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TECHNICAL INNOVATION

Feasibility of ultrashort TE (UTE) imaging of children at 1.5 T

Suraj D. Serai · Tal Laor · Jerry R. Dwek · Andrew M. Zbojniewicz · Michael Carl

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Abstract Ultrashort TE (UTE) is a relatively new MRI technique that allows for the visualization of tissue structures with short T2 components that show little or no signal on all conventional MR imaging sequences. This technique, to the best of our knowledge, has been described only in adults and uses a half excitation pulse and radial k-space data acquisition to produce echo times of less than 100 microseconds with no need for additional hardware modifications. We describe the feasibility of using a 2-D UTE sequence in vivo on a routine 1.5 T clinical MR scanner to depict various musculoskeletal structures in children.

Keywords Magnetic resonance imaging · Children · Musculoskeletal system · Imaging parameters

Introduction

Conventional MR imaging has shown that T2 relaxation is sensitive to the distribution of water content in the musculoskeletal tissues [1]. However, structures such as cortical bone, tendons, ligaments and menisci are comprised primarily of tissues with tightly bound protons that decay very quickly. This rapid decay results in very short T2 relaxation times, manifested as hypointense signal when using conventional MR imaging sequences [2]. Spin-echo imaging typically utilizes a minimum TE of approximately 8 to 10 milliseconds (msecs). A fast gradient echo sequence can shorten the TE down to 1 to 2 msecs. However, to acquire signal from tightly bound protons, a sequence that uses a very short TE is needed. Ultrashort TE, or UTE, is a relatively new MR imaging technique that uses even shorter TE values, on the order of microseconds (μs) [2]. These dramatically shortened TEs allow for the depiction of the short T2 components as hyperintense signal.

To date, UTE imaging has been applied primarily at higher field strengths and mostly for high-resolution, small field-of-view in vitro applications. These limitations stem from the relatively long acquisition times for imaging that are the result of the multiple excitations needed to gain extra signal [3–5]. For example, UTE has been applied successfully to human spine disk-bone specimens in high-resolution imaging to depict the calcified and uncalcified portions of the cartilaginous endplates [6]. For in vivo applications, a few limited adult patient population studies have been reported. In one recent study, UTE MR images have been shown to exhibit hyperintense linear signal from the uncalcified and calcified cartilage at the osteochondral junction of the patella [4]. UTE also has been used to quantitatively characterize the Achilles tendon [7]. Although the potential of in vivo applications of UTE imaging techniques has been apparent for many years, only a limited number of clinical studies, all in adults, have been published with the majority at 3 T. This limited use of UTE to date for in vivo human clinical scanning applications likely reflects the technical challenges associated with the pulse sequence design itself, the hardware and software limitations, and post-processing needs [2, 8].

To our knowledge, utilizing UTE imaging to evaluate normal anatomy or pathology in children is unique. Therefore, the purpose of this report is to illustrate the feasibility of

S. D. Serai · T. Laor (✉) · A. M. Zbojniewicz
Department of Radiology,
Cincinnati Children's Hospital Medical Center,
3333 Burnet Ave., Cincinnati, OH 45229, USA
e-mail: tal.laor@cchmc.org

J. R. Dwek
Department of Radiology,
Rady Children's Hospital and Health Center,
San Diego, CA, USA

M. Carl
GE Healthcare, San Diego, CA, USA

employing a 2-D application of UTE for musculoskeletal MR imaging of children on a clinical 1.5 T scanner and to suggest possible future applications of this sequence.

Description

The UTE sequence

The UTE sequence consists of a half variable-rate excitation pulse [2–4] (Fig. 1). TE is defined as the time between the end of the half-pulse excitation and the start of the readout gradient. The half-pulse excitation is a specially designed radiofrequency (RF) pulse that concentrates most of the RF energy at the end of the pulse for a much shorter duration than that of the routine symmetrical SINC pulse, which typically is used for 2-D imaging. In a typical imaging sequence, k-space (the raw data before reconstruction), is filled in a Cartesian manner, which is one raw data line filled in left to right per repetition time (TR). The raw data in the middle of k-space contains signal and contrast information, whereas the data in the periphery of k-space contains sharpness information. In a UTE sequence, to shorten the echo time even more, the raw data k-space is acquired radially so that the signal and contrast information can be acquired rapidly at the expense of image resolution or sharpness [3]. This radial technique acquires data in a spoke-like fashion (Fig. 1). Since the radial acquisition used in UTE imaging starts at the center of k-space, the spins do not need a phase acquisition gradient pulse or any additional time to get back to the center of k-space. The data acquisition can be initiated immediately after the excitation pulse while the gradient ramp-up is still in process and, thus, T2-signal decay between proton excitation and data acquisition is minimized [3]. The k-space sampling is non-uniform with dense sampling of the center of k-space and less dense sampling of the edges of k-space [3]. The k-space raw data images are then reconstructed with a gridding method that converts the k-space map from radial to square.

As UTE imaging is based on radial k-space sampling to severely shorten echo time, the sequence is sensitive to inherent hardware-based gradient timing errors, eddy currents and main magnetic field inhomogeneities. Therefore, to apply the sequence on a clinical 1.5 T scanner, the timing of the system gradients requires calibration to the timing of the half RF pulse. This calibration is unique to every scanner and must be performed once prior to initiation of the use of that specific magnet intended for UTE imaging. Once performed on a specific scanner, there is no need to repeat calibration prior to each patient. However, the calibration will need to be repeated if any major software or hardware changes are made to the imaging system. An annual calibration also is recommended.

Patients

All patients in our feasibility group who were evaluated with UTE underwent MR imaging studies as part of their routine clinical care. The MR imaging fell within the Institutional Review Board criteria previously established for a prospective study of sequence development and optimization on the clinical scanners. The standard patient safety settings of the scanner as provided by the vendor were not altered for the purposes

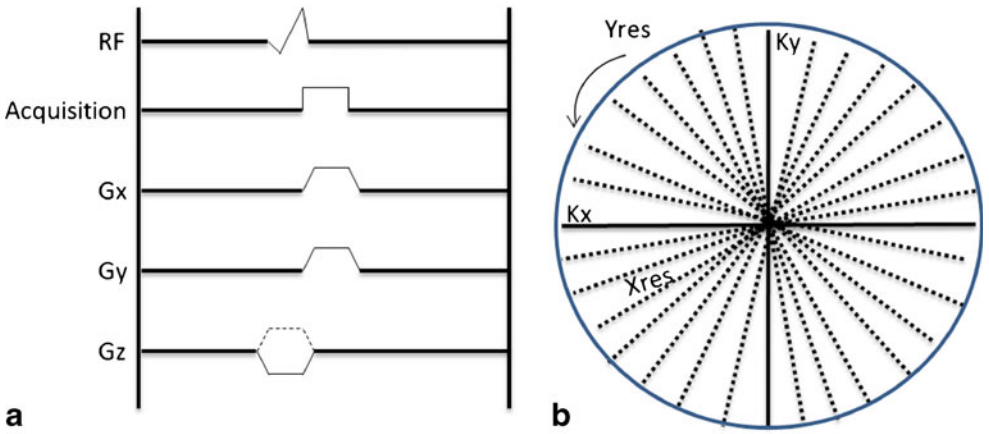

Fig. 1 UTE pulse sequence. **a** UTE pulse sequence timing diagram. The excitation pulse is the slice selective half-RF pulse (shown in top line). The acquisition starts rapidly when the gradient (Gx and Gy) ramp-up is in progress. **b** The radial acquisition acquires data in a spoke-like fashion. The number of spokes contributes to the Y resolution (*Yres*) and the number of data points on each spoke impacts the X resolution (*Xres*). All radial k-space lines are acquired twice with opposite polarity of the slice-select gradient and the data are then added together. The k-space sampling is non-uniform with dense sampling of the center of k-space and less dense sampling of the edges of k-space. The radially acquired data points of the k-space map are regridded into a Cartesian format. This format then undergoes Fourier transformation to generate an image

of the UTE sequence. When time allowed and clinical indications suggested, the UTE sequence was performed following completion of the routine clinical sequences. No sedated child was included in this feasibility cohort. UTE imaging was successfully performed on 35 children (28 boys, 7 girls) ranging in age from 4 to 17 years (mean age: 13 years). The joints evaluated to date include 28 knees (bilateral in one child), 6 ankles and 2 elbows. The imaging indications for the patients were acute traumatic injury, pain, suspected osteochondritis dissecans (OCD) or follow-up of a previously diagnosed OCD lesion.

MR imaging

All patients were scanned on a 1.5 T clinical scanner (HDxt; General Electric Healthcare, Waukesha, WI) with a 40 mT/m maximum gradient strength and 150 mT/m/msec maximum slew rate. For all studies, the built-in body volume coil was used for signal intensity transmission and an 8-channel knee coil or dual surface coils for signal intensity reception. All patients underwent standard anatomical imaging of the knee, elbow or ankle, which included T1-weighted, T2-weighted or intermediate-weighted with fat suppression, and 3-D isotropic proton-density weighted sequences.

The UTE imaging sequence consisted of three slices, 4 mm thick each. An interslice gap of 2 mm was used to reduce image acquisition cross-talk. Typical parameters used were: TR/TE1/TE2: 60 msec/100 μs/4.4 msec, and matrix: 256X512 and NEX: 8. The Y-resolution, or number of spokes in the radial acquisition, was maintained high to minimize streak artifacts. The slices were centered on any previously detected abnormality, whenever present. The images obtained at the first TE of 100 μs are defined as the UTE images. The images acquired at an in-phase TE of 4.4 msec were then subtracted from the UTE images acquired at 100 μs. We refer to the images that result after this calculation as "subtracted UTE images." The subtraction technique was graded to accommodate the sharp drop in signal intensity of the second echo image as compared to the first echo image. This graded subtraction is done to minimize the T1 signal contamination from incomplete recovery of the longitudinal magnetization. A relatively short TR was used, on the order of 60 msec, as to eliminate signal from the long T2 components. The total scan time was approximately 4 minutes per acquisition, a duration fairly comparable to that of other conventional pulse sequences. The resultant signal acquired with the UTE sequence is from only those structures with very short T2 relaxation times (Fig. 2). UTE imaging of the knee (Figs. 3, 4 and 5), of the ankle (Fig. 6) and of the elbow (Fig. 7) were successfully completed as prescribed.

Discussion

Human organs are comprised of various tissues that have a wide range of T2 relaxation time values. For example, tissues of the liver, the pancreas and the white matter of the brain consist of protons that typically have relatively long T2 relaxation times; therefore, they exhibit moderately hyperintense signal on T2-weighted images. However, several structures within the musculoskeletal system, such as cortical bone, ligaments, tendons and menisci, have very short T2 values that range from hundreds of microseconds to tens of milliseconds [2], and thus display uniformly hypointense signal on all conventional MR imaging sequences. We found it feasible to apply UTE imaging at 1.5 T to various joints in children to obtain signal from these typically hypointense structures, similar to reports in the adult literature. The UTE acquisitions were based on 2-D imaging with scan durations similar to conventionally utilized MR imaging sequences.

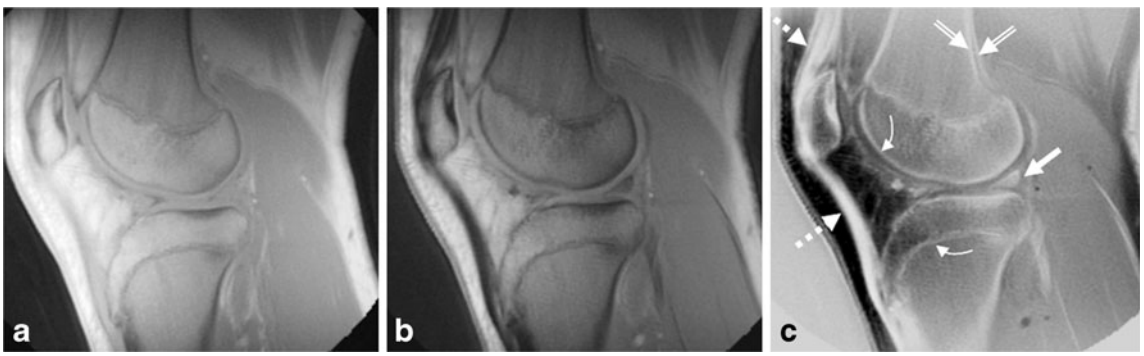

Fig. 2 UTE image acquisition. **a** Sagittal UTE image of the knee obtained at echo time (TE)=100 μs and repetition time (TR)=60 msec. **b** Sagittal image of the knee in the same location as (**a**) at TE=4.4 msec and TR 60 msec. **c** Sagittal subtracted UTE image of the knee in the same location obtained by a graded subtraction of (**b**) from (**a**). This subtraction leaves hyperintense signal in only those components that have very short T2 relaxation times. These structures include the meniscus (*arrow*), quadriceps and patellar tendons (*dashed arrows*), cortex and periosteum (*open arrows*) and osteochondral junctions (*curved arrows*)

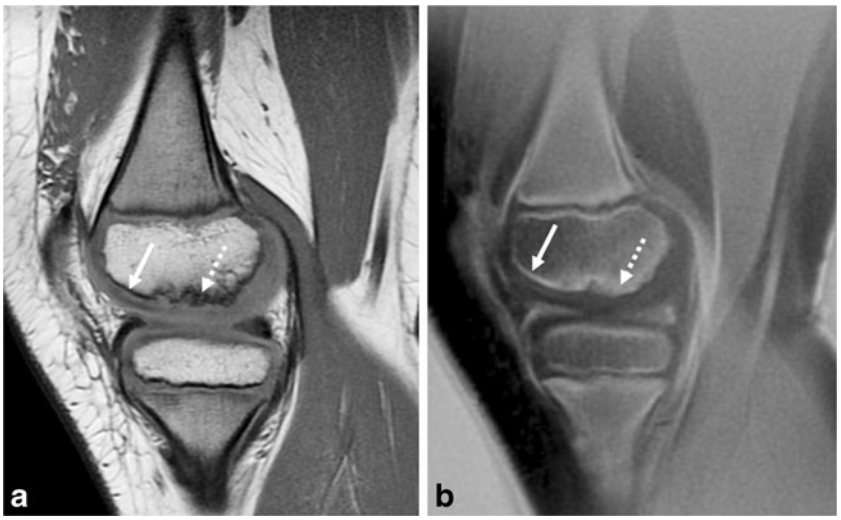

Fig. 3 Five-year-old boy with diffuse knee pain. **a** Sagittal proton density-weighted (1,700 msec/11.4 msec) image of the knee shows linear hypointense signal at the chondro-osseous junction (*arrow*) and irregular ossification of the weight-bearing portion of the medial femoral condyle. The linear hypointense signal at the chondro-osseous junction is not well identified at the site of osseous irregularity (*dashed arrow*). **b** Sagittal subtracted UTE image (60 msec/100 μs) shows thin, linear hyperintense signal at the osteochondral junction (*arrow*). This linear signal becomes less well defined in the area of osteochondral irregularity (*dashed arrow*)

In skeletally immature children with open physes, endochondral growth is characterized by an orderly progression from cartilage to bone, resulting in mineralization at the osteochondral junction. This zone of bony development is located at the interface between the most mature portion of a physis (the zone of provisional calcification) and the metaphysis or metaphyseal-equivalent location. As reported in an adult cadaveric study of the patella [4], the deepest layer of the unossified cartilage and the newly calcified cartilage of the osteochondral junction shows hyperintense UTE signal. Similarly, we found that the region of relatively analogous anatomy, that is, the uncalcified and calcified cartilage and the most newly formed bone at the physeal-metaphyseal junction in children, shows hyperintense signal on the UTE sequence. This junction between non-mineralized and mineralized substance can be found at the ends of growing long bones associated with a transverse physis, as well as deep to a spherical or hemispherical physis of an epiphysis or an epiphyseal-equivalent location (such as an apophysis).

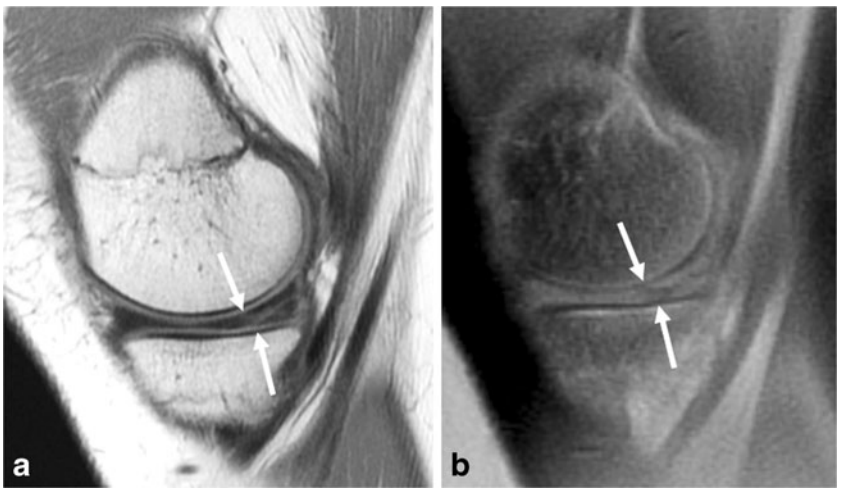

Fig. 4 Fifteen-year-old girl with an acute injury sustained while playing basketball. **a** Sagittal proton density-weighted (1,700 msec/12 msec) image of the medial side of the knee shows abnormal hyperintense signal (*arrows*) in the posterior horn of the medial meniscus. This was a tear (not shown in its entirety) confirmed at arthroscopy. **b** Sagittal subtracted UTE image (60 msec/100 μs) in approximately the same location shows interruption (*arrows*) of the hyperintense UTE signal of the posterior horn of the medial meniscus in a configuration similar to that identified in (**a**)

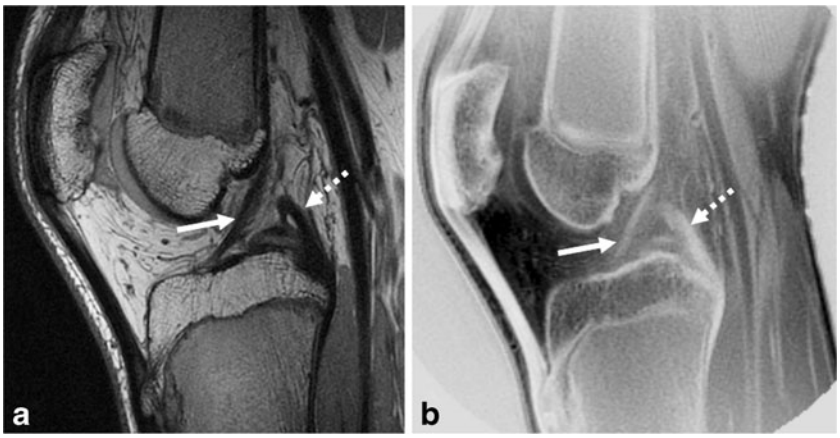

Fig. 5 Fifteen-year-old boy with recurrent patellar dislocation. **a** Sagittal proton density-weighted (1,400 msec/17 msec) image of the intercondylar region of the knee shows a normal hypointense anterior cruciate ligament (*arrow*) and a portion of the hypointense posterior cruciate ligament (*dashed arrow*). **b** Sagittal subtracted UTE image (60 msec/100 μs) in approximately the same location shows hyperintense signal from the anterior (*arrow*) and posterior cruciate (*dashed arrow*) ligaments. Note the hyperintense signal from the distal quadriceps tendon, patellar tendon, cortex, periosteum and osteochondral junctions

The osteochondral junction and most newly formed bone that was easily visible with UTE imaging in children, is a site associated with a variety of pathologies, such as chronic stress injuries, osteochondritis dissecans [9] and acute osteochondral fractures. Other structures, such as menisci, ligaments and tendons, that have been shown to exhibit hyperintense signal in adults, also were visible in our pediatric patient group. Future investigation is needed to evaluate whether UTE imaging in children assists in increasing conspicuity of abnormalities, such as meniscal tears, ligamentous disruptions or osteochondral defects. Additionally, whether UTE signal can offer insight into intact or altered endochondral bone growth as might be seen in various chondrodysplasias or metabolic bone abnormalities, such as rickets, is still unknown.

In conclusion, we have shown the technical feasibility of using UTE imaging in children at 1.5 T requiring less than 5 min of imaging time. This imaging sequence may be beneficial in evaluating pathology in the growing musculoskeletal system, particularly at osteochondral junctions and newly formed bone. It is possible that abnormalities may become more conspicuous when imaging with UTE. Whether pathology can be identified early, perhaps at a potentially reversible stage, is yet to be determined. While it remains to be established how UTE MR imaging appearance changes with disease and injury, our report suggests that this sequence might

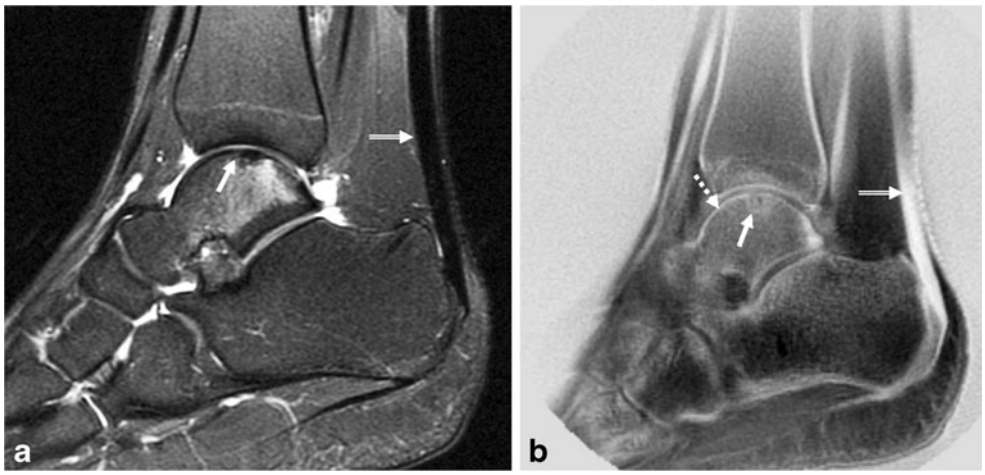

Fig. 6 Fourteen-year-old girl with ankle pain while playing soccer. **a** Sagittal fat-suppressed intermediate-weighted (3,000 msec/49 msec) image of the ankle shows an osteochondral lesion of the talar dome (*arrow*) with adjacent bone marrow edema pattern. The Achilles tendon (*double-line arrow*) shows uniform hypointense signal. **b** Sagittal subtracted UTE image (60 msec/100 μs) in the same location as (**a**) shows the intact thin hyperintense linear signal at the osteochondral junction of the anterior talar dome (*dashed arrow*), slightly less well-defined hyperintense signal extending deep to the lesion (*arrow*) and homogenous hyperintense signal of the Achilles tendon (*double arrow*)

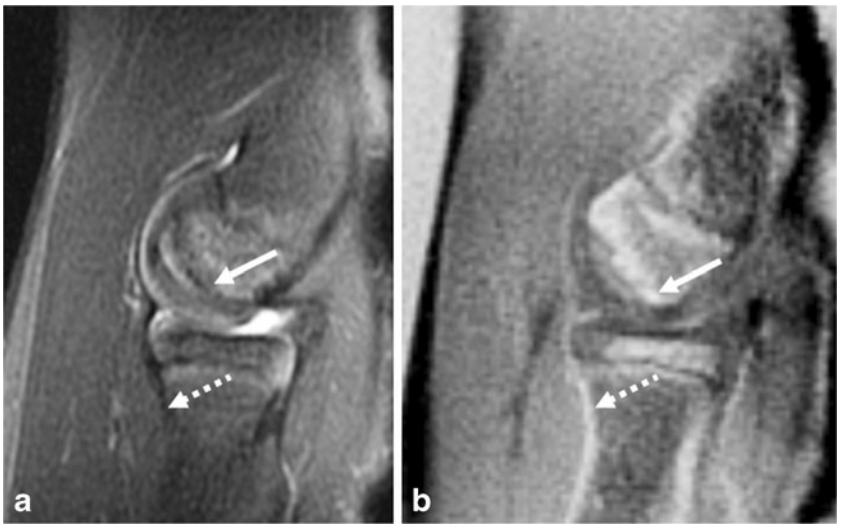

Fig. 7 Ten-year-old boy with elbow pain while playing baseball. **a** Sagittal fat-suppressed T2-weighted (2,350 msec/62 msec) image shows osseous irregularity of the capitellum with poorly delineated hypointense linear signal (*arrow*) at the interface with cartilage. Note the hypointense signal from the proximal radial cortex (*dashed arrow*). **b** Sagittal subtracted UTE image (60 msec/100 μs) in approximately the same location as (**a**) shows thick hyperintense signal (*arrow*) at the osteochondral junction. The cortex of the proximal radius has uniform linear hyperintense signal (*dashed arrow*)

offer new opportunities to evaluate various musculoskeletal structures, including those unique to growing children.

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Conflicts of interest Michael Carl, PhD, is an employee of GE Healthcare. Drs. Serai, Laor, Dwek and Zbojniewicz have no conflicts to report.

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