Can magnetic resonance imaging accurately and reliably measure humeral cortical thickness?

Peter N. Chalmers, MD, Garrett V. Christensen, MD, Hiroaki Ishikawa, PT, PhD, Heath B. Henninger, PhD, Eugene G. Kholmovski, PhD, Megan Mills, MD, Robert Z. Tashjian, MD

Department of Orthopaedic Surgery, University of Utah, Salt Lake City, UT, USA
Department of Radiology and Imaging Sciences, University of Utah, Salt Lake City, UT, USA

Background: Historically, imaging osseous detail in three dimensions required a computed tomography (CT) scan with ionizing radiation that poorly visualizes the soft tissues. The purpose of this study was to determine the accuracy and reliability of ultrashort echo time (UTE) magnetic resonance imaging (MRI) in measuring humeral cortical thickness and cancellous density as compared with CT.

Methods: This was a comparative radiographic study in nine cadavers, each of which underwent CT and UTE MRI. On images aligned to the center of the humeral shaft, anterior, posterior, medial, and lateral humeral cortical thickness was measured 5, 10, and 15 cm distal to the top of the head. Cancellous density was measured as signal within a 1-cm diameter region of interest in the center of the head, the subtuberosity head, the subarticular head, and the subarticular glenoid vault. Glenoid cortical thickness was measured at the center of the glenoid. Cancellous measurements were compared using mean differences and 95% confidence intervals, paired Student’s t-tests, and intraclass correlation coefficients (ICCs). We compared cancellous measurements using Pearson’s correlation coefficients. For all measurements, we calculated interobserver and intraobserver reliability using ICCs with 0.75 as the lower limit for acceptability.

Results: With regard to accuracy, for humeral cortical thickness measurements, there were no significant differences between MRI and CT measures, and ICCs were >0.75. The glenoid cortical thickness ICC was <0.75. There was no significant correlation between the cancellous signal on MRI and on CT in any region. For both MRI and CT, interobserver reliability and intraobserver reliability were acceptable (ie, >0.75) for almost all humeral cortical thickness measures.

Conclusion: UTE MRI can reliably and accurately measure humeral cortical thickness, but cannot accurately measure cancellous density or accurately and reliably measure glenoid cortical thickness.

© 2021 The Authors. Published by Elsevier Inc. on behalf of American Shoulder and Elbow Surgeons. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Assessing bone quality is a critical evaluation before shoulder surgery. Osteoporosis has been demonstrated to be a risk factor for complications in a variety of shoulder procedures. Historically, assessment of bone quality has relied on dual-energy x-ray absorptiometry (DEXA), which has multiple drawbacks. First, DEXA subjects patients to radiation. Second, this scan is not a standard orthopedic evaluation and is thus an additional test that is inconvenient for patients and surgeons. Third, this test provides no information specific to the shoulder as it assesses hip and spine bone density to provide only a global assessment of bone density. Finally, multiple studies have demonstrated that DEXA incompletely assesses fracture risk and bone quality. These factors of inconvenience, nonspecificity to the shoulder, and incomplete assessment of bone quality limit the utility of DEXA.

Computed tomography (CT) can reliably measure proximal humeral cortical thickness, which correlates with bone mineral density and can be used to rule out osteoporosis. This imaging is preferable to DEXA as it is specific to the joint, but exposes patients to significantly more ionizing radiation. However, although CT provides excellent visualization of osseous detail, it provides poor...
visualization of soft tissues, such as the rotator cuff tendons, labrum, and glenohumeral ligaments. As a result, CT is not an ideal preoperative imaging modality before a rotator cuff repair, arthroscopic labral repair, or anatomic shoulder arthroplasty.

Magnetic resonance imaging (MRI) provides excellent soft-tissue detail and can diagnose labral tears and rotator cuff tears with excellent sensitivity and specificity. Historically, MRI has provided poor osseous detail in comparison with CT. However, the ultrashort echo time (UTE) MRI sequence has recently been demonstrated to provide osseous detail sufficient to produce auto-segmented three-dimensional reconstructions that provide equivalent measurements of glenoid bone loss to CT in the setting of glenohumeral instability. UTE MRI, in complement with traditional MRI sequences, may provide the ideal preoperative imaging set for the shoulder as it has no ionizing radiation and excellent resolution of osseous and soft-tissue detail (Fig. 1).

Therefore, the purpose of this study was to determine the accuracy and intraobserver and interobserver reliability of UTE MRI in measurement of humeral cortical thickness, glenoid cortical thickness, and cancellous density as compared with CT.

Materials and methods

Imaging protocol

This is a prospective, cadaveric, controlled, comparative radiographic study. Cadavers from our laboratory underwent both CT and MRI, where both scans were obtained with specimens in a supine anatomic position. The imaging field-of-view included the entirety of the cadaver shoulder for both modalities. CT scans were obtained using a SOMATOM Definition Flash (Siemens, Erlangen, Germany), acquired with a 120 kV tube voltage, 0.6 pitch, 60 mAs tube current, 1.0 mm slice thickness, and 512 x 512 matrix (voxel size = 0.5 x 0.5 x 1.0 mm). MRI studies were performed on the 3 Tesla Prisma (Siemens, Erlangen, Germany) scanner using the head coil. UTE MRI scans were acquired with isotropic spatial resolution (voxel size = 0.7 x 0.7 x 0.7 mm). The scan parameters were echo time (TE) = 0.07 ms, repetition time = 3.64 ms, and flip angle = 6°. The scan time was 3 minutes and 46 seconds on average. All images were saved in the digital imaging and communication in medicine (DICOM) format and then reviewed by a fellowship-trained orthopedic shoulder and elbow surgeon (PNC) to ensure there was no visible shoulder pathology.

Measurement technique

All measurements were performed in third-party DICOM viewer analysis software (Horos, Pixmeo, Geneva, Switzerland). All humeral measurements were performed on axial images reoriented into the axial plane of the humerus, with both the coronal and sagittal planes parallel to a line down the center of the shaft, the origin defined as the point closest to the center of the head while still intersecting with the center of the shaft, and a line from the center of the head to the deepest point of the biceps groove defining anterior (Fig. 2). We then made measures at locations 5, 10, and 15 cm distal to the top of the head along this shaft center.

Figure 1 Representative axial images in ultrashort echo time magnetic resonance imaging (UTE MRI) (A and C) and computed tomography (CT) (B and D) in the same cadaver at the Center of the head (A and B) and 10 cm distal to the Top of the head (C and D).
line, and at each distance, we measured the maximum humeral cortical thickness at each axis (medial, lateral, anterior, posterior). To quantify cancellous density, we created circular regions of interest (ROIs) 1 cm in diameter, with the mean signal within each ROI representing cancellous density in that ROI. These ROIs were placed in the center of the head (as defined previously), just subcortical at the lateral most extent of the tuberosity on the coronal view, and just subcortical at the medial most portion of the head on the sagittal image (Fig. 3). In addition, a similar technique was used to measure ROI signal within the glenoid vault to measure cancellous density, which was normalized as described previously.

### Statistical methods

At each distance from the top of the head, the anterior, posterior, medial, and lateral cortical thickness measurements were used to calculate a mean cortical thickness for each imaging modality and specimen. We compared cortical measurements using intraclass correlation coefficients (ICCs) with a 2-way mixed average measure for absolute agreement. In addition, we compared cortical measurements using mean differences and 95% confidence intervals for these differences, using paired Student’s t-tests. We compared cancellous measurements using Pearson’s correlation coefficients.

---

**Figure 2** These computed tomographic coronal (A, orange line), sagittal (B, blue line), and axial (C, purple line) images demonstrate the planes for reorienting the axes to match the Center of the shaft, with anterior defined as a line from the Center of the head to the deepest point of the biceps groove (C).

**Figure 3** These ultrashort echo time magnetic resonance imaging (UTE MRI) images demonstrate the position of the 1-cm diameter region of interest (ROI) for the Center of the head (A, axial image), the subtuberosity region (B, coronal image), and the subarticular region (C, sagittal image).
and created Bland-Altman plots for the cortical measurements. All images were interpreted by two observers blinded to each other’s measurements and one observer twice separated by a period of 4 weeks. Interobserver reliability and intraobserver reliability were calculated using ICCs with a 2-way mixed model for absolute agreement and average or single measurements as appropriate. We conducted all analyses in Excel (version 16, Microsoft, Redmond, WA, USA) and SPSS (version 26, IBM, Armonk, NY, USA). A priori we selected 0.05 as our threshold for significance and 0.75 as our lower limit for acceptability for ICCs.

**Results**

**Cohort characteristics**

We included 9 shoulders on the right side from 7 male and 2 female cadavers with a mean age at the time of death of 69 years (range, 59-80 years). The mean ± standard deviations of their height and weight were 172.2 ± 5.6 cm and 66.1 ± 23.5 kg, respectively. Cortical thickness increased with distance from the head, from a mean (95% confidence interval) of 2.3 (2.1 to 2.6) mm...
at 5 cm distal to the head on CT to 4.2 (3.7 to 4.7) mm at 15 cm
distal to the head. On CT, glenoid subchondral cortical thickness
was 1 (0.9 to 1.1) mm at the center of the glenoid. On CT, cancell-
ous signal was lowest in the subtuberosity region and the center
of the head and highest in the subarticular region and glenoid
vault (Table II).

Table II
Cancellous signal measurements for both imaging modalities.

| Variable                | MRI        | CT         | Correlation | P value |
|-------------------------|------------|------------|-------------|---------|
| Center of the head      | 1.18 [1.10 to 1.26] | 106 [ 51 to 160] | −0.087      | .823    |
| Subtuberosity           | 1.15 [1.04 to 1.26] | 91 [ 66 to 116]  | −0.511      | .160    |
| Subarticular            | 1.20 [1.08 to 1.33] | 171 [141 to 200] | −0.491      | .179    |
| Glenoid vault           | 1.16 [1.05 to 1.27] | 259 [222 to 296] | 0.188       | .629    |

All data are presented as mean [95% confidence intervals]. P values are the results of Pearson’s correlation coefficients.

MRI data are presented as the ratio of osseous to muscle signal intensity, and CT data are presented in Hounsfield’s Units.

MRI, magnetic resonance imaging; CT, computed tomography; ICC, intraclass correlation coefficient.

Figure 5 Box plots of computed tomography (CT) and magnetic resonance imaging (MRI) measurements of humeral cortical thickness at varying distances distal to the Top of the head of the humerus. No statistically significant differences were observed between modalities. The boxes represent the interquartile range, with the central line representing the median. The whiskers represent the furthest nonoutlier, nonextreme value. The dot represents an outlier.

Figure 6 Box plots of computed tomography (CT) and magnetic resonance imaging (MRI) measurements of glenoid cortical thickness at the Center of the glenoid. No statistically significant difference was detected between modalities. The boxes represent the interquartile range, with the central line representing the median. The whiskers represent the furthest nonoutlier, nonextreme value.

Accuracy: UTE MRI vs. CT

For cortical thickness measurements, in all cases, the 95% confidence intervals of mean difference between MRI and CT measures included 0, and there was no statistically significant difference between measures made between modalities (Table I, Figs. 5–7).
Discussion

For humeral cortical thickness measurements at all three distances from the top of the head, the ICCs were >0.75. In combination, these results suggest that UTE MRI and CT measures of humeral cortical thickness are equivalent. However, the ICCs for glenoid subchondral thickness were <0.75, suggesting that UTE MRI and CT do not reliably provide the same measurements. There was no statistically significant correlation between cancellous signal on MRI and cancellous bone loss in the setting of glenohumeral instability, with differing results.24 Within the present study, glenoid cortical thickness could not be accurately measured, likely because the glenoid articular cortical thickness is only 1.1 mm. However, several studies have demonstrated MRI to be capable for accurately measuring long bone cortical thickness.7,27,28 In concert with our own findings, these suggest that UTE MRI is an accurate and reliable method for measuring proximal humeral cortical thickness.

Our results suggest that UTE MRI can reliably delineate proximal humeral cortical thickness. Prior research is conflicting on the ability of MRI to delineate cortical anatomy. For instance, several studies have examined use of standard MRI sequences to measure glenoid bone loss in the setting of glenohumeral instability, with differing results.2,10,11,19,22,29,35,39 Within the present study, glenoid cortical thickness could not be accurately measured, likely because the glenoid articular cortical thickness is only 1.1 mm. However, several studies have demonstrated MRI to be capable for accurately measuring long bone cortical thickness.27,28 In concert with our own findings, these suggest that UTE MRI is a reliable method for measuring proximal humeral cortical thickness.

For both MRI and CT, interobserver and intraobserver reliability was acceptable (ie, >0.75) for all humeral cortical thickness measures and cancellous density measures, with the exception of the interobserver reliability of the humeral subarticular region on MRI, and glenoid subchondral thickness measures did not have acceptable interobserver or intraobserver reliability on either MRI or CT (Table III).

Table III

| Variable                  | Interobserver |                     | Intraobserver |                     |
|---------------------------|---------------|---------------------|---------------|---------------------|
|                           | MRI           | CT                  | MRI           | CT                  |
| Humerus 5 cm              | 0.753 [0.949] | 0.898 [0.694 - 0.974] | 0.898 [0.549 - 0.977] | 0.968 [0.660 - 0.993] |
| Humerus 10 cm             | 0.799 [0.958] | 0.847 [0.842 - 0.971] | 0.775 [0.609 - 0.951] | 0.928 [0.681 - 0.984] |
| Humerus 15 cm             | 0.991 [0.998] | 0.761 [0.905 - 0.946] | 0.900 [0.904 - 0.950] | 0.983 [0.924 - 0.986] |
| Glenoid                   | -0.362 [-0.350] | 0.017 [-0.621 - 0.641] | -0.373 [-0.813 - 0.339] | 0.425 [-0.283 - 0.883] |
| Center of the head        | 0.954 [0.812] | 0.900 [0.862 - 0.977] | 0.987 [0.844 - 0.997] | 0.948 [0.789 - 0.988] |
| Subtuberosity             | 0.932 [0.871] | 0.895 [0.907 - 0.957] | 0.952 [0.904 - 0.989] | 0.841 [0.445 - 0.962] |
| Subarticular              | 0.575 [-0.089] | 0.855 [0.480 - 0.956] | 0.975 [0.895 - 0.994] | 0.908 [0.647 - 0.978] |
| Glenoid vault             | 0.989 [0.954] | 0.912 [0.660 - 0.959] | 0.967 [0.943 - 0.997] | 0.955 [0.613 - 0.990] |

All values represent intraclass correlation coefficients [95% confidence intervals]. Acceptable values, that is >0.75, are bolded.

MRI, magnetic resonance imaging; CT, computed tomography.
These scans were of normal cadavers, and thus, our results may not be generalizable to shoulders with glenohumeral osteoarthritis, rotator cuff tears, or glenohumeral instability. Both observers included in this study have extensive experience using the measurement techniques described herein, as similar techniques have been used in prior studies. However, these results are sufficiently promising to proceed with inclusion of the UTE pulse sequence within several of our clinical scan protocols, facilitating future research to confirm the accuracy and reliability of these results. Finally, for UTE MRI to fully replace CT in imaging for shoulder surgery, it will need to provide three-dimensional auto-segmentations sufficiently accurate for prearthroplasty planning software. Further studies will be necessary to assess UTE MRI’s capabilities in this regard.

Conclusion

UTE MRI can be used to reliably and accurately measure humeral cortical thickness, but cannot accurately measure cancellous density or glenoid cortical thickness.

Disclaimers:

Funding: The research reported in this publication was supported by the National Institute of Arthritis and Musculoskeletal and Skin Diseases (NIAMS) of the National Institutes of Health under award number RO1 AR067196, and a Shared Instrumentation Grant S10 OD021644. The research content herein is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

Conflicts of interest: Garrett Christensen, Hiroaki Ishikawa, Heath Henning, Eugene Kholmovski, and Megan Mills certify that they have no commercial associations (eg, consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) that might pose a conflict of interest in connection with the submitted article. Robert Tashjian is a paid consultant for Zimmer and Zimmer; has stock in CoNextions, Intrafuse, and KATOR; receives intellectual property royalties from Shoulder Innovations, Wright Medical, and Zimmer; receives publishing royalties from the Journal of Bone and Joint Surgery; and serves on the editorial board for the Journal of Orthopaedic Trauma. Peter Chalmers is a paid consultant for Depuy and DJO; is a paid speaker for Depuy, receives royalties from Depuy, and serves on the editorial board for the Journal of Shoulder and Elbow Surgery.

References

1. Alkawi I, Zmerly H. Osteoporosis: current Concepts. Joints 2018;08:122-7. https://doi.org/10.1055/s-0038-1660790.
2. Bishop JY, Jones CL, Renko MA, Donaldson C, Group MS. 3-D CT is the most reliable imaging modality when quantifying glenoid bone loss. Clin Orthop Relat Res 2013;471:1251-6. https://doi.org/10.1007/s11999-012-2607-x.
3. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986;1:307-10.
4. Cancienne JM, Brockmeier SF, Kew ME, Deasy MJ, Werner BC. The association of osteoporosis and Bisphosphonate Use with Revision shoulder surgery after Hemorrhagic Cysts Hyperintense Enough on T1-weighted MRI to Be Distinguished from Renal Cell Carcinomas? A Retrospective analysis of 204 patients. Am J Roentgenol 2019;213:1267-73. https://doi.org/10.2214/ajr.19.21257.
5. Ostor AJK, Richards CA, Tytherleigh-Strong G, Bearcroft PW, Prevest AT, Speed CA, et al. Validation of clinical examination versus magnetic resonance imaging and arthroscopy for the detection of rotator cuff tears. Clin Rheumatol 2013;32:1283-91. https://doi.org/10.1007/s10067-012-2600-0.
6. Prevest AT, Brossman KW, Brossman J, Dohan PS, Pedowitz R, Maeseneer MD, Trudell D, et al. Measurements of cortical thickness in experimentally created endosteal bone lesions: a comparison of radiography, CT, MR imaging, and anatomic sections. Am J Roentgenol 1997;168:1501-5.
7. Ramme AJ, Vica S, Horca A, Miller R, Welbeck A, Hong S, et al. A Novel MRI Tool for evaluating cortical bone thickness of the proximal Femur. Bull Hosp Jt Dis 2013;71:115-21.
8. Renko MA, Pan X, Donaldson C, Jones GL, Bishop JY. Comparison of various imaging techniques to estimate quantified glenoid bone loss in shoulder instability. J Shoulder Elbow Surg 2013;22:528-34. https://doi.org/10.1016/j.jse.2012.08.016.
9. Reuther F, Mühlhäuser B, Wahi D, Nys S. Functional outcome of shoulder hemiarthroplasty for fractures: a multicentre analysis. Inj 2010;41:506-12. https://doi.org/10.1177/0308023109342471.
10. Sharma AK, Toussaint ND, Elder CJ, Masterson R, Holt SG, Robertson PL, et al. Magnetic resonance imaging based assessment of bone microstructure as a non-invasive alternative to histomorphometry in patients with chronic kidney
32. Sharma AK, Toussaint ND, Elder GJ, Rajapakse CS, Holt SG, Baldock P, et al. Changes in bone microarchitecture following kidney transplantation—beyond bone mineral density. Clin Transpl 2018;32:e13347. https://doi.org/10.1111/ctr.13347.

33. Smark CT, Barlow BT, Vachon TA, Provencher MT. Arthroscopic and magnetic resonance arthrogram features of Kim’s lesion in posterior shoulder instability. Arthrosc J Arthrosc Relat Surg 2014;30:781-4. https://doi.org/10.1016/j.arthro.2014.02.038.

34. Sollmann N, Löffler MT, Kronthaler S, Böhm C, Dieckmeyer M, Ruschke S, et al. MRI-Based quantitative osteoporosis imaging at the spine and Femur. J Magn Reson Imaging 2020. https://doi.org/10.1002/jmri.27260.

35. Stecco A, Guenzi E, Cascone T, Fabiano F, Fornara P, Oronzo P, et al. MRI can assess glenoid bone loss after shoulder luxation: inter- and intra-individual comparison with CT. La Radiologia Med 2013;118:1335-43. https://doi.org/10.1007/s11547-013-0927-x.

36. Wehrli FW, Ladinsky GA, Jones C, Benito M, Magland J, Vasilic B, et al. In Vivo magnetic resonance Detects Rapid Remodeling Changes in the Topology of the trabecular bone Network after Menopause and the Protective Effect of Estradiol. J Bone Miner Res 2008;23:730-40. https://doi.org/10.1359/jbmr.080108.

37. Werthel J-D, Schoch BS, van Veen SC, Elhassan BT, An K-N, Cofield RH, et al. Acromial fractures in Reverse shoulder arthroplasty: a clinical and radiographic analysis. J Shoulder Elbow Arthroplast 2018;2:2471549218777628. https://doi.org/10.1177/2471549218777628.

38. Xie Y, Liu S, Qu J, Wu P, Tao H, Chen S. Quantitative magnetic resonance imaging UTE-T2* mapping of tendon Healing after arthroscopic rotator cuff repair: a Longitudinal study. Am J Sports Med 2020:0363546520946772. https://doi.org/10.1177/0363546520946772.

39. Yanke AB, Shin JJ, Pearson I, Bach BR, Romeo AA, Cole BJ, et al. Three-dimensional magnetic resonance imaging quantification of glenoid bone loss is equivalent to 3-dimensional computed tomography quantification: cadaveric study. Arthrosc J Arthrosc Relat Surg 2017;33:709-15. https://doi.org/10.1016/j.arthro.2016.08.025.