This sequence can be performed during free-breathing, and the radial sampling of *k*-space mitigates the effect of respiratory motion such that image quality is superior to the traditional breath-hold Cartesian VIBE [24]. The product version of this sequence is called StarVIBE, which is our standard for T1-weighted imaging in pediatric patients. Although the acquisition time is longer than a traditional VIBE sequence, the respiratory motion is distributed throughout the image such that there is little perception of the motion within the image. This technique is especially helpful for post-gadolinium enhanced imaging in the liver, kidneys, and bowel (Fig. 8). The ability to obtain high spatial-resolution, motionless imaging in patients who are freely breathing has dramatically altered our approach to sedating patients. We utilize the StarVIBE sequence in any child undergoing abdominopelvic imaging, for both pre and post-contrast fat-suppressed imaging.



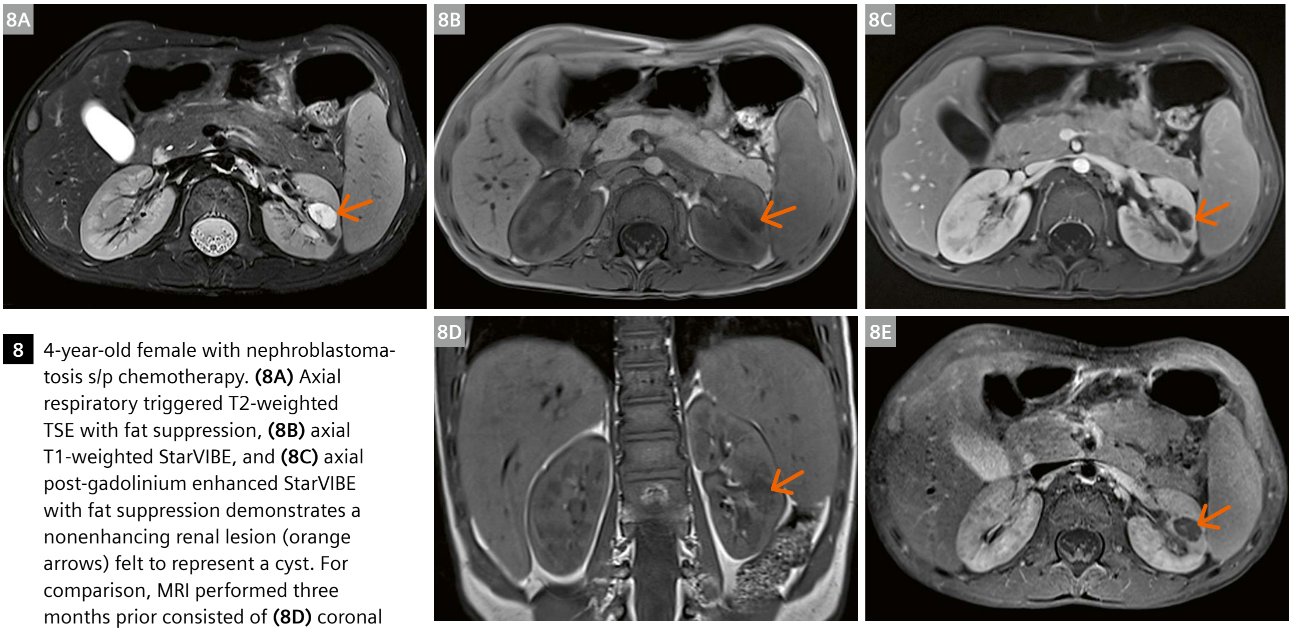
5 11-year-old female with lateral femoral condylar impaction fracture (orange arrow) seen on both **(5A)** sagittal PD-weighted SPACE sequence, and **(5B)** corresponding sagittal PD-weighted CAIPIRINHA SPACE sequence for comparison.



6 15-year-old female with ACL tear (white arrow). **(6A)** Sagittal PD-weighted SPACE sequence and **(6B)** corresponding sagittal PD-weighted CAIPIRINHA SPACE sequence through the ruptured ACL for comparison.



7 20-year-old female with FNH-like liver lesion. **(7A)** Coronal T1 VIBE with breath-holding after administration of Eovist contrast media reveals delayed uptake in a liver lesion (orange arrows), though images are degraded by motion. **(7B)** Sequence repeated with StarVIBE sequence with free-breathing demonstrates reduced motion artifact with better depiction of the lesion.



8 4-year-old female with nephroblastomatosis s/p chemotherapy. **(8A)** Axial respiratory triggered T2-weighted TSE with fat suppression, **(8B)** axial T1-weighted StarVIBE, and **(8C)** axial post-gadolinium enhanced StarVIBE with fat suppression demonstrates a nonenhancing renal lesion (orange arrows) felt to represent a cyst. For comparison, MRI performed three months prior consisted of **(8D)** coronal respiratory triggered T1-weighted TSE, **(8E)** axial post-gadolinium enhanced T1 TSE with fat suppression. Motion artifact is noted in the image from respiration.

The lack of breath-holding as a requirement for imaging obviates the requirement for endotracheal intubation, unless there are other reasons for which it would be required. A dynamic StarVIBE sequence is also available which allows for both high temporal resolution in addition to high spatial resolution images during dynamic contrast injection [29, 30], using compressed sensing techniques as a means to vastly undersample the data and reduce imaging times [20]. We are currently investigating this technique in the pediatric population, particularly with regard to renal, hepatic and bowel wall imaging.

9 3T MAGNETOM Prisma MR scanner embedded in a sandcastle design. The room is decorated with decals in the theme of an ocean scene.

MR imaging in pediatric patients requires a team approach and collective efforts toward reducing our dependency upon sedation as a mechanism to acquire diagnostic, motion-free images. These include tailored protocoling, real-time monitoring, and utilization of accelerated or motion robust sequences. With the use of SMS TSE and CAIPIRINHA SPACE, MSK imaging examinations in children can be dramatically shortened without compromising image quality. StarVIBE imaging in the abdomen allows for high-resolution, free-breathing, T1-weighted imaging thereby eliminating requirement for endotracheal intubation for abdominal MRI in sedated patients. Reducing the anxiety and apprehension around the scanner and the scan room is also important in achieving patient cooperation. This can be achieved through embedding the scanner in a structure, such as a sandcastle, train, or boat (Fig. 9), decorating the room with colorful designs, distracting the patient with a movie during the scan, or preparing prior to the scan at a mock scanner or simulating the experience with virtual reality headsets. All of these strategies are currently employed at our hospital, oftentimes in combination. Further developments in prospective motion correction using motion cameras embedded in the magnet and sensors on the patient are currently being developed through collaborations with KinetiCor (Honolulu, HI, USA), with broad applications in the pediatric population. Our hope is that through these collective efforts we will drastically reduce the number of children requiring sedation for MRI, and improve the patient experience by reducing exam lengths and delays.

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