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ROTATOR CUFF REPAIR (M TAO AND M TEUSINK, SECTION EDITORS)

Partial and Full-Thickness RCT: Modern Repair Techniques

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Abstract

Purpose of Review The purpose of this article is to review the recent literature concerning modern repair techniques related to partial- and full-thickness rotator cuff tears.

Recent Findings The understanding of rotator cuff pathology and healing continues to evolve, beginning with emerging descriptions of the anatomic footprint and natural history of rotator cuff tears. Significant controversy remains in treatment indications for partial-thickness rotator cuff lesions as well as optimal surgical repair techniques for both partial- and full-thickness tears. Techniques such as margin convergence and reduction of the so-called "comma" tissue have improved the ability to anatomically reduce large and retracted tears. Repair strength and contact pressures are improved with double-row repairs and transosseus-equivalent techniques compared to traditional single-row repairs. Future work is directed towards obtaining reliable radiographic healing and demonstrating clinical superiority and cost-effectiveness of a single technique.

Summary Much recent work regarding rotator cuff anatomy and pathology has been reported. Newer techniques improve repair strength. Despite these advances, significant questions remain concerning surgical indications and clinical outcomes.

Keywords Rotator cuff · Repair · Anatomy · Technique · Review · Outcomes

Introduction

Rotator cuff tears are a very common musculoskeletal injury and source of disability in the shoulder. Tears are most closely associated with increasing age and estimated to be present in approximately 25% of individuals in their 60s and in 50% of individuals in their 80s [1]. Tear size has been shown to progress over time even in asymptomatic individuals, with larger tears progressing more quickly [2] and correlate with increasing shoulder pain [3, 4•]. While previous studies did not find a correlation between enlargement of tears and progression of muscle degeneration, Keener et al., in a more recent prospective study with a larger cohort with longer follow-up, showed that progression of even smaller tears was associated with muscle degeneration and atrophy, which may preclude successful surgical repair [4•, 5, 6].

Much of the work the past two decades regarding rotator cuff injury focused on arthroscopic techniques. Today, the vast majority of rotator cuff repairs are performed arthroscopically. Despite significant advances in surgical technique, there continues to be a discord between healing assessed by postoperative ultrasound and/or MRI and patient outcomes, particularly in large and massive tears and in older patients [7]. Some studies have shown that while only about 43% of patients over the age of 65 had evidence of healing at 18 months postoperatively after an arthroscopic full-thickness rotator cuff repair, over 80% had satisfactory clinical results [8, 9]. However, Jost and colleagues showed reduced strength and poorer clinical outcomes in patients with persistent rotator cuff defects compared to structurally intact repairs, and Miller et al. showed that recurrent tears occurring in the early postoperative period were associated with inferior clinical outcomes [10, 11]. This conflict was initially attributed to heterogeneity in repair technique.

Therefore, improving structural healing rates continues to be a main focus of research in rotator cuff surgery [12]. The past 5 years much work has been done looking at alternative factors that may influence healing and function, including the

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Table 1 Anatomic descriptions of the supraspinatus and infraspinatus footprint

Study	Supraspinatus		Infraspinatus	
	AP length (mm)	Medial-lateral length (mm)	AP length (mm)	Medial-lateral length (mm)
Curtis et al. [14]	16	23	19	29
Dugas et al. [17]	16.3	12.7	16.4	13.4
Mochizuki et al. [16••]	12.6	6.9	32.7	10.2

anatomy and vascularity of the rotator cuff, the role of the subscapularis repair, and modern repair techniques of both partial-thickness and full-thickness rotator cuff tears. The purpose of this article will be to review the emerging literature regarding these concepts.

Modern Anatomy

Descriptive anatomy of the rotator cuff dates back to Codman in 1934. The modern term *footprint* was initially coined in 1999 by Curtis et al. who reported a consistent, measureable insertional pattern of the individual rotator cuff tendons [13, 14]. Originally thought to run in parallel and insert onto discreet segments of the greater and lesser tuberosity, several recent studies show significant inter-digitation of the supraspinatus and infraspinatus tendons near the footprint [15]. Most recently, Mochizuki et al. studied 113 cadaveric specimens and found that the infraspinatus tendon occupied the majority of the footprint on the greater tuberosity, while the supraspinatus insertion was significantly smaller than previously described by Curtis et al. and Dugas et al. (Table 1) [14, 16••, 17]. Specifically, the supraspinatus insertion is triangular in shape, broad along the articular margin, and converging to its apex at the anterior-most aspect of the greater tuberosity footprint. The infraspinatus insertion covered the remainder of the footprint curving much further anteriorly as it extended laterally. (Fig. 1). This concept helps explain the observation that infraspinatus muscle atrophy is often seen with what was previously thought to be isolated supraspinatus tears [18]. While some authors postulated that increased tension on the suprascapular nerve from supraspinatus muscle/tendon retraction was the underlying cause of infraspinatus muscle atrophy, Vad et al. demonstrated that most patients did not have abnormal electromyographic (EMG) results [18, 19]. Mochizuki et al. suggest instead that there may be a higher frequency of involvement of the infraspinatus in rotator cuff tears due to a better understanding of the anatomy. As the infraspinatus is now recognized as an important abductor of the shoulder, restoration of the infraspinatus anatomy may be important for more complete restoration of shoulder motion and overall function.

Critical Shoulder Angle

While the concept that variability in scapular morphology may play a role in the pathogenesis of rotator cuff disease is not new, Moor and colleagues introduced the "critical shoulder angle" (CSA) in 2013—a novel radiographic parameter that incorporated both glenoid inclination and lateral extension of the acromion. The CSA is formed by a line extending from the superior to inferior aspect of the glenoid and a second line extending from the inferior aspect of the glenoid to the inferolateral aspect of the acromion (Fig. 2) [20]. Increased

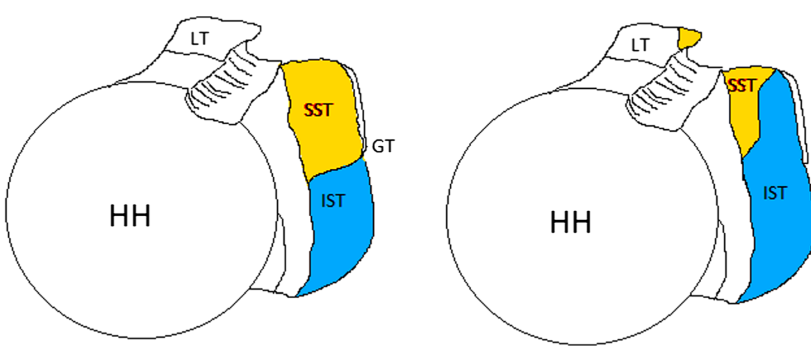

Fig. 1 Humeral insertions of the supraspinatus tendon (SST) and infraspinatus tendon (IST). The left figure depicts the traditional anatomic description in which the SST attaches to the highest impression of the greater tuberosity (GT) and the IST attaches to the middle impression of the GT. The right depicts the anatomic footprint as described by Mochizuki et al. Adapted from [15]

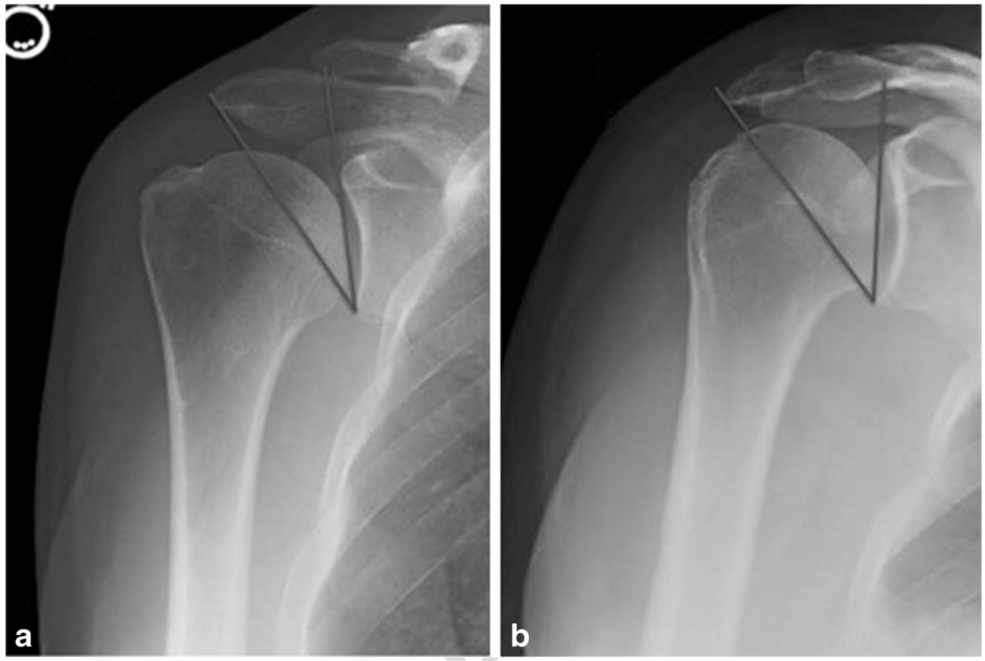

Fig. 2 AP Grashey views of right shoulder. The critical shoulder angle is formed by a line extending from the superior to inferior aspect of the glenoid and a second line extending from the inferior aspect of the glenoid to the inferolateral aspect of the acromion on true anteriorposterior film with the arm in neutral rotation. **a** CSA = 26°. **b** CSA = 40°

glenoid inclination and acromial "overhang" both produce a more vertically directed net force vector during deltoid contraction (superior humeral head migration), requiring the rotator cuff to exert a greater compensatory force to stabilize the humeral head [20–22]. Wong et al. showed that a positive glenoid inclination of 10° resulted in a 30% decrease in the force required to produce superior head migration [23]. In another biomechanical study, Gerber et al. showed that larger CSAs (> 35°) increased the supraspinatus tendon load by 35% to compensate for the increased shear force [24]. In an observational clinical study, Moor and colleagues found a significantly higher prevalence of rotator cuff tears (RCTs) in patients with CSAs > 35° and this correlation has since been supported by several more recent studies [25–28].

Garcia et al. found that patients with CSA > 38° had increased risk of re-tear following rotator cuff repair (odds ratio 14.8), with higher CSAs associated with worse ASES scores at short-term follow-up [29]. However, other authors have been unable to find a difference in patient-reported outcome scores at 24 months follow-up in patients with higher CSAs [30, 31]. Some authors advocate for lateral acromioplasty in order to reduce the CSA to 30° to 35° to offload the supraspinatus. Katthagen et al. performed a cadaveric study showing that 5 mm lateral acromion resection reduced the CSA by nearly 3° without damaging the deltoid origin [32]. Marchetti et al. then showed that both 5 and 10 mm lateral acromial resection did not significantly reduce the mechanical or structural integrity of the lateral deltoid origin when loaded to failure [33]. More research is necessary as there are currently no outcomes published for lateral acromioplasty in combination with RCR.

Acromioplasty

Multiple Level 1 and 2 studies published recently comparing arthroscopic RCR with and without "traditional" acromioplasty (coracoacromial ligament release and anterior acromial resection) have shown no difference in functional or patient reported outcomes or re-tear rates [34–36].

Partial-Thickness Rotator Cuff Tears

The prevalence of partial thickness rotator cuff tears (PTRCTs) ranges from 15 to 32% in the general population, and as high as 40% in the dominant arm of asymptomatic elite overhead athletes [37, 38]. The natural history is poorly understood, but recent studies show that tear progression is correlated with the percentage of tendon thickness involved on initial presentation. Patients with < 50% (Ellman grades I and II) tendon involvement had a 14% chance of tear progression, while patients with > 50% (grade III) tendon involvement progressed 55% of the time [2]. Healing of PTRCTs does not appear to occur spontaneously based on multiple imaging and histologic studies, nor do non-anatomic procedures such as open or arthroscopic acromioplasty alone prevent further progression [39–43].

The indications and methods for treatment of PTRCTs remain controversial. In general, tears involving < 50% of the tendon are initially treated non-operatively. Surgical options are reserved for those who fail non-operative treatment or for tears involving > 50% of the tendon. Surgical management options include arthroscopic debridement ± acromioplasty, in situ-repair, or tear completion with full-thickness rotator cuff repair. Several studies have reported excellent clinical outcomes with arthroscopic debridement and subacromial decompression for grade I and II tears [44, 45]. However, in one study bursal surface tears were significantly more likely to fail than articular surface tears (29 vs. 3%, respectively) [42]. This has led some authors to consider repair over debridement in partial bursal-sided tears involving < 50% of the tendon. Xiao et al. repaired grade II (< 50%) bursal sided tears with either a single-row or suture bridge construct and found 89% of repairs to be intact on postoperative MRI, as well as significant improvements in both UCLA and Constant scores [46].

Formal arthroscopic rotator cuff repair is generally accepted for grade III (> 50%) bursal and articular-sided tears. There are several described techniques, though generally divided into either conversion repair or in-situ repair options. Conversion repair involves completing a PTRCT into a full-thickness defect followed by repair utilizing standard arthroscopic RCR techniques. While conversion has the advantage of removing devitalized tissue, there is some concern about detaching residual intact rotator cuff and disrupting the native tendon length-tension relationship. However, conversion repair has shown excellent results in several recent studies evaluating both tendon integrity and outcome scores. Iyengar et al. showed significant improvements in UCLA scores and 82% tendon repair integrity by MRI at 2 years follow-up [47]. Kamath et al. reported 88% tendon integrity by ultrasound at an average of 11 months following conversion repair, and patient satisfaction rates greater than 90% [48]. In both studies, absence of structural healing did not appear to negatively affect clinical results. When comparing bursal versus articular sided tears treated by conversion repair, authors have shown improved clinical outcomes (VAS, UCLA, ASES, and Constant) in both groups without significant difference in retear rates [49, 50].

In-situ repairs have the advantage of maintaining the intact lateral insertion of the rotator cuff while re-fixing the medial articular insertion. While the intact anatomy is preserved, the surgical techniques become more demanding. Several repair techniques for articular-sided tears have been described including the transtendon repair (most common), an all-inside intra-articular repair, and transosseus repair. In the transtendon technique, a suture anchor is inserted into the medial aspect of the footprint through the intact tendon. Sutures are then shuttled through intact tendon with a passer in a horizontal mattress fashion and then tied in the subacromial space, reducing tendon to bone. The repair is then assessed with the arthroscope in the glenohumeral joint. Shin et al. showed significant improvements in VAS, ASES, and Constant scores with 92% patient satisfaction rate and no recurrent tears on follow-up MRI [51]. Despite high patient satisfaction, some authors report over 40% of patients may experience stiffness, discomfort at terminal motion, and difficulty with activities of daily living [52]. Some surgeons attribute the residual symptoms to tension mismatch between the delaminated tendon and intact tendon [53]. This observation led to the development of an all-inside intra-articular repair technique, in which only the delaminated articular sided tear is reduced to bone [54]. While this may provide a more anatomic repair, prospective data is lacking. Spencer et al. performed a retrospective review of 20 patients who underwent all-inside intra-articular repair for grade III articular-sided lesions and found improved clinical outcome scores without major post-operative clinical stiffness [55].

In separate biomechanical studies, both Peters et al. and Lomas et al. compared transtendon repair versus conversion repair with double row construct and found significantly higher ultimate load to failure and lower gap formation in the transtendon technique [56, 57]. However, two randomized clinical studies failed to show a difference in clinical outcome scores or re-tear rates between the two groups [58, 59]. Both studies did show significant improvements in VAS, ASES, and Constant scores as well as similarly low re-tear rates on follow-up MRIs in both groups.

Partial articular-sided supraspinatus tendon avulsion (PASTA) injuries are a more recognized subset of PTRCTs. Treatment indications are controversial and follow similar rationale as other partial tears. Similar to the above discussion, numerous techniques have been described for PASTA injuries including debridement, conversion repair, and in-situ repair. Stuart et al. showed good to excellent results in 93% of PASTA lesions treated with a transtendinous technique at 12 years follow-up [60].

Full-Thickness Rotator Cuff Tears

Open Versus Arthroscopic

Given the relatively high re-tear rates in large and massive tears, debate remains regarding mini-open versus arthroscopic techniques for rotator cuff repair. Though some report mini-open techniques to have superior healing rates in large and massive tears (62 and 40%) compared to arthroscopic repair (24 and 12%) [61, 62], multiple systematic reviews have not shown a significant difference between the two techniques [63, 64]. In addition, Carr et al. recently published a multicenter randomized trial that found no difference in effectiveness between open and arthroscopic repair of cuff tears regardless of size of tear or patient age [65].

Margin Convergence and Interval Slides

Techniques to assist with large and massive tears, often deemed irreparable when contracted and immobile, were designed to address these poor healing rates. Margin convergence, initially described by Burkhardt et al., converts longitudinal U- and L-shape tears into smaller crescent tears by adjoining anterior and posterior limbs in a side-to-side repair [66]. The lateral free margin of the crescent tear can then be mobilized and repaired to the anatomic footprint without excessive tension on the rotator cuff repair. Several studies have shown reduced strain and tension on the repair with this technique, with corresponding satisfactory clinical outcomes [67–69]. The anterior interval slide, described by Tauro in 1999, is a technique to improve mobility of a retracted, supraspinatus tendon by releasing the coracohumeral ligament and rotator interval tissue [70]. Lo et al. expanded on this concept and described a posterior interval slide in which the plane of tissue between the supraspinatus and infraspinatus is released along the scapular spine in tears that require increased mobility after anterior interval release [71]. Complications from this technique include possible devascularization of the rotator cuff tissue when concomitant slides are performed. Additionally, a recent study comparing large-to-massive contracted rotator cuff tears treated with either complete repair with posterior interval slide or partial repair without posterior interval slide showed no difference in clinical outcomes. The group that underwent complete repair with posterior interval slide showed a significantly higher re-tear rate (91%) and greater defects on 2-year follow-up MR arthrogram [72•].

Repair Techniques: Single-Row, Double-Row, and Transosseus-Equivalent (TOE)

Single-row repair constructs have the advantage of reduced cost and decreased surgical time. Although there are many configurations, typically two double-loaded suture anchors are placed in a single row and suture passed and tied in a horizontal-mattress configuration. Double row repairs were designed to improve healing rates by increasing compression and tendon-bone contact-area with both medial and lateral rows [73]. The double row is performed in a similar fashion to a single row by placing pre-loaded suture anchors in both medial and lateral rows and suture passed and tied in a horizontal mattress configuration. A systematic review by Duquin and colleagues showed that double-row constructs had superior healing rates than single-row configurations in tears larger than 1 cm [74]. Nho et al. performed a systematic review and concluded that while some studies did show improved tendon healing with double-row constructs, there were no differences in clinical outcomes between single-row and double-row suture anchor repair techniques [75]. The TOE technique (suture-bridge) was designed to improve the biomechanical repair construct in an effort to further decrease re-tear rates [76•]. In cadaveric studies, TOE repairs showed improved tendon-bone contact area and higher ultimate load to failure compared to double-row repairs [77–79]. The TOE repair begins in the same way as a single row repair, where first a medial row of pre-loaded anchors is placed. Next, one limb from each anchor is brought over the top of the repair and secured to the lateral margin of the greater tuberosity footprint with a knotless anchor. Recently there has been some debate about the necessity of tying medial row knots prior to placing the knotless lateral row. Some others have advocated for tying medial row knots while authors have proposed faster knotless (speedbridge) techniques. With the addition of tying knots at the medial row compared to knotless techniques, Mall et al. showed greater hysteresis, less gap formation, and higher ultimate load in the medially knotted groups in biomechanical studies only [80•]. Clinical data is limited comparing single row, double-row, and TOE repair techniques. Mihata et al. published their clinical data which retrospectively looked at structural and functional outcomes comparing single-row, double-row, or TOE (suture-bridge) techniques and found lower re-tear rates and higher functional outcome scores in the suture-bridge group for large and massive tears [81•].

Subscapularis Tears And “Comma” Tissue

Once originally described as “hidden lesions” given the difficulty identifying their presence, subscapularis tears have since been identified in almost 30% of arthroscopic shoulder procedures [82, 83]. Recognition of subscapularis tears was aided by the description of the comma sign, hypothesized to be composed of humeral attachments of the superior glenohumeral and coracohumeral ligaments, by Lo and Burkhart in 2003 [84•]. Although others have proposed an alternative pathoanatomy for this arthroscopic finding, the reduction of the tissue that represents the comma tissue to the remnant subscapularis has been shown to recreate the intraarticular aspect of the torn subscapularis while concurrently reducing the leading edge of the supraspinatus [85]. Short-term and long-term results of isolated subscapularis and combined rotator cuff tears involving the subscapularis have consistently been shown to lead to good or excellent results in the vast majority of cases, with structurally intact repairs evaluated via ultrasound and magnetic resonance imaging reported as high as 93% [86–92]. Additionally, the reduction of the comma tissue to the torn subscapularis tendon can help reduce the leading edge of supraspinatus tears when found concomitantly.

Conclusion

Despite an improved understanding of the native rotator cuff footprint and the role of the subscapularis tendon, predictable healing of large and massive rotator cuff tears still remains inconsistent. Some studies have shown inferior clinical outcomes associated with non-healed tears following arthroscopic repair, while others have shown no difference.

Nevertheless, improving the structural integrity of rotator cuff repairs continues to be a main focus of research. The evolution of arthroscopic rotator cuff repair techniques is supported by biomechanical studies, but clinical data at this stage are promising but inconclusive. Further clinical studies are necessary to determine the optimal repair method as our understanding of anatomy and technique improves.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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Q1. Please provide annotations for references 4, 16, 72, 76, 80, 81, 84.