UC San Diego

UC San Diego Previously Published Works

Title

Feasibility of using an inversion-recovery ultrashort echo time (UTE) sequence for quantification of glenoid bone loss.

Permalink

<https://escholarship.org/uc/item/2j01m80g>

Journal

Skeletal radiology, 47(7)

ISSN

0364-2348

Authors

Ma, Ya-Jun
West, Justin
Nazaran, Amin
et al.

Publication Date

2018-07-01

DOI

10.1007/s00256-018-2898-4

Peer reviewed

Feasibility of using an inversion-recovery ultrashort echo time (UTE) sequence for quantification of glenoid bone loss

Ya-jun Ma^{1,2} · Justin West³ · Amin Nazaran^{1,2} · Xin Cheng^{1,4} · Heinz Hoenecke³ · Jiang Du¹ · Eric Y. Chang²

Received: 27 November 2017 / Revised: 11 January 2018 / Accepted: 18 January 2018 / Published online: 2 February 2018
© This is a U.S. Government work and not under copyright protection in the US; foreign copyright protection may apply 2018

Abstract

Objective To utilize the 3D inversion recovery prepared ultrashort echo time with cones readout (IR-UTE-Cones) MRI technique for direct imaging of lamellar bone with comparison to the gold standard of computed tomography (CT).

Materials and methods CT and MRI was performed on 11 shoulder specimens and three patients. Five specimens had imaging performed before and after glenoid fracture (osteotomy). 2D and 3D volume-rendered CT images were reconstructed and conventional T1-weighted and 3D IR-UTE-Cones MRI techniques were performed. Glenoid widths and defects were independently measured by two readers using the circle method. Measurements were compared with those made from 3D CT datasets. Paired-sample Student's *t* tests and intraclass correlation coefficients were performed. In addition, 2D CT and 3D IR-UTE-Cones MRI datasets were linearly registered, digitally overlaid, and compared in consensus by these two readers.

Results Compared with the reference standard (3D CT), glenoid bone diameter measurements made on 2D CT and 3D IR-UTE-Cones were not significantly different for either reader, whereas T1-weighted images underestimated the diameter (mean difference of 0.18 cm, $p = 0.003$ and 0.16 cm, $p = 0.022$ for readers 1 and 2, respectively). However, mean margin of error for measuring glenoid bone loss was small for all modalities (range, 1.46–3.92%). All measured ICCs were near perfect. Digitally registered 2D CT and 3D IR-UTE-Cones MRI datasets yielded essentially perfect congruity between the two modalities.

Conclusions The 3D IR-UTE-Cones MRI technique selectively visualizes lamellar bone, produces similar contrast to 2D CT imaging, and compares favorably to measurements made using 2D and 3D CT.

Keywords Glenoid bone loss · MRI · UTE · Glenohumeral instability

Introduction

Accurate assessment of glenoid bone loss is important since it is a major determining factor in the success of arthroscopic soft tissue procedures versus the need for glenoid bone

grafting [1]. Currently, three-dimensional (3D) computed tomography (CT) of the injured shoulder is largely considered to be the most reliable preoperative imaging method of assessing the percent bone loss [2]. In a cadaveric study, 3D CT was shown to be the most accurate with the highest inter- and intra-

✉ Eric Y. Chang
ericchangmd@gmail.com

Ya-jun Ma
yam013@ucsd.edu

Justin West
jwwest21@gmail.com

Amin Nazaran
anazaran106@gmail.com

Xin Cheng
tchengxin@jnu.edu.cn

Heinz Hoenecke
hhoenecke@gmail.com

Jiang Du
jiangdu@ucsd.edu

¹ Department of Radiology, University of California, San Diego Medical Center, San Diego, CA 92103, USA

² Radiology Service, VA San Diego Healthcare System, 3350 La Jolla Village Drive, MC 114, San Diego, CA 92161, USA

³ Department of Orthopedic Surgery and Sports Medicine, Scripps Clinic, La Jolla, CA 92037, USA

⁴ Department of Histology & Embryology, Medical College, Jinan University, Guangzhou 510632, China

observer agreement for predicting percentage of glenoid bone loss when compared to two-dimensional (2D) CT, magnetic resonance imaging (MRI), and radiographs [3]. However, CT of the shoulder requires the patient to undergo an additional study leading to increased patient and healthcare time and costs as well as radiation exposure in usually young patients. Most patients with a history of shoulder instability are initially evaluated by radiography followed by MRI for soft tissue evaluation (including labrum and capsule), with CT ordered at a later time if there is suspicion of glenoid bone loss. It would be clinically beneficial to have an accurate and reliable MRI method to evaluate bone loss and eliminate the need for CT scans in younger patients.

Conventional MRI techniques are fundamentally limited in their assessment of bone due to the extremely short $T2/T2^*$ of lamellar bone [4]. Using conventional MRI sequences with longer echo times (TEs), the signal of short $T2/T2^*$ structures has decayed to background levels prior to acquisition. Rather, the contours of lamellar bone are inferred by visualizing fatty bone marrow or surrounding soft tissue, potentially resulting in imprecise localization. Techniques involving ultrashort echo time (UTE) can directly image lamellar bone, with newer methods incorporating fat and adjacent soft tissue suppression [4, 5]. These techniques produce images of cortical bone that are more similar in quality to those currently available by CT scan [6]. This yields itself well to the evaluation of patients with shoulder instability where MRI is performed early in their treatment course. Adoption of MRI as a primary method to assess glenoid bone defects could lead to less need for CT scans as well as lower healthcare costs and radiation exposure to patients. The purpose of this study is to utilize the 3D inversion recovery prepared ultrashort echo time with cones readout (IR-UTE-Cones) MRI technique for direct imaging of lamellar bone with comparison to the gold standard of CT.

Materials and methods

The institutional review board approved this Health Insurance Portability and Accountability Act-compliant study, which included an anonymized cadaveric portion and a human, in vivo portion. Written informed consent was obtained prior to patient participation in this study.

Specimens and patients

Eleven shoulder specimens (six females, five males; age range, 61–98 years; mean age, 86 years) were used for the cadaveric portion of this study. The specimens were frozen at -80°C and were thawed at room temperature for 24 h prior to imaging. All shoulder specimens underwent the CT and MRI protocols while intact, including soft tissues and bone. Based on the CT, five shoulder specimens with the least amount of glenoid bone loss (such as erosions or cyst-like changes) were chosen, the scapulae were dissected free of surrounding soft tissues, and glenoid lesions were created with an osteotome. CT and MRI protocols were then repeated on the deficient glenoids without their soft tissue envelope. In addition, three patients (one female, two males; age range, 20–64 years; mean age, 38 years) with glenohumeral joint complaints were imaged, including one with severe glenohumeral arthritis and two with glenohumeral instability.

CT and MRI

All shoulders included in this study underwent both 64-slice CT (VCT, GE Healthcare, Milwaukee, WI, USA) and 3-T MRI (Signa HDx 3-T or MR750 3-T, GE Healthcare). The CT protocol consisted of 0.625-mm axial images using the following parameters: 120 kV, 597 mA, and pitch of 0.98.

Fig. 1 3D IR-UTE-Cones sequence. **a** Pulse sequence diagram showing an adiabatic inversion recovery preparation sequence followed by a 3D Cones acquisition with ultrashort echo time. **b** Magnetization scheme of three proton pools including bone, during the course of the inversion recovery preparation. **c** Coronal IR-UTE-Cones image shows selective

visualization of lamellar bone, similar to computed tomography. *IR* inversion recovery, *RF* radiofrequency, *G* gradient, *DAW* data acquisition window, *TE* echo time, *FID* free induction decay, *M* magnetization, *TI* inversion time

Fig. 2 Reference standard method used to calculate glenoid bone loss. **a** A best-fit circle was placed along the inferior portion of the glenoid on the 3D CT image of the intact glenoid and the diameter was measured. **b** The circle and diameter measurements were digitally copied to the 3D CT

image of the fractured glenoid, the width of bone loss was measured (*red line*), and the measured defect was divided by the diameter of the best-fit circle

The axial images were used to reconstruct 2D sagittal oblique images of the glenoid with 2-mm thickness. The sagittal oblique plane was plotted based on both axial and coronal localizer planes in order to create an optimized en face view. Specifically, the anterior and posterior glenoid margins were identified on the axial images, the superior and inferior glenoid margins were identified on the coronal images, and the optimized sagittal oblique plane (en face view) was

verified to include the supra- and infra-glenoid tubercles in a single plane. In addition, 3D volume-rendered reconstructions were generated. The MRI protocol included conventional sequences, including axial and sagittal oblique T1-weighted (repetition time/echo time [TR/TE], 741/8.2 ms) images using the following parameters: field of view (FOV) of 15 cm, matrix of 384×320 , slice thickness of 3 mm, 0.3-mm interslice gap, with acquisition time of approximately 2 min per

Fig. 3 A 30-year-old patient with glenohumeral instability. **a** T1-weighted image shows poor definition of glenoid cortical bone contour and measurement of 2.56 cm was obtained. **b** IR-UTE-Cones image shows excellent depiction of bone contours and measurement of 2.79 cm was obtained, which is nearly perfect when compared to 3D CT measurement. **c** 2D CT image also shows excellent depiction of contours with 2.74-cm glenoid diameter. **d** 3D CT image was used as the reference standard

Table 1 Comparison of 2D CT, T1-weighted MRI, and IR-UTE-Cones MRI with 3D CT as a reference standard

Reader, modality	Mean $\pm$ SD (cm), <i>p</i> value	ICC
Reader 1		
3D CT	2.93 $\pm$ 0.27	
2D CT	2.97 $\pm$ 0.28, 0.111	0.963
T1-weighted	2.75 $\pm$ 0.32, 0.003	0.875
IR-UTE-Cones	2.88 $\pm$ 0.25, 0.080	0.968
Reader 2		
3D CT	2.94 $\pm$ 0.28	–
2D CT	2.98 $\pm$ 0.32, 0.265	0.962
T1-weighted	2.78 $\pm$ 0.39, 0.022	0.907
IR-UTE-Cones	2.92 $\pm$ 0.30, 0.618	0.950

n = 14 (intact specimens and in vivo cases)

Values in bold highlight *p*-values < 0.05

sequence. For MRI, the sagittal oblique plane was also oblique based on axial and coronal localizing planes similar to the CT.

In addition to the conventional T1-weighted images, the 3D IR-UTE-Cones sequence was employed, which utilizes an adiabatic inversion recovery pulse followed by a prototype 3D UTE acquisition (Fig. 1a). The 3D IR-UTE-Cones sequence employs a short rectangular pulse for signal excitation, which in combination with a time-efficient centric trajectory, allows for signal acquisition from rapidly decaying tissue components [7]. Bone images are obtained by inverting the longitudinal magnetization of the long T2 signal components (i.e., muscle and bone marrow fat) while saturating the signal from cortical bone [6, 8–11]. The Cones acquisition starts after an inversion time (TI) delay, which is used to null the long T2* components while permitting detection of recovered cortical bone signal (Fig. 1b). By using the 3D UTE-Cones sequence, 3D volumetric UTE imaging can be

obtained in an efficient way to maximize signal-to-noise ratio [6, 8] (Fig. 1c). The following parameters were used: FOV of 16 cm, matrix of 192 $\times$ 192, slice thickness of 3–4 mm, and TE of 0.03 ms. TI, TR, and flip angle (FA) for cadaveric imaging were 55 ms, 134 ms, and 18° whereas the values were 45 ms, 106 ms, and 16° for in vivo imaging. Selection of TI, TR, and FA varied between cadaveric and in vivo imaging largely due to temperature, which affects T1 relaxation [12]. The 3D IR-UTE-Cones technique was performed in the same imaging planes as the conventional sequences, including axial and sagittal oblique, with imaging time of approximately 3 to 4.5 min per sequence, depending on the number of slices required to cover the anatomy.

Image evaluation

2D CT, 2D T1-weighted MRI, and 3D IR-UTE-Cones MRI images were assessed using a clinical picture archiving and communication system (PACS) (Impax version 6.6.1, Agfa Healthcare, Ridgefield Park, NJ, USA). 3D volume-rendered CT images were measured using OsiriX (version 5.8, Pixmeo, Bernex, Switzerland). Cases were randomized and two readers independently made measurements, including a fellowship-trained musculoskeletal radiologist (E.Y.C. with 6 years of experience) and a fellowship-trained orthopedic surgeon (J.W. with 1 year of experience). Using images of the glenoid en face, a best-fit circle was placed along the inferior portion of the glenoid and the diameter was measured using electronic calipers [13]. For the bone loss cases, a vertical line bisecting the glenoid along its long axis was drawn from the supraglenoid tubercle and the center of the best-fit circle overlaid this vertical line. The width of the glenoid defects was measured and the percentage of bone loss was calculated as the width of the defect divided by the diameter

Table 2 Measured glenoid bone loss

Reader, modality	Measurement (%)	Error (%)	Change in accuracy (95% CI)
Reader 1			
Reference standard	18.28 $\pm$ 3.79	–	
3D CT	18.60 $\pm$ 4.86	1.63 $\pm$ 1.87	–0.7 to 4.0%
2D CT	16.25 $\pm$ 6.48	3.68 $\pm$ 2.60	0.5 to 6.9%
T1-weighted	18.99 $\pm$ 5.81	3.13 $\pm$ 2.95	–0.5 to 6.8%
IR-UTE-Cones	19.72 $\pm$ 5.98	2.96 $\pm$ 2.88	–0.6 to 6.5%
Reader 2			
Reference standard	19.04 $\pm$ 4.46	–	
3D CT	18.43 $\pm$ 4.18	3.22 $\pm$ 0.95	2.0 to 4.4%
2D CT	18.35 $\pm$ 4.60	1.46 $\pm$ 0.60	0.7 to 2.2%
T1-weighted	15.77 $\pm$ 2.85	3.27 $\pm$ 2.60	0.4 to 6.5%
IR-UTE-Cones	15.12 $\pm$ 4.66	3.92 $\pm$ 2.16	1.2 to 6.6%

Data are reported as mean $\pm$ SD. Reference standard measurements were made using both pre- and post-lesion 3D CT datasets

Table 3 Inter-observer reliability

Modality	<i>P</i> value	ICC
3D CT	0.151	0.997
2D CT	0.226	0.991
T1-weighted	0.033	0.957
IR-UTE-Cones	0.051	0.983

Values in bold highlight *p*-values < 0.05

of the best-fit circle. For the reference standard measurement of glenoid bone loss, both the 3D CT of the intact and fractured glenoid was utilized for maximal confidence (Fig. 2). Specifically, the best-fit circle drawn on the intact glenoid was digitally copied to the fractured glenoid and the glenoid defect was then measured.

In addition, for all cases, registration of the 2D CT and 3D IR-UTE-Cones MRI datasets was performed after binary thresholding and linear registration via the FSL FLIRT program (FMRIB's Linear Registration Tool, fsl.fmrib.ox.ac.uk/fsl/fslwiki/FLIRT). Registered images were digitally overlaid and qualitatively evaluated in consensus by the two readers to assess congruity.

Statistical analysis

Descriptive statistics were performed. For the shoulders without glenoid bone loss, paired-sample Student's *t* tests and intraclass correlation coefficients (ICC) were used to compare the measurements made on 2D CT, 2D T1-weighted MRI, and 3D IR-UTE-Cones MRI images to the reference standard images (3D CT) for each reader. For the cases with glenoid defects, the percentage of bone loss calculated for each modality was compared with the reference standard of 3D CT (using both pre- and post-lesion datasets). The absolute value of the difference between the imaging measure and reference standard assessment was calculated and mean and standard deviations

were performed. Based on the difference between the imaging measure and reference standard assessment, 95% confidence intervals were also performed. To assess reliability between readers, paired-sample Student's *t* tests and ICCs were also used to compare all measurements made for each modality and sequence. An ICC of 0.01 was considered poor agreement, 0.01 to 0.2 was considered slight agreement, 0.21 to 0.4 was considered fair agreement, 0.41 to 0.6 was considered moderate agreement, 0.61 to 0.8 was considered substantial agreement, and 0.8 to 1.0 was considered almost perfect agreement [14]. *P* values less than 0.05 were considered significant. All statistical analyses were performed using the SPSS software package (version 21; SPSS, Chicago, IL, USA).

Results

Figure 3 shows representative images of T1-weighted, IR-UTE-Cones, 2D CT, and 3D CT in a 30-year-old patient with glenohumeral instability. Confidence in lamellar bone margin was lacking on the T1-weighted images, whereas the margins were well identified on IR-UTE-Cones and CT imaging.

Table 1 shows the mean ($\pm$ standard deviation [SD]) of the intact glenoids as measured on each modality for each reader with comparison statistics. Compared with the reference standard (3D CT), measurements made on 2D CT and IR-UTE-Cones were not significantly different for either reader, whereas T1-weighted images underestimated the diameter (mean difference of 0.18 cm, $p = 0.003$ and 0.16 cm, $p = 0.022$ for readers 1 and 2, respectively). Despite this, ICCs for 2D CT, T1-weighted images, and IR-UTE-Cones images were near perfect when compared to 3D CT.

Table 2 shows the mean ($\pm$ SD) of the measured percent glenoid bone loss for each modality. Using the reference standard of pre- and post-lesion 3D CT, mean % glenoid bone loss was measured at 18.28 ± 3.79 and 19.04 ± 4.46 by reader 1

Fig. 4 Registered images from a shoulder specimen. **a** IR-UTE-Cones image shows high-contrast lamellar bone imaging of the glenoid en face. **b** Registered sagittal CT image after binary thresholding. **c** Overlaid CT

image (in green) on the MRI image shows near-perfect correlation of lamellar bone contours

Fig. 5 Axial images of a shoulder specimen. **a** T1-weighted MRI image shows the posterior glenoid contour to appear rounded (*arrow*) due to over-reliance on marrow contour and poor visualization of lamellar bone.

b 2D CT image at the same location shows that the posterior glenoid is pointed (*arrow*) due to an osteophyte. **c** IR-UTE-Cones MRI image shows the same findings as 2D CT

and reader 2, respectively. If only the post-lesion 3D CT were used for measurement, the maximum change in accuracy expected in terms of percentage was -0.7 to 4.0% (reader 1) and 2.0 to 4.4% (reader 2) with 95% confidence. If only the post-lesion 2D CT were used for measurement, the maximum change in accuracy expected would be 0.5 to 6.9% (reader 1) and 0.7 to 2.2% (reader 2) with 95% confidence. If only the post-lesion T1-weighted MRI were used for measurement, the maximum change in accuracy expected would be -0.5 to 6.8% (reader 1) and 0.4 to 6.5% (reader 2) with 95% confidence. If only the post-lesion IR-UTE-Cones MRI were used for measurement, the maximum change in accuracy expected would be -0.6 to 6.5% (reader 1) and 1.2 to 6.6% (reader 2) with 95% confidence.

Table 3 shows inter-observer reliability statistics. Measurements made by readers 1 and 2 were not significantly different for 3D CT, 2D CT, and IR-UTE-Cones measurements, but T1-weighted MRI measurements were different between readers ($p = 0.033$). ICCs were near perfect for all modalities.

Registration and overlay of the 2D CT and 3D IR-UTE-Cones MRI datasets yielded essentially perfect congruity between the two modalities (Fig. 4).

Discussion

In this study, we utilized the 3D IR-UTE-Cones MRI sequence to evaluate the glenoid in both specimens and in vivo. This MRI sequence differs from existing conventional sequences in its ability to directly obtain a signal from lamellar bone while simultaneously suppressing fat and surrounding soft tissues. The resulting contrast is similar to 2D CT. The UTE sequence, which utilizes TEs short enough to capture lamellar bone signal, was first described nearly three decades ago [15], but only in recent years has advances in hardware and software technology allowed for high-quality imaging in clinically compatible imaging times. UTE sequences have been successfully implemented on every major MRI vendor system [4], but have not yet been offered as a product sequence. We believe that demonstrating this exciting application for assessment of glenoid bone stock will be important in pushing the product into clinics.

Some studies have suggested that quantitative measurements made on conventional MRI sequences are similar to those made on CT [16–19], whereas others have shown a higher performance of CT [3, 20, 21]. More recently, 3D MRI sequences were implemented with a Dixon fat-

Fig. 6 Potential source of error in non-circular glenoids. **a** Glenoid bone loss measurement based on best-fit circle obtained from the pre-lesion 3D CT (same image as Fig. 2b). Width of fragment measured 3.9 mm and

length 2.664 cm. **b** When only the post-lesion 3D CT was used for measurement, a best-fit circle resulted in a fragment measurement of 4.4 mm and length 2.676 cm. 14.7% bone loss was calculated ($0.39/2.66$). 16.4% bone loss calculation ($0.44/2.68$)

suppression technique, which enabled soft tissue subtraction and increased contrast from lamellar bone [22–24]. However, as no signal is directly obtained from the lamellar bone, this type of image manipulation results in artifactual signal increase of all black pixels (e.g., zero signal air is also displayed as high signal in addition to lamellar bone). Moreover, post-processing times were reported to be approximately 10–25 min for experienced 3D lab technologists [22, 23], which is prohibitory for most clinical practices. With the 3D IR-UTE-Cones sequence, no post-processing is required, as images can be directly visualized and measured using any standard PACS software.

We have shown that the 3D IR-UTE-Cones sequence allows for direct and selective visualization of lamellar bone, which aligns nearly perfectly when registered to 2D CT. When used to evaluate the width of the intact glenoid, the 3D IR-UTE-Cones sequence performed equally well to 3D and 2D CT, whereas measurements made on T1-weighted images significantly underestimated the width. This may be due to a lack of confidence in estimating the cortical margin (Fig. 3a) and/or over-reliance on the hyperintense marrow fat (Fig. 5).

With regards to measurement of glenoid bone loss, we used the reference standard of 3D CT datasets before and after lesion creation. This was chosen as the gold standard since knowledge of the uninjured glenoid diameter allowed us to be most confident in both the numerator and denominator of the glenoid bone loss equation. We were surprised at the relatively poor performance of all the modalities for measuring glenoid bone loss, including the post-lesion 3D CT images. Upon retrospective review of all of our glenoid bone loss cases, we found the worst performance in glenoids that did not demonstrate a completely circular shape. In these cases, the loss of bone anteriorly coupled with the remaining non-circular margin resulted in incorrect estimation of the native bone contour (Fig. 6). Other authors have noted similar limitations when using the best-fit circle method [18, 25]. However, we found that measuring glenoid diameters using IR-UTE-Cones and 2D CT were very accurate when compared to our reference standard of 3D CT and reliable between raters. We emphasize that the IR-UTE-Cones technique and CT corresponded nearly perfectly when digitally registered and therefore measurement errors were not due to modalities, but limitations in the measurement technique. Also of note is that all of our glenoid bone loss cases fell between 12 and 25%, which Bishop et al. showed to be the range with the worst inter-observer performance ($\kappa < 0.4$ using 3D CT) [3].

Our study has several limitations. First, our study utilized a limited sample size. We believe that the data demonstrate that this new MRI technique is feasible and is quite comparable to CT. However, establishment of non-inferiority of the UTE MRI compared to the gold standard would require a much larger number of subjects. Second, it is important to highlight that although the IR-UTE-Cones is a 3D MRI sequence, it is

highly anisotropic. Unlike CT, which utilizes sub-millimeter slice thicknesses, the signal-to-noise of lamellar bone remains too low to utilize these resolutions with the 3D IR-UTE-Cones sequence. Therefore, if 3D volume-rendered imaging is desired, alternative methods are required. Third, our study was performed at 3 T and imaging at lower field strengths, such as 1.5 T, will certainly incur a time penalty for similar image quality. In addition, we did not perform a systematic study for optimization of the 3D IR-UTE-Cones sequence and this will be explored in a future study. Finally, this new sequence is not yet available in routine clinical practice. However, we performed this study using two different MRI machines (including one over 12 years old) and the UTE sequence has been successfully employed on machines from every major vendor. This sequence only requires a software package to be installed without any hardware modifications or post-processing steps. We feel that demonstrating the utility of this novel technique is the most important step for manufacturers to incorporate this sequence into software package upgrades.

In conclusion, in this pilot study, we have utilized a new MRI technique (3D IR-UTE-Cones), which selectively visualizes lamellar bone and produces similar contrast to 2D CT imaging. This sequence can be added to conventional MRI examinations with minimal increases in imaging times and may eventually eliminate the need for pre-surgical CT examinations.

Acknowledgements The authors acknowledge support from the VA Clinical Science Research and Development Service (I01CX001388), NIH (R01AR062581 and R01AR068987), and GE Healthcare.

Compliance with ethical standards

Conflict of interest There are no conflicts of interest to disclose related to this work.

References

1. Bhatia S, Ghodadra NS, Romeo AA, Bach BR, Verma NN, Vo ST, et al. The importance of the recognition and treatment of glenoid bone loss in an athletic population. *Sports Health*. 2011;3(5):435–40.
2. Saliken DJ, Bornes TD, Bouliane MJ, Sheps DM, Beaupre LA. Imaging methods for quantifying glenoid and Hill–Sachs bone loss in traumatic instability of the shoulder: a scoping review. *BMC Musculoskelet Disord*. 2015;16:164.
3. Bishop JY, Jones GL, Rerko MA, Donaldson C, Group MS. 3-D CT is the most reliable imaging modality when quantifying glenoid bone loss. *Clin Orthop Relat Res*. 2013;471(4):1251–6.
4. Chang EY, Du J, Chung CB. UTE imaging in the musculoskeletal system. *J Magn Reson Imaging*. 2015;41(4):870–83.
5. Chang EY, Du J, Bae WC, Chung CB. Qualitative and quantitative ultrashort echo time imaging of musculoskeletal tissues. *Semin Musculoskelet Radiol*. 2015;19(4):375–86.
6. Carl M, Bydder GM, Du J. UTE imaging with simultaneous water and fat signal suppression using a time-efficient

- multispoke inversion recovery pulse sequence. *Magn Reson Med.* 2016;76(2):577–82.
7. Gurney PT, Hargreaves BA, Nishimura DG. Design and analysis of a practical 3D cones trajectory. *Magn Reson Med.* 2006;55(3):575–82.
 8. Chen J, Chang EY, Carl M, Ma Y, Shao H, Chen B, et al. Measurement of bound and pore water T1 relaxation times in cortical bone using three-dimensional ultrashort echo time cones sequences. *Magn Reson Med.* 2017;77(6):2136–45.
 9. Li S, Ma L, Chang EY, Shao H, Chen J, Chung CB, et al. Effects of inversion time on inversion recovery prepared ultrashort echo time (IR-UTE) imaging of bound and pore water in cortical bone. *NMR Biomed.* 2015;28(1):70–8.
 10. Horch RA, Gochberg DF, Nyman JS, Does MD. Clinically compatible MRI strategies for discriminating bound and pore water in cortical bone. *Magn Reson Med.* 2012;68(6):1774–84.
 11. Du J, Carl M, Bydder M, Takahashi A, Chung CB, Bydder GM. Qualitative and quantitative ultrashort echo time (UTE) imaging of cortical bone. *J Magn Reson.* 2010;207(2):304–11.
 12. Han M, Rieke V, Scott SJ, Ozhinsky E, Salgaonkar VA, Jones PD, et al. Quantifying temperature-dependent T1 changes in cortical bone using ultrashort echo time MRI. *Magn Reson Med.* 2015;74(6):1548–55.
 13. Huysmans PE, Haen PS, Kidd M, Dhert WJ, Willems JW. The shape of the inferior part of the glenoid: a cadaveric study. *J Shoulder Elb Surg.* 2006;15(6):759–63.
 14. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics.* 1977;33(1):159–74.
 15. Pauly JM, Conolly SI, Nishimura D, Macovski A. Slice-Selective Excitation for Very Short T2 Species. Amsterdam: ISMRM 8th Scientific Meeting & Exhibition; 1989. p. 28.
 16. Huijsmans PE, Haen PS, Kidd M, Dhert WJ, van der Hulst VP, Willems WJ. Quantification of a glenoid defect with three-dimensional computed tomography and magnetic resonance imaging: a cadaveric study. *J Shoulder Elb Surg.* 2007;16(6):803–9.
 17. Gyftopoulos S, Hasan S, Bencardino J, Mayo J, Nayyar S, Babb J, et al. Diagnostic accuracy of MRI in the measurement of glenoid bone loss. *AJR Am J Roentgenol.* 2012;199(4):873–8.
 18. Lee RK, Griffith JF, Tong MM, Sharma N, Yung P. Glenoid bone loss: assessment with MR imaging. *Radiology.* 2013;267(2):496–502.
 19. Stecco A, Guenzi E, Cascone T, Fabbiano F, Fornara P, Ortonzo P, et al. MRI can assess glenoid bone loss after shoulder luxation: inter- and intra-individual comparison with CT. *Radiol Med.* 2013;118(8):1335–43.
 20. Rerko MA, Pan X, Donaldson C, Jones GL, Bishop JY. Comparison of various imaging techniques to quantify glenoid bone loss in shoulder instability. *J Shoulder Elb Surg.* 2013;22(4):528–34.
 21. Moroder P, Resch H, Schnaitmann S, Hoffelner T, Tauber M. The importance of CT for the pre-operative surgical planning in recurrent anterior shoulder instability. *Arch Orthop Trauma Surg.* 2013;133(2):219–26.
 22. Gyftopoulos S, Yemin A, Mulholland T, Bloom M, Storey P, Geppert C, et al. 3DMR osseous reconstructions of the shoulder using a gradient-echo based two-point Dixon reconstruction: a feasibility study. *Skelet Radiol.* 2013;42(3):347–52.
 23. Gyftopoulos S, Beltran LS, Yemin A, Strauss E, Meislin R, Jazrawi L, et al. Use of 3D MR reconstructions in the evaluation of glenoid bone loss: a clinical study. *Skelet Radiol.* 2014;43(2):213–8.
 24. Stillwater L, Koenig J, Maycher B, Davidson M. 3D-MR vs. 3D-CT of the shoulder in patients with glenohumeral instability. *Skelet Radiol.* 2017;46(3):325–31.
 25. De Wilde LF, Berghs BM, Audenaert E, Sys G, Van Maele GO, Barbaix E. About the variability of the shape of the glenoid cavity. *Surg Radiol Anat.* 2004;26(1):54–9.