Current Concepts

# Arthroscopic Rotator Cuff Repairs: An Anatomic and Biomechanical Rationale for Different Suture-Anchor Repair Configurations

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**Abstract:** The goal of rotator cuff repairs is to achieve high initial fixation strength, minimize gap formation, maintain mechanical stability under cyclic loading, and optimize the biology of the tendon-bone interface until the cuff heals biologically to the bone. We have seen an evolution in our approaches to fixing rotator cuff tears from open to mini-open to all arthroscopic. In our arthroscopic techniques, we have also seen a change in the types of anchors and sutures we use and our repair techniques including an evolution in techniques that include single row, double row, and, most recently, transosseous equivalent fixation. Single-row repairs are least successful in restoring the footprint of the rotator cuff and are most susceptible to gap formation. Double-row repairs have an improved load to failure and minimal gap formation. Transosseous equivalent repairs have the highest ultimate load and resistance to shear and rotational forces and the lowest gap formation. This review will discuss the anatomy and biomechanics of a normal rotator cuff, the biomechanical factors that play a role in rotator cuff repairs, the initial fixation repair mechanics, and finally propose an algorithm for rotator cuff fixation based on tissue quality and tear configuration. **Key Words:** Rotator cuff—Footprint—Single row—Double row—Transosseous equivalent—Arthroscopy.

The goal of rotator cuff repairs is to achieve high initial fixation strength, minimize gap formation, maintain mechanical stability under cyclic loading, and optimize the biology of the tendon-bone "healing zone" until the cuff heals biologically to the bone. We know from outcome studies that healed cuffs have better function. Ultimately, a successful repair should lead to the elimination of pain, improved strength, and range of motion. Over the years, we have seen an evolution in our approaches to fixing rotator cuff tears from open to mini-open to all arthroscopic. In our arthroscopic techniques, not only have we changed the types of anchors and sutures implemented but also the procedures themselves including single-row, double-row, and, most recently, transosseous equivalent fixation.[1-20] This review will discuss the anatomy and biomechanics of a normal rotator cuff, the biomechanical factors that play a role in rotator cuff repairs, and the initial fixation repair mechanics and finally propose an algorithm for rotator cuff fixation based on tissue quality and tear configuration.

## INDICATIONS FOR CHANGE IN REPAIR TECHNIQUES

Rotator cuff repair techniques have evolved over the past decade because of the emerging reports on

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failure and retear rates.[21-24] Because of technical difficulties and steep learning curves, our early arthroscopic repair techniques failed to restore the anatomic footprint of the rotator cuff leading to incomplete and biomechanically weaker constructs.[25] As surgeons became more comfortable in their arthroscopic techniques, the next goal was to replicate the anatomic restoration of the footprint seen in open procedures. Open transosseous techniques can capture a wider section of the rotator cuff footprint leading to a more secure repair.

## MECHANISM OF REPAIR FAILURES

Early rotator cuff failures and retears are caused by a number of potential causes including anchors pulling out of the bone, suture failure, and knot loosening.[25] As stronger suture materials were introduced, failures occurred more often at the suture-tendon interface with the sutures pulling out of poor quality tissue before it could heal to the bone. In addition, some of the stronger suture configurations such as the Mason-Allen configuration,[26] which is often used in open techniques, are very difficult to replicate arthroscopically, and our simple and mattress sutures alone may not be sufficient to maintain the rotator cuff tendon to its boney bed until it heals. In reality, biomechanical causes of retears are often multifactorial including a combination of anchor and suture-tendon interface failures.

## THE ANATOMIC ROTATOR CUFF FOOTPRINT

Recent anatomic studies have clearly described the anatomy of the supraspinatus footprint on the greater tuberosity.[27] The anterior-posterior dimension was measured to be about 25 mm and the medial-lateral dimension to be 14 mm. This calculates to a total of 350 mm$^2$. This is an important consideration because achieving an anatomic repair requires restoration of the cuff footprint. This footprint should be thought of as the maximum 2-dimensional "healing zone." The greater the extent to which a given repair covers and secures tendon over the healing zone, the greater the chance for tendon-bone healing. Conversely, techniques that secure less tendon over a smaller area of this healing zone should be expected to have higher failure rates. Some rotator cuff tears may not be amenable to complete closure and reattachment to the anatomic footprint, as is occasionally the case in massive chronic retracted tears. Repair strategies for these situations will be discussed later.

## NORMAL ROTATOR CUFF MECHANICS

When considering which fixation techniques to use, one has to first examine the in vivo forces experienced by the normal rotator cuff muscles before they fail. Cadaveric studies have attempted to shed light on this concept. A study by Hughes and An[28] used a Cybex machine (Lumex, New York, NY) to measure the rotator cuff forces during a maximal isometric exertion. The supraspinatus forces were greatest with the arm abducted and externally rotated and measured 175 N. The infraspinatus forces were greatest with the arm adducted and externally rotated and measured 909 N.

A study by Chang et al.[29] calculated the muscle forces in the shoulder in internal rotation by using a Monte Carlo simulation. This method uses a random-number generator and is used to simulate variability in muscle moment arms allowing the estimation of muscle forces. The subscapularis and pectoralis major were the two major internal rotators, and although the supraspinatus force was 190 N, the infraspinatus was only 55 N.

Recently, a study by Wakabayashi et al.[30] used 2-dimensional finite element analysis and magnetic resonance imaging (MRI) to study the geometry of and the stress on the supraspinatus tendon. Results of the study showed that the supraspinatus experienced the highest stress on the articular side near its insertion. Because the shoulder is progressively abducted, the stress shifted laterally toward the insertion point.

Finally, a study by Juul-Kristensen et al.[31] used MRI of 20 healthy shoulders to determine the anthropometric and moment arms of the supraspinatus and infraspinatus. The supraspinatus had a maximal force of 353 N and 8.5 Nm of torque, and the infraspinatus had a maximal force of 665 N and 15.0 Nm of torque.

Although the results of these studies vary and their measurement methods differ, they share a common conclusion that shoulder rotation and abduction/adduction has an effect on the forces experienced by the supraspinatus and the infraspinatus and these forces are not static. The supraspinatus forces ranged from 43 to 350 N based on shoulder position and the infraspinatus forces ranged between 55 and 900 N. Furthermore, these forces are more concentrated laterally at the insertion of the muscles on the greater tuberosity and moved more laterally with increased abduction. These conclusions may theoretically support medial row fixation in which the tendon experiences the highest amount of stress.

## ROTATOR CUFF FUNCTIONAL MORPHOLOGY

It is also important to determine differences in stress distribution within the rotator cuff tendon itself. Itoi et al.[32] studied the tensile properties of the supraspinatus tendon using human cadaveric shoulders. They divided the tendon into 3 strips (anterior, middle, and posterior). The modulus of elasticity was greatest in the anterior strip along with the ultimate load and stress. They concluded that the anterior third of the supraspinatus was the strongest portion of the muscle tendon and seemed to perform the strongest role in its function.

In another study by Fallon et al.,[33] it was noted that the medial portion of the supraspinatus tendon contained parallel fascicles without interdigitation and some convergence laterally. On the other hand, the tendon attachment contained more disorganized fascicles with a basket-weave pattern. The importance of these 2 studies is that fixation that takes advantage of the more uniform and more organized tissue seen medially in combination with more disorganized pattern laterally may best resist suture-tendon failure. In addition, repairs should whenever possible include the most anterior aspect of the supraspinatus.

## ROLE OF CHRONICITY IN ROTATOR CUFF REPAIRS

The role that time plays on the quality of rotator cuff tissue has been the subject of a number of studies. A study by Gimbel et al.[34] in a rat model showed that the tension experienced by the repaired cuff tendon increased with delayed repairs. Similarly, Gerber et al.[35] showed that in a sheep model, early repairs had the lowest forces and that chronic rotator cuff tears showed increasing and irreversible changes including fatty infiltration. Coleman et al.[36] showed that chronic tears were associated with decreased contraction forces, increased fatty infiltration, and increased modulus of elasticity.

Therefore, one has to consider in selecting the type and timing of repair that greater time periods between the time of injury and surgical repair leads to increased repair stress and poorer quality tissue. Thus, improved repair mechanics may benefit the chronic or neglected rotator cuff tear.

## BIOMECHANICAL STUDIES ON DIFFERENT REPAIR TECHNIQUES

Multiple studies have compared interface anatomy and failure mechanics of various repair techniques. Transosseous repairs refer to the repairs that are performed by using open and mini-open techniques in which sutures are placed directly through transosseous tunnels for soft-tissue fixation. Single-row repairs are performed by placing the anchors in a linear fashion (usually 1 to 2 anchors placed laterally). Double-row repairs include techniques that use some configuration of a medial row of suture anchors placed at the articular cartilage margin of the anatomic neck and a second more laterally placed row along the lateral edge of the rotator cuff footprint along the tuberosity. Transosseous equivalent repairs use suture anchors to achieve what is considered to resemble biomechanically traditional open transosseous repair. A knotless anchor device named Pushlock distributed by Arthrex (Naples, FL) was designed to achieve the transosseous equivalent repairs. Two traditional suture anchors are used to secure the medial side of the torn tendon. The sutures are placed through the tendon in a horizontal mattress fashion and are not cut. The suture tails are passed into the Pushlock anchors, which are inserted into the lateral aspect of the footprint. The suture tails are tensioned over the cuff thereby achieving the same purpose as a standard transosseous repair. Although the main disadvantage of this device is its added cost, the following biomechanical studies show that, in some tears, the Pushlock device can improve the security and pull-out strength of the rotator cuff repair.

All of the biomechanical studies noted later assess repair quality at time equal zero. There are a number of disadvantages to those studies. First, they are generally performed on cadaveric or animal models and are therefore not appropriate for determining the rate or quality of healing. Furthermore, they lack chronicity, which is believed to be a critical factor in healing rates. However, there are advantages to comparing various repair configurations using a time equal zero model. These include the ability to study failure modality, interface motion, gap formation, and repair surface area, all of which are important factors in a successful repair and all are relevant to achieve an optimal environment for biologic healing. The following summarizes the studies comparing the previously mentioned techniques.

## Double Row Versus Single Row

Kim et al.[37] compared single-row and double-row repairs with respect to cyclic loading, gap formation, and failure loads. Compared with single-row repairs, double-row repairs had 42% less gap formation, 46% more stiffness, and 48% more ultimate load to failure. The strain experienced in the footprint of double-row repairs was one third of that seen in single row.

Another study by Mazzocca et al.[38] compared 4 different repair configurations. In their study, although the gap formation and load to failure were similar among the different groups (all exceeding 250 N), the double-row configurations were the most successful in restoring the repair footprint.

A similar study by Ma et al.[39] compared double-row techniques with three different single-row suturing techniques (simple, massive cuff, and Mason-Allen). The gap formation seen in double-row repairs was similar to that seen in massive cuff suture configuration. The ultimate load in double row was 287 N, which was higher than all the different single-row techniques tested.

## Transosseous Versus Single Row

There are a number of studies that compared the quality of repair of arthroscopic single-row techniques with the traditional transosseous repairs done during open surgery. Ahmad et al.[40] compared the motion at the bone-tendon interface between the 2 techniques. Transosseous repairs were found to have less interface motion.

A similar study by Apreleva et al.[41] studied the 3-dimensional footprint of different repairs including 2 transosseous repairs (simple and mattress sutures) to 2 similar single-row repairs. The transosseous simple suture repair achieved 85% of the original supraspinatus footprint compared with the other 3 repairs, which only achieved about 65% of the original geometry. They concluded that the transosseous simple repair had the best ability to restore the 3-dimensional anatomy of the supraspinatus.

Cummins et al.[42] showed that in a sheep model, the more anchors, the more sutures per anchor, and the more spread out the pattern of repair, the higher the ultimate load to failure. Finally, a study by Park et al.[43] in a bovine model showed that transosseous repairs compared with 2 different single-row repairs had the largest footprint (67 mm$^2$ *v* 26-34 mm$^2$) and the highest pressure on the cuff (0.32 MPa *v* 0.25-0.26 MPa). In conclusion, traditional transosseous techniques were superior to single-row techniques in ultimate load to failure, interface motion, restoring the footprint, and achieving the best pressure on the repair.

## Transosseous Versus Double Row Versus Single Row

Waltrip et al.[44] compared 3 types of fixation (single row, transosseous, and double row by using medial anchors augmented with a transosseous lateral technique). The double row incorporating the transosseous lateral technique had the highest number of the cycles to failure compared with the other 2. Similarly, Sano et al.[45] compared the stress distribution by using single-row, double-row, and transosseous techniques. In transosseous repairs, the stress was concentrated at the attachment site to bone and no stress was seen on the bursal side. On the other hand, single-row repairs had the highest stress concentration on the bursal side in the anchor area. A similar pattern was seen in double-row repairs with the stress more concentrated on the medial anchors. They hypothesized that the high stress concentration seen in single- and double-row techniques at the anchor sites may explain the high rate of recurrence rates seen in anchor repairs.

## Transosseous Equivalent Versus Double Row

These are the latest studies that have emerged comparing double-row techniques with the transosseous equivalent techniques by using the Pushlock knotless anchor. The Pushlock technique is also known as a suture bridge. Siskoksy et al.[46] used matched pairs of human cadaveric shoulders to compare the 2 techniques. They used cyclic loading and measured the ultimate load to failure and gap formation. The transosseous equivalent (TOE) had an ultimate load of 380 N compared with 285 N in the double-row technique. No statistical differences were seen in initial stiffness or gap formation. Another recent study presented at the 2006 AAOS meeting by Park et al.[47] compared 3 techniques (4-suture bridge TOE, 2-suture bridge TOE, and standard double row) by using pressure sensitive film. The contact area for the 4-suture bridge was 115 mm$^2$, the 2-suture bridge was 91 mm$^2$, and the double row was 56 mm$^2$. The pressure exerted by the 4-suture bridge was 0.27 MPa, the 2-suture bridge was 0.23 MPa, and the double row was 0.19 MPa. The 4-suture bridge transosseous repair clearly had the best contact area and pressure over the footprint compared with the other 2 techniques.

Finally, Costic et al.[48] recently presented their work on cadaveric cuff tears repaired with TOE. By using cyclic loading, the authors were able to create a crescent shaped tear. The tears were repaired by using the TOE technique. The repaired footprint was restored to 75% to 150% of the original. The cyclic creep was equivalent between the intact and repaired cuff and the ultimate load to failure of the TOE was 500 N.

To summarize the previously mentioned studies, single-row repairs had an ultimate load to failure of 275 to 300 N. They were not successful in restoring the footprint of the native rotator cuff and were most susceptible to gap formation. Double-row repairs had an ultimate load of 300 to 350 N. They were more successful than single-row repairs in restoring the footprint and had minimal gap formation. TOE repairs had the highest ultimate load ranging between 350 and 400 N. They were the most resistant to rotational and shear forces and most closely restored the native footprint leading to minimal gap formation.

## EARLY CLINICAL OUTCOMES

Because our rotator cuff repair techniques are evolving rapidly, there is no level I data available at this point, especially for TOE repairs. However, emerging outcomes evaluating these techniques remains promising. Sugaya et al.[49] retrospectively compared the functional outcomes of single-row versus double-row rotator cuff repairs at an average of 35 months. Thirty-nine patients were treated with single-row repairs and 41 using the double-row repair. Both groups had statistically similar subjective functional outcomes. Postoperative cuff integrity that was evaluated by using magnetic resonance imaging showed a statistically better structural outcome to the double-row technique.

DeBeer et al.[50] reviewed their data on 58 patients treated with a modified double-row technique with interlocking suture method. The patients had an average of a 15-month follow-up. Overall, 90% of the patients reported good to excellent results, and 89% of the cuff repairs were intact by ultrasonography.

Similarly, Lafosse et al.[51] reported their data on 105 patients treated with a double-row technique. The patients were followed for a minimum of 24 months. The average patient constant score increased from 43 preoperatively to 80 postoperatively. Only 11.4% of patients had a structural failure seen on computed tomography scan or MRI. In our patient follow-up using double-row or TOE repairs, we have observed earlier restoration of range of motion and subjective and objective results similar to or better than we have seen in single-row techniques.

## AUTHORS' PREFERRED TECHNIQUE

The authors prefer, according to the algorithm stated later, to perform TOE arthroscopic rotator cuff repair by using 2 Arthrex 5.5-mm fully threaded Bio-Corkscrew anchors double loaded with FiberWire placed at the medial edge of the rotator cuff footprint with 2 simple sutures stabilizing the anterior and posterior edges of the rotator cuff cable separated by 2 horizontal mattress sutures. The anterior and posterior simple sutures are tied and cut. The anterior and posterior horizontal sutures are tied but not cut. One suture of each horizontal mattress is retrieved, and an Arthrex Pushlock anchor is used to secure the 2 retrieved sutures to the lateral edge of cuff footprint anteriorly, and the sutures are cut. The same is repeated to retrieve the last 2 sutures and place them through another Pushlock anchor in the posterior-lateral edge of the footprint. If any question exists regarding the quality of the lateral fixation, a few alternating half-hitch sutures can be advanced into the Pushlock hole to prevent the suture from migrating from its apposition to the anchor's body. The final configuration should demonstrate a balanced interconnectivity of all sutures with the medial row of the repair neutralizing force transmission to the lateral row (Fig 1).

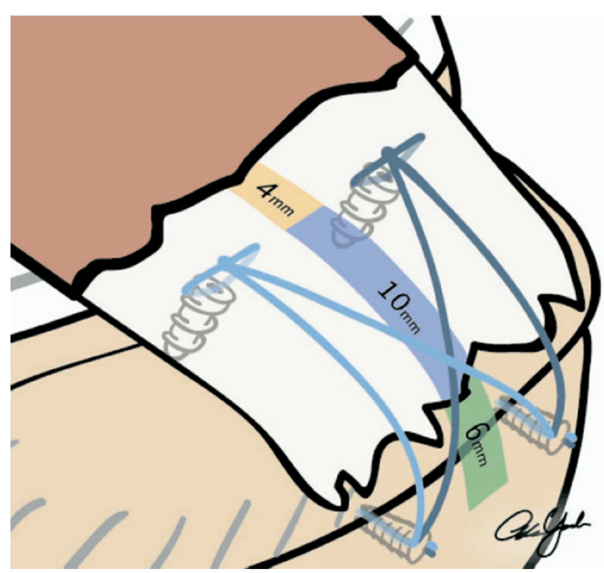


FIGURE 1. The suture bridge transosseous equivalent technique using 2 medial anchors and 2 lateral PushLocks. The "bridge" configuration provides compression of the rotator cuff to the footprint.

## ROTATOR CUFF REPAIR ALGORITHM

Based on the biomechanical data presented in the literature and our recent experience with new repair techniques, we have developed a repair algorithm that we believe can help the surgeon determine the appropriate technique and configuration based on tear configuration.

It is important in any repair to follow the general techniques that have been well described.[52,53] It is crucial to define the tear pattern and to perform margin convergence when necessary to reduce U-shaped and L-shaped tears to more crescenteric type tears. Furthermore, it is important to achieve a tension-free repair using anterior and/or posterior interval releases as described by Lo and Burkhart.[54] Finally, regardless of the repair technique used, it is very important to balance the forces of the repairs in both the coronal and transverse planes and to achieve the best knot and loop security possible during arthroscopic knot tying.[55]

For acute tears that are either partial thickness in nature or full thickness but do not involve the entire cuff footprint (i.e., under 12 mm in length), we believe that a single-row repair may be sufficient. The ultimate load to failure of a single row of about 275 N, we believe, is sufficient to withstand the loads experienced by the repair and to adequately keep the repair intact until biology has taken over.

As for more chronic tears, inferior tissue quality and tears larger than 12 to 15 mm in the anterior to posterior dimension, we strongly believe that a double-row or TOE repair will best achieve the goals of restoring the anatomic footprint, interconnectivity, and mechanical stability to optimize the anatomic healing rates. Basically, anytime it is possible to close the cuff tear and completely cover and reattach the footprint without excessive repair tension, we believe it is best to do so. In tears in which excessive central cuff crescent tissue erosion or retraction has occurred, the humeral head may not be able to be completely covered, but if the cables (anterior and posterior extent of the tear) can be reattached, the cuff will have improved function. Medializing the repair site on the footprint may occasionally be necessary to achieve tendon repair; however, biologic healing rates may be lower in such cases.

## SUMMARY

After years of treating rotator cuff repairs using the same single-row techniques and having seen the recurrence rates, our latest techniques have attempted to solve some of the problems seen in single-row repairs (inability to restore the footprint anatomy, failure to optimize tissue and bone contact, and inadequate mechanics of repair) and improve outcomes. In vitro data suggests that double-row and transosseous equivalent repairs have the ability to maximize repair mechanics. By “spreading” the repair over a larger area, the 3-dimensional footprint is more accurately restored. In addition, from a biomechanical perspective, the double-row and TOE repairs provide more uniform compression and contact between the cuff and the bone, and neutralize the forces medially where the cuff experiences the largest in vivo forces. Furthermore, they minimize gap formation and shear resistance and allow the patients to progress through physical therapy with greater confidence. TOE repairs had the highest ultimate load and were the most resistant to rotational and shear forces and the most closely restored the native anatomic footprint. Clearly, prospective studies with direct comparison to traditional techniques will be required to substantiate the abundance of in vitro data available at this time.

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