Footprint size matters: wider coronal greater tuberosity width is associated with increased rates of healing after rotator cuff repair

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**Background:** The purpose of this study was to determine whether greater tuberosity morphology (1) could be measured reliably on magnetic resonance imaging (MRI), (2) differed between patients with rotator cuff tears (RCTs) compared with those without tears or glenohumeral osteoarthritis, or (3) differed between patients with rotator cuff repairs (RCR) who healed and those that did not.

**Methods:** This is a retrospective comparative study. (1) We measured greater tuberosity width (coronal and sagittal), lateral offset, and angle on MRI corrected into the plane of the humerus. To determine reliability, these measurements were made by two observers and intraclass correlation coefficients were calculated. (2) We compared these measurements between patients with a full-thickness RCT and patients aged ≥50 years without evidence of a RCT or glenohumeral osteoarthritis. (3) We then compared these measurements between those patients with healed RCRs and those with evidence of retear on MRI.

**Results:** (1) In a validation cohort of 50 patients with MRI, all inter-rater intraclass correlation coefficients were greater than 0.75. (2) There were no differences between our RCT group of 110 patients and our comparison group of 100 patients in tuberosity coronal width, sagittal width, or lateral offset. The RCT group had a significantly smaller greater tuberosity angle (63 ± 4° vs 65 ± 5°, P = .003). (3) In our group of 110 RCRs, postoperative MRI scans were obtained at a mean follow-up of 23.6 ± 15.7 months showing 84 (76%) patients had healed RCRs. Larger coronal tuberosity width was associated with healing (1.3 ± 0.2 vs 1.2 ± 0.2 cm, P = .032), as was smaller tear width (P < .001), and retraction (P < .001). When coronal width was dichotomized, there was a significantly higher healing rate with a width over 1.2 cm (85 vs 66%, P = .02). No other greater tuberosity morphological characteristics were associated with RCR or postoperative healing.

**Conclusion:** RCTs do not appear to be associated with greater tuberosity morphology. Postoperative rotator cuff healing based on MRI is 76%. Higher rates of healing occur with a wider coronal tuberosity width (ie, rotator cuff tendon footprint). Consideration could be given to widening the footprint intraoperatively in an effort to improve healing rates although this remains to be validated.

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shoulder angle, and glenoid inclination. However, humeral morphology, specifically the morphology of the greater tuberosity may also play a role.

Biomechanically, the morphology of the greater tuberosity may play an important role in the development of rotator cuff tears (RCTs). Prior finite element analyses have suggested that the morphology of the greater tuberosity and humeral head concentrates tension at the articular margin. In support of this theory, several articles have demonstrated that the greater tuberosity angle, which includes both the lateral offset and the coronal width of the tuberosity, correlates with rotator cuff pathology. This angle is thought to both increase the risk for extrinsic impingement and increase the intrinsic tensile load on the tendon.

These measurements have thus far been performed on two-dimensional radiographs. While the authors who initially proposed this measurement suggested it to be stable to humeral rotation, it is unclear how much variation there is in rotation in a retrospective radiographic study. Therefore, confirming these findings with a three-dimensional measurement method that can be rotated into the same humeral slice on each patient is desirable. However, no prior studies have determined whether magnetic resonance imaging (MRI) can be used to reliably measure tuberosity morphology, nor whether these measurements associate with rotator cuff tearing or healing after repair. Furthermore, many studies have lacked adequate comparison groups. Specifically, most prior studies have not provided comparison patients of a similar age to cuff-tear patients. Thus, there is a gap within our current knowledge as to whether greater tuberosity morphology associates with RCTs or healing after repair.

Thus, the purposes of this study were to determine whether greater tuberosity morphology (1) can be measured reliably on MRI, (2) differs between patients with RCT compared with those without evidence of RCTs or glenohumeral osteoarthritis, and (3) differs between patients with rotator cuff repairs (RCR) that healed and those that did not. The according hypotheses were as follows: greater tuberosity morphology can be reliably measured on MRI; RCT is associated with increased greater tuberosity width, length, lateral offset, and angle; higher rates of rotator cuff healing occur with decreased greater tuberosity width, length, lateral offset, and angle.

Materials and methods

Patient selection

This is a retrospective radiographic study approved by the institutional review board. We included three patient groups: (1) patients with a RCT, (2) controls without a RCT or glenohumeral arthritis, and (3) patients who underwent a RCR with postoperative imaging to assess healing. Prior research performed at our institution has used these groups and have previously been described.

RCT group: Our institution has conducted several prior studies regarding healing after RCR and these patient populations were pooled to form the basis of this study. These prior studies each have 1-year healing outcomes on MRI and follow-up rates of >83%. From these studies, we eliminated duplicate patients, patients without preoperative MRIs, and patients without a postoperative MRI at a minimum of 1 year from surgery. Postoperative MRIs were obtained on all patients in the cohort to assess healing, not because of concern for failure.

Comparison group: We searched the logs of our hospital system for all patients who underwent an MRI of the shoulder within our hospital system. A research associate then reviewed each radiology report. Only those reports in which there was no description of either a RCT or glenohumeral osteoarthritis were included. An attending orthopedic surgeon, fellowship trained in shoulder and elbow surgery, personally reviewed all imaging studies to confirm that included patients met these criteria.

Measurement technique

For all patients we measured greater tuberosity coronal and sagittal width, greater tuberosity lateralization, and the greater...
tuberosity angle. These measurements were made on MRI using a third-party viewer (Horos, Pixmeo Sarl, Bern, Switzerland). This viewer allows sliced planes on three-dimensional imaging studies to be reoriented to optimize the two-dimensional slices relative to the anatomy and control for rotation. The subsequent measurements, while in two-dimensions, are independent of the gantry angle set by the radiology technician or the position of the patient within the scanner. Thus, humeral rotation and alignment can be adjusted for with postprocessing, unlike with two-dimensional radiographs. The measurements were made in centimeters using the viewer’s line and angle measuring features. Optimal two-dimensional slices were created by first orienting the coronal and sagittal planes to be in line with the axis of the humeral shaft at the level of the widest aspect of the greater tuberosity (Fig. 1). Then on the view containing the axial plane, at the center of the humeral head, the parasagittal plane was reoriented to intersect with both the bicipital groove and the posterior border of the greater tuberosity and the coronal plane was reoriented to bisect the greater tuberosity (Fig. 2). This provides a coronal image with a profile of the greater tuberosity. We used these images to obtain measurements. On a coronal view, the coronal width of the tuberosity was measured by drawing a line parallel to the shaft passing through the superomedial aspect of the tuberosity, that is, the articular side of the cuff attachment. The distance from this line to the most lateral aspect of the tuberosity was measured (A). This image also demonstrates the measurement technique for the greater tuberosity angle (B).

Figure 3 This magnetic resonance image in the coronal plane demonstrates the measurement technique for the greater tuberosity coronal width. On this image, the lateral offset of the tuberosity was measured by drawing a line parallel to the shaft from the superomedial aspect of the tuberosity, as the articular margin of the rotator cuff attachment and the superolateral margin of the articular surface. The distance from this line to the most lateral aspect of the tuberosity was measured (A). This image also demonstrates the measurement technique for the greater tuberosity angle (B).

Statistical methods

We calculated and reported descriptive statistics. All analyses were performed in Excel (Microsoft, Redmond, WA) and SPSS 25 (IBM, Armonk, NY, USA). To determine interobserver reliability, we compared measurements between observers using intraclass correlation coefficients (ICCs) using a two-way mixed model of consistency type and the single-measures result. To determine the association between tuberosity morphology and rotator cuff morphology, we compared greater tuberosity coronal width, lateral offset, sagittal width, and angle between the RCT group and the comparison group using Student’s t-tests and Mann-Whitney U tests as appropriate depending on data normality as determined using the Kolmogorov-Smirnov test. To determine the association between tuberosity morphology and RCR healing, we compared each of the greater tuberosity measures between the healed and nonhealed group using Student’s t-tests and Mann-Whitney U tests as appropriate depending on data normality as determined using the Kolmogorov-Smirnov test. P values of < .05 were considered statistically significant.
Results

Included patients

We included 110 patients in the RCT and RCR group. These patients were 59 ± 10 years old, 64% male, and had tears that were 26 ± 13 mm wide and 21 ± 12 mm retracted (Table I). We included 100 patients in the comparison group. These patients were 64 ± 6 years old and 40% male, which was significantly older and with fewer males than the RCT group (P < .001). Postoperative MRI scans were obtained at a mean follow-up of 23.6 ± 15.7 months showing 84 patients (76%) had healed repairs. Inter-rater reliability within MRI measurements was generally excellent, with all ICCs > 0.75 (Table II).

Association between cuff pathology and tuberosity morphology

Comparing MRI findings in patients with RCT and those without, the only significant difference in morphology was a smaller greater tuberosity angle at 63 ± 5° compared with 65 ± 4° (P = .003). There were no differences in greater tuberosity coronal width, lateral offset, or sagittal width (Table III, Fig. 6).

Association between cuff healing and tuberosity morphology

Minimum 1-year postoperative MRI demonstrated that rotator cuffs that healed compared with those that retore had a larger greater tuberosity coronal width (1.3 ± 0.2 vs 1.2 ± 0.2 cm, P = .032), a smaller anterior to posterior tear size (24 ± 12 vs 33 ± 12 mm, P < .001), a smaller tear area (522 ± 561 vs 1035 ± 636 mm², P < .001), and less tear retraction (18 ± 10 vs 30 ± 12 mm, P < .001). When coronal width was dichotomized, there was a significantly higher healing rate when width was greater than 1.2 cm (85% vs 66%, P = .02, Fig. 7). There were no differences in greater tuberosity lateral offset, sagittal width, or angle (Table IV, Fig. 8).
While numerous factors have been investigated regarding RCT and postoperative healing rates, little has been reported about the impact of greater tuberosity morphology. First, this study demonstrates that greater tuberosity morphology (coronal and sagittal width, lateral offset, and greater tuberosity angle) can reliably be measured on MRI. Second, patients with a RCT compared with those without tear or glenohumeral arthritis had a smaller greater tuberosity angle, although the mean difference was $2^\circ$ which may be clinically insignificant. Finally, in evaluating postoperative MRI at minimum 1-year, patients with healed rotator cuffs compared with those that retore had a larger coronal tuberosity width by 1mm. This suggests that a wider coronal tuberosity width, that is, cuff tendon footprint width, is associated with a higher rate of RCR healing, possibly because of an increased area of tendon and bone contact. Thus, to improve rotator cuff healing, consideration could be given to intraoperative widening of the footprint.

Acromial and glenoid morphology has been the subject of prior investigations. Balke et al reported that degenerative compared with traumatic RCT had a higher acromial slope, acromiohumeral distance, lateral acromial index, and critical shoulder angle. Chalmers et al found that patients with a degenerative RCT had a higher CSA than those without tear, although CSA was not associated with the baseline tear length or tear progression over time. Similarly, Moor et al observed that patients with a RCT had a higher CSA than those with an intact cuff. In patients with osteoarthritis, Mantell et al noted that full-thickness RCT was associated with a higher CSA. Daggett et al also found that glenoid inclination was higher in patients with massive RCTs than in those with

**Figure 6** Boxplot of greater tuberosity coronal width for those with and without healing after rotator cuff repair. This difference was statistically significant with $P = 0.02$. The top and bottom borders of the boxes represent the interquartile range, with the center line representing the median. The whiskers represent the furthest nonoutlier, nonextreme value. The outliers, those values between 1.5 and 3 box lengths from either end of the box are denoted with (○). Extreme values, those values more than 3 lengths from either end of the box, are denoted with (*).

**Figure 7** Boxplot of greater tuberosity coronal width for those with and without healing after rotator cuff repair. This difference was statistically significant with $P = 0.02$. The top and bottom borders of the boxes represent the interquartile range, with the center line representing the median. The whiskers represent the furthest nonoutlier, nonextreme value. The outliers, those values between 1.5 and 3 box lengths from either end of the box are denoted with (○). Extreme values, those values more than 3 lengths from either end of the box, are denoted with (*).
study vs. younger comparison group in the prior study). Within our slice, or comparison groups (older comparison group in our own MRI), measurement technique (single x-ray view vs. reoriented MRI prior study may arise due to differences in imaging study (x-ray vs. tears instead of larger). Differences between our study and this tuberosity angle is in the opposite direction (ie, smaller for cuff and thus contribute to tearing. Within our study, there were no osity, which would put the tendon at a mechanical disadvantage be associated with a signi-

While the focus has primarily been on glenoid and acromial morphology, there has been limited investigation on how the morphology of the greater tuberosity affects the rotator cuff. Within our study, based on three-dimensional imaging, RCT was performed study. Cunningham et al demonstrated a signi-

Regarding healing, Lee et al reported that CSA greater than 35 degrees was associated with improved outcomes scores after RCR at 6 months, but this difference was not present at 24 months. In our series, the only tuberosity measurement associated with healing of the rotator cuff after surgical repair was coronal width. Greater tuberosity lateral offset, sagittal width, and angle did not appear to affect the likelihood of healing. There are no prior studies on tuberosity morphology and rotator cuff healing. Greater coronal width may influence healing as it provides a larger footprint for the tendon to be repaired to and subsequently heal. While the difference we observed was only 1mm, this is measurable and clinically significant as it can be up to 10% of the coronal footprint. Tuberosity width can be changed intraoperatively by debriding a small amount of the medial articular margin of the footprint with a burr to increase coronal width of the footprint. Our findings suggest that consideration could be given to widening the footprint intraoperatively to improve healing rates. Based on our results, a target width of 1.2 cm is associated with a higher rate of healing. As this width is readily measurable intraoperatively (three probe ends worth or three burr widths with a 4 mm burr), this may provide a no-cost, easy to apply, intraoperative method to augment healing rates.

This study has several limitations. First, the comparison group was a convenience sample from the medical record and it is thus not a “normal” group. Thus, there were varied indications for osteoarthritis, while Chalmers et al observed a higher glenoid inclination in patients with RCT than in those without tear. Regarding healing, Lee et al reported that CSA greater than 35 degrees was associated with improved outcomes scores after RCR at 6 months, but this difference was not present at 24 months.

While the focus has primarily been on glenoid and acromial morphology, there has been limited investigation on how the morphology of the greater tuberosity affects the rotator cuff. Within our study, based on three-dimensional imaging, RCT was associated with a smaller greater tuberosity angle than patients with intact rotator cuffs. These results are in contrast to a previously performed study. Cunningham et al demonstrated a significantly larger greater tuberosity angle for those with rotator cuff pathology than controls. These authors theorized that a larger angle would be associated with a significantly more lateral offset of the tuberosity, which would put the tendon at a mechanical disadvantage and thus contribute to tearing. Within our study, there were no differences in tuberosity lateral offset and our difference in greater tuberosity angle is in the opposite direction (ie, smaller for cuff tears instead of larger). Differences between our study and this prior study may arise due to differences in imaging study (x-ray vs. MRI), measurement technique (single x-ray view vs. reoriented MRI slice), or comparison groups (older comparison group in our own study vs. younger comparison group in the prior study). Within our study, the difference in this measurement is small and thus likely clinically insignificant.

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### Table IV
Demographics, greater tuberosity measurements, and preoperative tear size for both those with healed and nonhealed rotator cuff tears postoperatively.

| Patient, greater tuberosity, and tear characteristics | Healed, mean ± SD | Nonhealed, mean ± SD | P value |
|------------------------------------------------------|-------------------|----------------------|--------|
| Age, yr                                               | 58 ± 10           | 63 ± 10              | .097   |
| Sex, male                                            | 55 (65%)          | 15 (58%)             | .471   |
| Follow-up MRI, months                                | 22 ± 15           | 27 ± 17              | .102   |
| Coronal width, cm                                    | 1.3 ± 0.2         | 1.2 ± 0.2            | .032   |
| Lateral offset, cm                                   | 1.8 ± 0.5         | 1.9 ± 0.8            | .481   |
| Sagittal width, cm                                   | 3.6 ± 0.4         | 3.5 ± 0.4            | .204   |
| Greater tuberosity angle, °                          | 64 ± 4            | 62 ± 3               | .08    |
| Preoperative tear size                               |                   |                      |        |
| Anterior to posterior, mm                            | 24 ± 12           | 33 ± 12              | <.001  |
| Preoperative tendon                                   |                   |                      |        |
| Retraction, mm                                       | 18 ± 10           | 30 ± 12              | <.001  |
| Preoperative tear area, mm²                           | 522 ± 561         | 1035 ± 636           | <.001  |

Data presented with standard deviation (SD). Statistically significant P values <.05 are bolded.

![Figure 8](image-url) Boxplot of greater tuberosity lateral offset and sagittal width for those with and without healing after rotator cuff repair. The top and bottom borders of the boxes represent the interquartile range, with the center line representing the median. The whiskers represent the furthest nonoutlier, nonextreme value. The outliers, those values between 1.5 and 3 box lengths from either end of the box are denoted with *(.) Extreme values, those values more than 3 lengths from either end of the box, are denoted with *.
obtaining these MRIs and many of the patients for whom these MRIs were obtained had shoulder complaints, which could be due to tuberosity morphological differences in the absence of an RCT. However, as these patients were free from rotator cuff pathology and glenohumeral osteoarthritis, this comparison group allows an answer to the question of whether tuberosity morphology associated with rotator cuff pathology, but not whether tuberosity morphology differs between “normal” and RCT. Second, patients within the comparison group could have developed RCT after these MRIs were obtained. A comparison group of older age minimizes this concern. In addition, this difference would bias our analysis toward the null hypothesis and is thus conservative. Third, because no pre-existing data exist for sagittal tuberosity width, coronal tuberosity width, and lateral tuberosity offset, no a priori power analysis was possible and thus our study may be underpowered. To mitigate this limitation, we have included as many patients as possible, hundreds of patients, within this study. The fact that a significant difference was found also suggests that this study was appropriately powered. Finally, we cannot determine humoral retroversion because our imaging did not extend distal to the level of the epicordyles.

Conclusion

These results suggest that tuberosity morphology can reliably be assessed on MRI. Although a smaller greater tuberosity was found with RCT, it was only 2 degrees and therefore unlikely clinically significant. No other parameters were associated with RCT. However, a wider coronal tuberosity width, that is, cuff tendon footprint width, is associated with a higher rate of RCR healing. To improve rotator cuff healing, consideration could be given to intraoperative medialization of the articular margin to widen the footprint. This remains yet to be validated and may be the focus of future investigation.

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