Introduction

Hyaline cartilage development is essential in pediatric musculoskeletal growth. Although in an adult patient, we focus solely on the articular cartilage, in the pediatric population, the articular, epiphysial and physial cartilage play an important role in skeletal maturation. The epiphysial and physial cartilage participate in enchondral ossification and contribute to a child’s longitudinal growth while the articular cartilage buffers and transmits forces across joints. Although functionally and anatomically different, the three different types of cartilage in the pediatric population are histologically alike.

Magnetic resonance imaging (MRI) is the ideal modality for the assessment of pediatric cartilage due to its lack of ionizing radiation and inherent excellent soft tissue contrast [1]. An optimal MRI sequence designed specifically for imaging hyaline cartilage should be able to accurately detect cartilage thickness and volume, characterize subtle morphological alterations as well as assess the adjacent bone. Three-dimensional (3D) MRI with isotropic, high resolution voxels is suitable for the pediatric population because it enables the radiologist to perform multiplanar reformats after a single sequence acquisition. This approach will also reduce scan time, which enhances the child’s compliance.

3T MR scanners with multichannel dedicated coils allow obtaining image data with high signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) [2]. Conventional spin echo and turbo spin echo sequences (T1, T2, and intermediate-weighted Proton Density sequences with or without fat suppression) as well as gradient echo techniques (incoherent GRE sequence, such as FLASH and coherent or steady state sequence, such as DESS) have been used for many years in cartilage imaging.

In this article, we will discuss the technical considerations as well as various clinical applications of Dual Echo Steady State (DESS) in imaging of the pediatric articular, epiphysial and physial cartilage on the 3T MAGNETOM Verio (Siemens Healthcare, Erlangen, Germany).

*Siemens disclaimer: 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.
Technical considerations

Dual Echo Steady State (DESS) is a 3D coherent (steady state) gradient echo sequence. Steady state sequences (FISP, TrueFISP, DESS, PSIF, CISS) share two major characteristics. Firstly, a short repetition time (TR) prevents transverse magnetization to decay before the next radiofrequency (RF) pulse is applied. Secondly, the slice or slab selective RF pulse is evenly spaced. When phase-coherent RF pulses with the same flip angle are applied with a constant TR that is shorter than the T2 of the tissue, a dynamic equilibrium is achieved between transverse magnetization (TM) and longitudinal magnetization (LM) [3]. Once this equilibrium is reached, two types of echoes and therefore two types of MR images are produced. The first type is post excitation signal (S+ or FISP (fast imaging steady state precession)) that consists of free induction decay (FID) arising from the most recent RF pulse. The second type is an echo reformation which occurs prior to excitation (S- or PSIF (reversed FISP)) and results when residual echo is refocused at the time of the subsequent RF pulse [4, 5]. DESS combines S+ and S- signals into one. High T2 contrast is obtained due to the PSIF contribution; whereas, morphological images are obtained by the FISP contribution. The variable T2-weightings of both echoes allow the calculation of quantitative T2. Therefore, the DESS sequence combines morphological and functional analysis from the same data set with high resolution in a relatively short imaging time [6].

In DESS, two or more gradient echoes are acquired. Each of these group of echoes are separated by a refocusing pulse and the combined data results in higher T2*-weighting, creating high signal in cartilage and synovial fluid [7]. The most important parameter which needs to be kept in mind while acquiring a DESS is the flip angle (FA). According to Hardy et al. [8], the appropriate flip angle for the 3D DESS sequence is 60 degrees which allows for high SNR and CNR.

Although hyaline cartilage is intermediate signal intensity and synovial fluid is high signal intensity in both 2D fat suppressed turbo spin echo proton density and 3D DESS, slice thickness is thinner in 3D DESS suggesting that this technique may detect smaller cartilage defects than the 2D technique (Fig. 1). Water excited or fat suppressed 3D gradient echo imaging is recommended for measuring the exact cartilage thickness without partial volume effects, even though the contrast-to-noise ratio between cartilage and bone marrow is relatively poor [9]. Chemical shift artifact can affect the cartilage-bone interface and fat suppression helps to reduce this, of particular importance in the physical cartilage.

The disadvantages of 3D gradient echo imaging techniques are relatively long scan time. In addition, fat suppressed turbo spin echo proton density is superior for intra-articular and periarticular structures and is obtained in short imaging time, but it has the previously mentioned disadvantage of partial volume effects.

Clinical applications

3D DESS allows quantitative assessment of cartilage thickness and volume with good accuracy and precision [10]. Although there have been longitudinal studies in adults regarding accuracy of DESS sequence in assessing the articular cartilage, there are no large comparative studies in the pediatric population [11]. We will discuss the potential applications of the DESS technique in assessment of pediatric epiphyseal, physial and articular hyaline cartilage.

Congenital: Skeletal dysplasias affect the normal epiphyseal cartilage zonal architecture [12, 13] and may manifest on MRI as disruptions in the zone of provisional calcification. Neonates with cartilage abnormalities, such as achondrogenesis and type II hypochondrogenesis, have shown a significant increase in the number and size of the epiphyseal vascular channels [14, 15].

12-year-old boy with prior history of Salter Harris II fracture of the distal tibia with DESS sequence (TR 12.8 ms, TE 4.7 ms, SL 0.5 mm, FOV 9.4 x 10 cm, matrix 320 x 320, Flip angle 45 degrees, acquisition time 7 minutes 30 seconds). Note the central loss of physial cartilage and development of physial bar (arrow).
In the setting of tarsal coalition, DESS can potentially be useful in distinguishing fibrous from cartilaginous fusion. In addition the volumetric 3D acquisition allows for multiplanar reformats which can be useful in assessment of complex subtalar joint morphology.

**Metabolic:** Metabolic disturbances, such as rickets and scurvy, can result in abnormal epiphysial cartilage development.

**Trauma:** The physis is a relatively weak region and is easily damaged by trauma, infection, tumor invasion, ischemia, radiation, metabolic and hematologic disorders, electrical and thermal burns, and frostbite [11, 12, 16–22]. Traumatic physial injuries may be seen in the various types of Salter-Harris fractures [22]. Generally, the frequency of growth arrest is directly proportional to the increasing Salter-Harris number [17]. Angular deformity such as in Blount disease, altered joint mechanics, leg-length discrepancy, and long-term disability can also result from injury to the physis at weight-bearing sites, such as the knees [16, 17]. Vertical physial injuries crossing growth plates can result in transphysial vascular communication. This communication can lead to the formation of bony bridges (Fig. 2). The DESS is ideal for assessment of physial bridges due to isotropic acquisition which can be used to generate multiplanar reformations and axial maximum-intensity-projection maps of the physial plate, all of which show high-signal cartilage interrupted by a low-intensity physial bridge [16–18]. Metaphysial vascular injury can result in the arrest of endochondral ossification and thickening of the injured physis (as in gymnast’s wrist) [17].

**Idiopathic:** Legg Calve Perthes disease (LCP) is an idiopathic cause of hip pain and limp in preadolescent children due to osteonecrosis (or osteochondrosis) of the femoral epiphysis. In the avascular phase, DESS can be used to assess acetabular cartilage and labral hypertrophy (Fig. 3). In the revascularization and reparative phase, findings that suggest possible physial involvement by LCP disease include increased undulation of the growth plate (W- or M-shaped), deepening of the growth plate or ‘cupping’, epiphysial–metaphyseal osseous fusion (bone bridge or bar formation across the physis), or physial cystic change [23].

7-year-old boy with left hip Leff Calve Perthes disease with coronal and sagittal DESS images (TR 12.9 ms, TE 5 ms, SL 0.75 mm, FOV 24 × 24 cm, matrix 256 × 240, flip angle 25 degrees, acquisition time 4 minutes 20 seconds). Although there is coxa magna and plana, there is also formation of fibrocartilage (arrow) within the central femoral articular cartilage. The sagittal FSPD sequence (TR 5171 ms, TE 36 ms, SL 3.0 mm /3.3 sp, FOV 18 × 19 cm) does not demonstrate the cartilage signal heterogeneity to the same advantage.
19-year-old young woman with remote history of septic arthritis on DESS sequence (TR 12.8 ms, TE 4.69 ms, SL 0.5 mm, FOV 9.4 × 10 cm, FA 45 degrees, acquisition time 6 minutes 18 seconds). The entire tibiotalar hyaline cartilage demonstrates diffuse intermediate grade thinning with large central lateral talar dome subchondral cyst (arrow).

16-year-old girl with high grade defect in the right central medial femoral condyle (arrow) on the preoperative MRI with DESS sequence (TR 14.1 ms, TE 5 ms, SL 0.6 mm, FA 25 degrees, FOV 15 × 15 cm, matrix 512 × 512, acquisition time 3 minutes 36 seconds). The patient underwent autologous chondrocyte implantation of the high grade defect in the central medial femoral condyle. Postoperative MRI with DESS (TR 14.1 ms, TE 5 ms, SL 0.6 mm, FA 25 degrees, FOV 15 × 15 cm, matrix 512 × 512, acquisition time 3 minutes 36 seconds) shows repair cartilage tissue that is homogeneous in signal intensity and flush with native cartilage with small focus of hypointense fibrocartilage formation (arrow). Note normal subchondral bone plate and interval resolution of minimal subchondral edema noted on the preoperative MRI.
Inflammation/Infection: Hyaline cartilage damage can also result from inflammatory conditions such as juvenile idiopathic arthritis as well as infection (Fig. 4). Sequelae of osteochondral injury include total-thickness loss of articular and epiphysial cartilage, cartilage contour irregularity, and intrinsic signal heterogeneity.

Post-operative: MRI is also used to follow cartilage repair procedures, such as microfracture, osteochondral autografts and allografts, and autologous chondrocyte implantation. The DESS sequence can assess cartilage repair via evaluation of repair tissue signal characteristics, border integration, thickness relative to native cartilage, chondral clefts and changes within the subchondral bone plate (Fig. 5).

Conclusions
The physical, epiphysial and articular hyaline cartilage is affected in various congenital, post-traumatic, idiopathic and inflammatory conditions in children. 3D DESS techniques have many advantages in assessment of pediatric cartilage pathology including higher SNR, increased cartilage-to-fluid contrast and isotropic resolution, which helps to reduce partial volume effects. 3D DESS techniques are also of essential importance in the pediatric population due to the lack of ionizing radiation.

References