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SHOULDER

History of rotator cuff surgery

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Abstract
Purpose Rotator cuff surgery is a rapidly evolving branch in orthopaedics, which has raised from a minor niche to a fully recognized subspecialty. This article summarizes its history, examining the development of its key principles and the technical advancements.
Methods Literature was thoroughly searched, and few senior surgeons were interviewed in order to identify the significant steps in the evolution of rotator cuff surgery.
Results A wide variety of surgical options is available to reduce pain and restore function after rotator cuff tears. Rotator cuff repair surgical techniques evolved from open to arthroscopic and are still in development, with new fixation techniques and biological solutions to enhance tendon healing being proposed, tested in laboratory and in clinical trials. Although good or excellent results are often obtained, there is little evidence that the results of rotator cuff repair are improving with the decades. An overall high re-tear rate remains, but patients with failed rotator cuff repairs can experience outcomes comparable with those after successful repairs.
Conclusions Rotator cuff repair techniques evolve at a fast pace, with new solutions often being used without solid clinical evidence of superiority. It is necessary to conduct high-level clinical studies, in which data relating to anatomical integrity, patient self-assessed comfort and function, together with precise description of patient's condition and surgical technique, are collected.
Level of evidence IV.

Keywords Rotator cuff · Shoulder · Arthroscopic rotator cuff repair · Open rotator cuff repair · History of surgery

Introduction

Rotator cuff surgery is nowadays considered an independent, highly specialized sector of orthopaedics; thousands of repairs are performed every year, and this impacts significantly on patient's quality of life, surgical departments' economics and orthopaedic companies' innovation drive.

However, if we turn back our attention to 200 years ago, then only once a torn rotator cuff had been depicted, and 100 years ago the world overall count of published rotator cuff repairs did not reach a dozen.

This article will summarize the history of rotator cuff surgery, examining the development of its key principles and the advancements in its technology, presenting both the well-established approaches used by the majority of surgeons and the innovative ideas which may revolutionize this surgery in the near future.

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Early history

The very first description of a torn rotator cuff appeared in 1788, when Alexander Monro depicted a tear in supraspinatus and infraspinatus in his book "A Description of All the Bursal Mucosae of the Human Body" (Fig. 1; Table 1) [122].

Almost 50 years later, John Smith [154] published the first series of rotator cuff tears; in his cadaver study, many of the rotator cuff tear types known today and associated pathologies were described, including dislocation of the long head of the biceps and rotator cuff arthropathy.

In the following decades, plenty of anatomical studies were conducted in Europe, which detailed rotator cuff disorders and their relationship with other shoulder diseases [29, 72].

In 1855, the French surgeon Jean-François Malgaigne [109] postulated the role of dislocations in the aetiology of rotator cuff avulsions identified in cadaver specimens.

Later, the British Flower [64] and Adams [1] described in their books different examples of rotator cuff tears, the latter postulating arthritic rather than traumatic aetiology.

In Germany, Franz Freiherr von Pitha [21] was the first author who described in 1884 a torn rotator cuff after a shoulder dislocation and, in the same year, Jossel and von Waldeyer-Hartz [93] depicted examples of cuff tear arthropathy after recurrent dislocation and fatty muscle degeneration after tendon avulsion and retraction. In the same decade, Krönlein [100] and Bardenheuer [15] suggested the possibility to re-attach the torn tendons to the humerus after a dislocation (1882, 1888).

Between 1860 and 1980, other aetiologies for shoulder pain were investigated, including impingement of the thickened bursa under the acromion, entrapment or dislocation of the long head of the biceps [89] and subacromial stiffness and adhesions [53].

After the introduction of X-rays in 1895, calcifications were identified as a cause of subacromial bursitis by several authors, firstly by Charles F. Painter in 1907 [18, 132, 172].

Attempts of surgical repair were, however, extremely rare before the beginning of the nineteenth century. In 1870, Karl Hüter firstly re-attached torn cuff tendons to the humeral diaphysis after a humeral head resection in chronic dislocation, and in 1898, Wilhelm Müller repaired rotator cuff tears to the humeral head during a surgical intervention for shoulder stabilization [138].

The new century represented the beginning of a new era for rotator cuff surgery.

Perthes [138] reported in 1906 about a series of three rotator cuff repairs in which for the first time suture anchors were used, and in 1911, Codman [38] firstly described in the USA the surgical technique to repair supraspinatus tendon lesions, in an article which is considered a milestone in rotator cuff surgery.

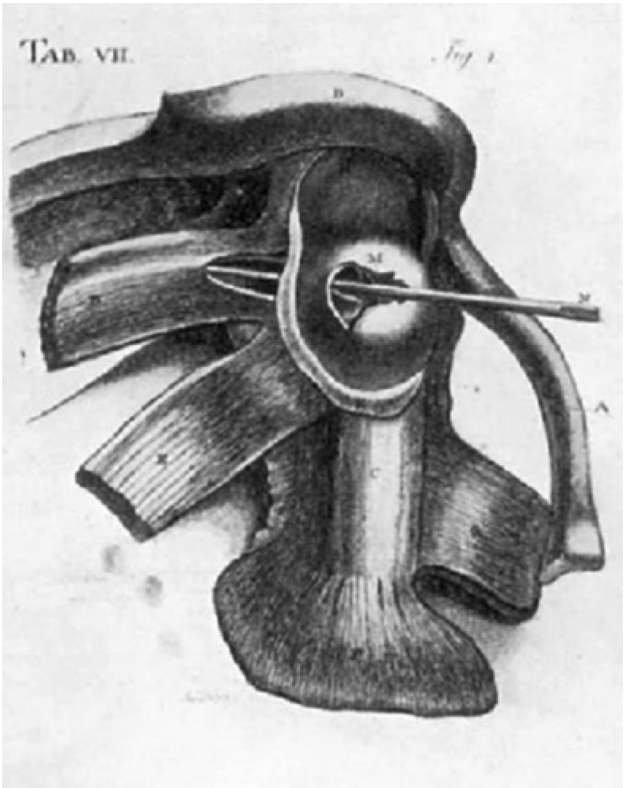

Fig. 1 First known illustration of a rotator cuff tear. Reprinted from: British Journal of Surgery, Volume 38, Issue 151 (January) 1951, pp. 340–369, Copyright © 1951 British Journal of Surgery Society Ltd, H. F. Moseley, "Ruptures of the rotator cuff", with permission from John Wiley and Sons

After Codman, in order to repair more complex lesions, advances in open surgical techniques were performed. In this period, several open fixation techniques were used, among which the transosseous repair was considered the gold standard [2, 32, 41, 60, 62, 79, 84, 88, 145].

The development of rotator cuff surgery was significantly incremented by the progress in imaging techniques. Arthrography conjugated the possibility to visualize bony structures with the opportunity to enlarge the joint space with a radio-opaque contrast medium. Arthrography was used in 1949 to diagnose rotator cuff tears [171], and the next year Kessel [96] described a standardized method to diagnose traumatic bursitis, frozen shoulder, rotator cuff tears and osteochondromatosis. Twenty-five years later arthrography was considered a proven and well-established diagnostic tool [127] and was used also as therapeutic solution for frozen shoulder (Fig. 2) [4, 44].

Magnetic resonance imaging represented a revolution in shoulder imaging and permitted to dramatically improve rotator cuff tear classifications. This was a key element for the surgeon, who was able to plan the suitable repair technique for each type of lesion before surgery.

Table 1 Rotator cuff surgery timeline

Year	Authors	Contribution
1788	Alexander Monro	First description of a tear in supraspinatus and infraspinatus
1834	John Gregory Smith	First series of rotator cuff tears in cadavers
1855	Jean-François Malgaigne	Role of dislocations in the aetiology of rotator cuff tears
1870	Karl Hüter	First repair of a torn rotator cuff to the humeral diaphysis (after humeral head resection in chronic dislocation)
1872	Simon Emmanuel Duplay	Role of stiffness and adhesions in shoulder pain
1873	Robert Adams	Role of arthritis in the aetiology of rotator cuff tears
1898	Wilhelm Müller	First repair of a torn rotator cuff in an operation for instability
1906	Georg Clemens von Perthes	First case series in Europe (three rotator cuff repairs)
1907	Charles F. Painter	Description of calcific deposits in subdeltoid region
1911	Ernest Amory Codman	First case series in USA (two rotator cuff repairs)
1931	Michael Samuel Burman	First shoulder arthroscopy on a cadaver
1944	Harrison L. McLaughlin	Description of treatment for retracted lesions
1957	Masaki Watanabe	First Atlas of Arthroscopy
1961	Jean Debeyre	Lateral advancement of the supraspinatus muscle to repair large lesions
1972	Charles S. Neer	Anterior acromioplasty
1974	Masaki Watanabe	Foundation of the International Arthroscopy Association
1978	Masaki Watanabe	Description of posterior portal for shoulder arthroscopy
1978	Julius S. Neviaser	First autologous scaffold for rotator cuff augmentation
1979	V. Conti	Description of anterior portal for shoulder arthroscopy
1982	Robert Cofield	Subscapularis transfer
1985	James Andrews	Arthroscopic debridement for partial supraspinatus tears
1986	Jiro Ozaki	First synthetic scaffolds for rotator cuff augmentation
1987	Harvard Ellman	First large case series of arthroscopic subacromial decompression (50 cases)
1987	Paul Grammont	Reverse shoulder arthroplasty
1988	Christian Gerber	Latissimus dorsi transfer for massive tears
1989	Eugene M. Wolf	Detailed description of anterior portals for shoulder arthroscopy
1990	Howard J. Levy	Arthroscopically assisted rotator cuff repair
1992	Louis U. Bigliani	Operative treatment of failed repairs of the rotator cuff
1993	Stephen J. Snyder	First report of arthroscopic rotator cuff repair
1994	Stephen S. Burkhart	Partial repair for massive rotator cuff tears
1996	Stephen S. Burkhart	Margin-convergence technique for large rotator cuff tears
1999	Joseph C. Tauro	Arthroscopic interval slide for retracted rotator cuff tears
2003	Ian K. Lo	Double-row arthroscopic rotator cuff repair
2006	Maxwell C. Park	Transosseous-equivalent rotator cuff repair
2006	Nicolas Matis, Nikola Cikak	Devices for arthroscopic transosseous repair, first published attempts
2007	Enrico Gervasi	Arthroscopic latissimus dorsi transfer
2009	Eugenio Savarese	Subacromial biodegradable spacer
2008	Pietro Randelli	Platelet-rich plasma in arthroscopic rotator cuff repair: the first pilot study
2012	João L. Ellera Gomes	Rotator cuff repair complemented with autologous stem cells
2013	Chih-Chien Tsai, Pietro Randelli, Hajime Utsunomiya	Isolation of human mesenchymal stem cells from shoulder tissues
2014	Noboru Taniguchi	Arthroscopic surface-holding repair

Ellman [58], Patte [135], Snyder [155] and Habermeyer et al. [81] proposed different classification systems for partial lesions, based either on the medio-lateral or on the transversal extension of the lesion. For complete lesions, the first classification dates back to 1944, when Harrison L. McLaughlin distinguished transversal, vertical and retracted tears [116]; more precise and complete classifications were suggested recently by De Orio and Cofield [50], Harryman et al. [83], Ellman and Gartsman [59] and Snyder [155].

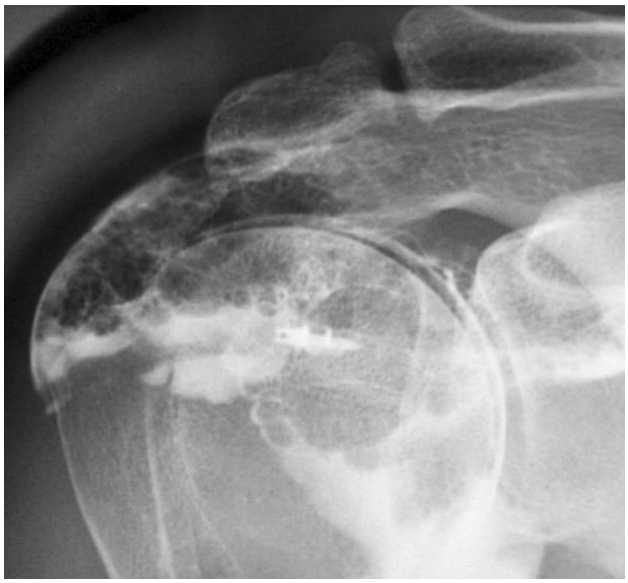

Fig. 2 Shoulder arthrography showing rotator cuff re-rupture

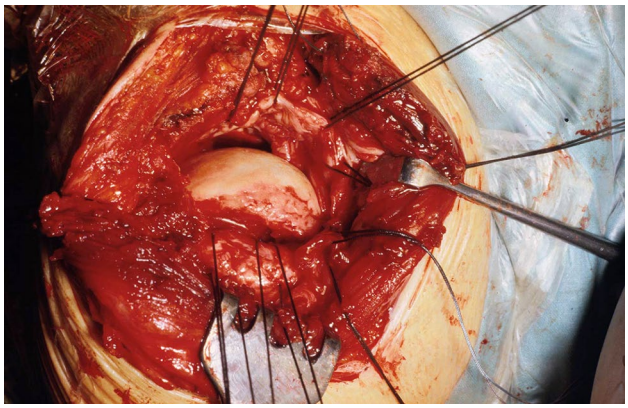

Fig. 3 Open repair of a massive rotator cuff lesion: the tendon margin is identified and prepared before re-insertion through bony tunnels

Nowadays, Millstein and Snyder's (or "Southern California Orthopaedic Institute") classification is the most frequently used pre-operative scoring system; it is a comprehensive classification which distinguishes between articular, bursal and complete lesions and classifies them according to their medio-lateral extension or retraction. For arthroscopic intra-operative diagnosis, a revision of Ellman's classification proposed in 2010 by Davidson and Burkhart [43] is widely used; this "geometric" classification considers the shape of the lesion and provides for each type operative suggestions.

Open techniques

Open surgery with transosseous fixation was considered the gold standard in rotator cuff repairs until the beginning of the new century [2, 60, 79, 84, 88, 145].

Open rotator cuff repair is traditionally performed with the patient in a beach-chair position. After identification of the appropriate bony landmarks, a 3- to 6-cm incision is made over the anterior–superior aspect of the shoulder, parallel to the lateral border of the acromion, in the direction of Langer's lines. After careful identification of the deltoid insertion, the muscle is detached from the acromion, generally beginning at the acromioclavicular joint, extending along the anterior border of the acromion, then splitting the deltoid laterally for 3–5 cm. Subacromial decompression, bursal resection and debridement of adhesions from the tendon are performed. After bone preparation, a trough running the length of the exposed bone of the greater tuberosity is created using a burr osteotome. Between the medial and lateral drill holes, it is to be preferred to maintain an approximately 1.5 cm bridge of hard cortical bone, with the lateral hole exiting cortical bone distal to the greater tuberosity. A suture is passed through the bony tunnels and then through the torn tendon. A locking-stitch technique, known as the modified Mason-Allen stitch, is preferred to simple sutures because it provides better holding power, especially with poor rotator cuff tissue quality. Deltoid re-attachment to the acromion is a fundamental passage of open rotator cuff repair; the longitudinal deltoid split is repaired with non-absorbable sutures in a simple fashion, while re-attachment to bone is often performed through tunnels in the acromion (Fig. 3).

Historically, important steps of open rotator cuff repair surgery are represented by McLaughlin's [116] technique to repair retracted lesions and Jean Debeyre and Patte's [45] supraspinatus advancement to repair large rotator cuff tears (Fig. 4).

Neer's [125] introduction of anterior acromioplasty to reduce the supraspinatus wear caused by the friction of a hooked acromion with the tendon represented another milestone in shoulder surgery.

Tendon transfers, which had previously been used to treat neurological palsies [85, 103], were first performed for the treatment of rotator cuff tears by Cofield [39] and Gerber et al. [67, 69].

Bigliani et al. [20] dealt with the problem of rotator cuff repair failure and was the first to suggest operative guidelines for revision surgery to repair massive tears.

Arthroscopic techniques

The most relevant innovation in rotator cuff surgery was represented by the development and introduction of the arthroscopic technique.

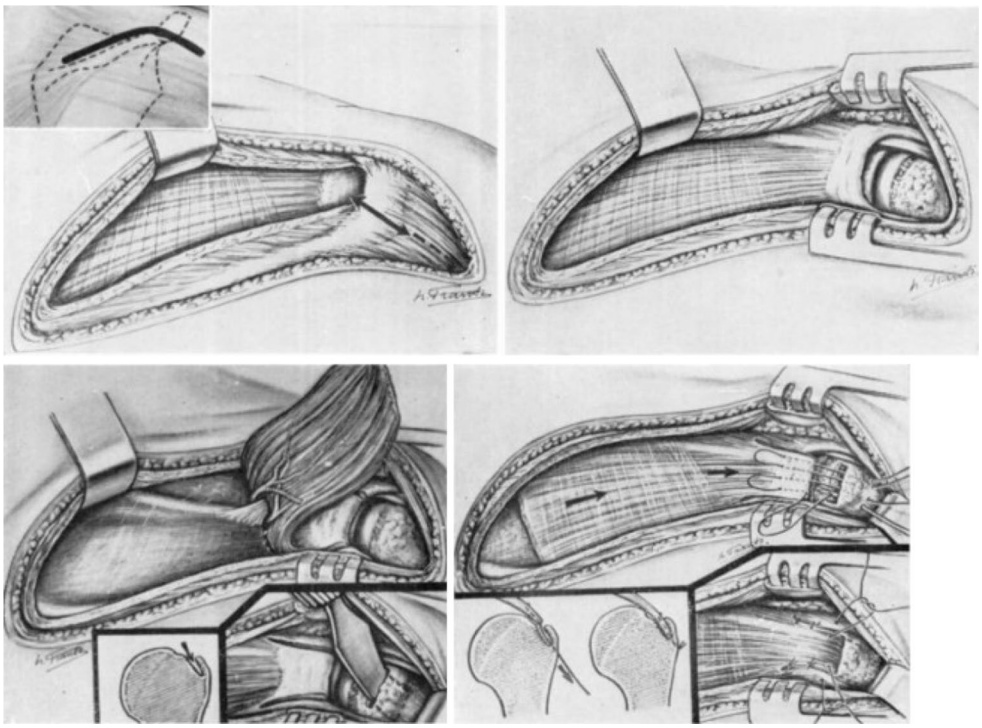

Fig. 4 Operative steps for rotator cuff repair with supraspinatus advancement. Reprinted from: The Journal of Bone & Joint Surgery (British Volume), Vol. 47-B No. 1, February 1965, pp. 36–42, Copyright © 1965 The British Editorial Society of Bone & Joint Surgery, J. Debeyre, D. Patte and E. Elmelik, "Repair of Ruptures of the Rotator Cuff of the Shoulder—With a Note on Advancement of the Supraspinatus Muscle", with permission from Springer Healthcare

The premises to shoulder arthroscopy date back to 1806, when the German urologist Philipp Bozzini built an instrument that could be introduced in the human body to visualize the internal organs using a candle as source of light. He called this instrument "Lichtleiter" and was therefore credited to be the inventor of the first endoscope (Fig. 5) [31].

The first recorded application of an endoscope to examine a joint occurred in 1912, when the Danish surgeon Severin Nordentoft used a laparoscope to examine the interior of knees [98].

Takagi [160], a Japanese orthopaedist, proved that a cystoscope could be used to examine knees affected by tuberculosis in 1918, and in 1919, in Europe again, the Swiss Eugene Bircher was the first surgeon to perform 21 knee arthroscopies on live patients, publishing his results in 1922 (Fig. 6) [97].

Masaki Watanabe, a former student of Takagi, is remembered for the fundamental improvements to the design of the arthroscope and for his "Atlas of arthroscopy", which permitted to spread this technique widely. Fibre optics were firstly used in arthroscopy by this Japanese surgeon (1967, Fig. 7) [46].

Burman [30] was the first to perform diagnostic shoulder arthroscopy on cadavers, in 1931, in the USA. He performed 90 arthroscopies on different cadaver joints, among which 25 were shoulders, and compared the arthroscopic findings with those seen when the joint was opened.

Fig. 5 Bozzini's endoscope "Lichtleiter". Reprinted with permission from the Archives of the American College of Surgeons

Fifty years later, arthroscopy began to be used in vivo as a diagnostic instrument to confirm clinical diagnosis of

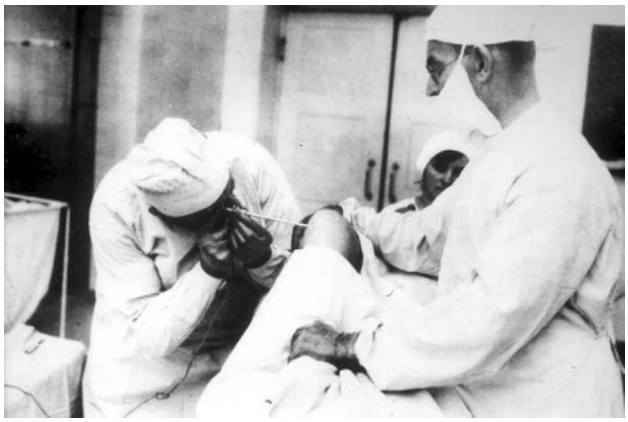

Fig. 6 Eugen Bircher performing a knee arthroscopy. Reprinted from: Arthroscopy: The Journal of Arthroscopic and Related Surgery, Vol 19, No 7, September 2003, pp. 771–776, Copyright © 2003 Elsevier Inc, Christopher W. Kieser, Robert W. Jackson, "Eugen Bircher (1882–1956) The First Knee Surgeon to Use Diagnostic Arthroscopy", with permission from Elsevier

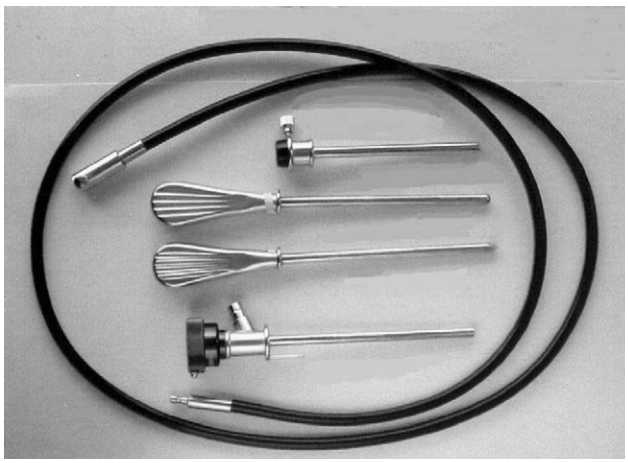

Fig. 7 Watanabe's arthroscope No. 22, the first direct-view scope with cold-light illumination. Reprinted from: Arthroscopy: The Journal of Arthroscopic and Related Surgery, Vol 22, No 4, April 2006, pp. 345–350, Copyright © 2006 Elsevier Inc, Christopher W. Kieser, Robert W. Jackson, "How Cold Light Was Introduced to Arthroscopy", with permission from Elsevier

frozen shoulder, rotator cuff tears, instability, arthritis, fractures and villonodular synovitis [40, 80, 105, 107].

Operative arthroscopy was mostly developed in the USA with the first report in the late 1980s by Ellman [56], who performed subacromial decompression in 50 consecutive patients, and by James Andrews, who performed arthroscopic debridement of supraspinatus lesions in 36 patients [5].

In 1990, Howard J. Levy suggested the possibility to combine arthroscopy with arthrotomy to better diagnose and repair rotator cuff lesions and reported results of 25 patients treated with this "arthroscopically assisted" or "mini-open" technique at a minimum of 1 year of follow-up [104].

In order to perform mini-open repair, after diagnostic arthroscopy and preparation, the antero-superior portal is extended by 1–2 cm, and the fibres of the deltoid are split, without detaching the muscle from the acromion, to obtain access to the humeral head for secure tendon-to-bone fixation. With this approach, rotator cuff preparations, including debridement of tendon edges, releases and mobilization are all performed arthroscopically.

This technique represented a transition phase in rotator cuff surgery, which soon evolved to all-arthroscopic techniques.

In the 1990s, arthroscopic surgery was used to remove loose bodies, treat instability, calcific tendonitis, septic arthritis and other disorders [57] and, eventually, to repair rotator cuff tears. After a preliminary report by Snyder [156], Raymond Thal published in 1993 a technical note on how to arthroscopically place mattress sutures, a technique which paved the way to modern arthroscopic rotator cuff repairs [165].

Nowadays, arthroscopic rotator cuff repair can be performed in beach-chair or lateral decubitus position. After traction is performed, standard posterior and antero-superior portals are created. Before performing rotator cuff repair, tear pattern has to be identified, cuff tear mobilized and the footprint prepared. To repair supraspinatus tendon lesions, the first arthroscopic repair techniques used either a single anchor or a row of anchors placed from anterior to posterior, implanted a few millimetres lateral to the tendon footprint [163, 165]. This repair technique is known as single-row repair.

A supero-lateral portal is used to introduce the anchors and to place them along the articular margin of the humeral head at a 45° inclination following the "deadman angle" theory [25]. If a single anchor is used, it is placed in the centre of the lesion; if multiple anchors are used, they are placed from anterior to posterior in order to cover the whole extent of the lesion (Fig. 8).

Arthroscopic techniques evolved quickly in the last two decades, and numerous strategies were proposed to improve clinical results of the single-row technique; Lo and Burkhart [106] presented a novel technique called double row, which claimed biomechanical superiority to single-row repairs.

As for single-row repair, standard portals are created and diagnostic arthroscopy is performed. Tear pattern is identified, bone bed is prepared, and mobilization of the cuff is done as necessary, performing it subacromially as well as intra-articularly. The medial row of anchors is placed first and located just lateral to the articular surface of the humeral head. The lateral row of anchors may be placed on the lateral

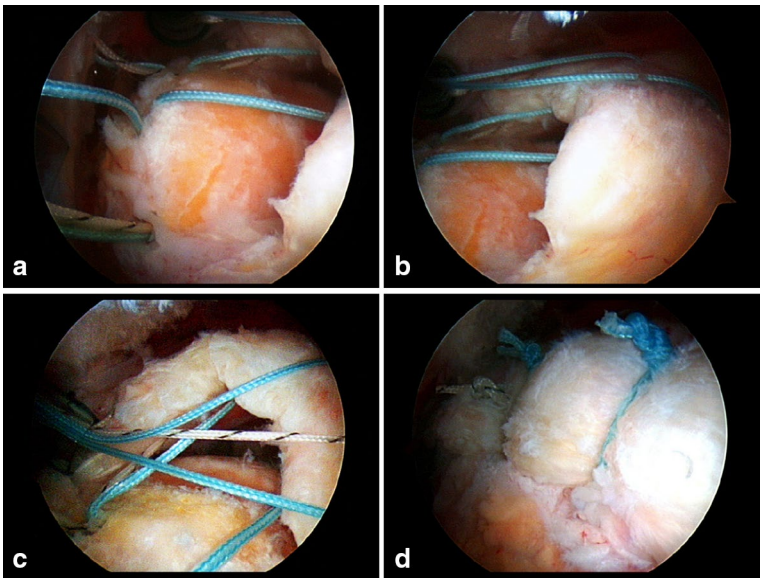

Fig. 8 Single-row rotator cuff repair: after preparation of the greater tuberosity with three suture anchors, **a** the sutures are passed in the cuff with a single stitch configuration (**b**) and retrieved through the lateral cannula (**c**); cuff repair, final view (**d**)

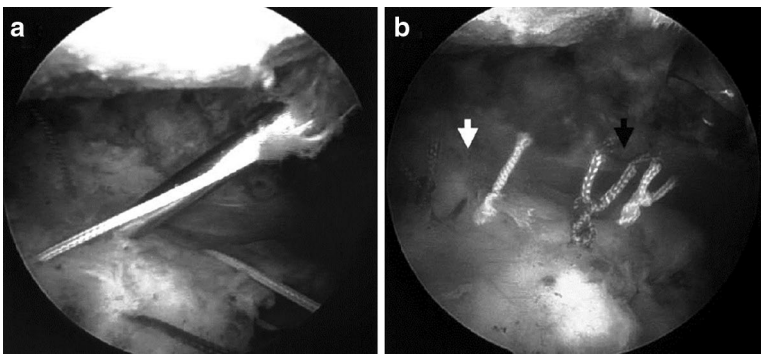

Fig. 9 Double-row rotator cuff repair: suture tying viewed through a posterior portal (**a**) and completed double-row rotator cuff repair with medial (*white arrow*) and lateral (*black arrow*) rows of fixation. Reprinted from: Arthroscopy: The Journal of Arthroscopic and Related Surgery, Vol 19, No 9, November 2003, pp. 1035–1042, Copyright © 2003 Elsevier Inc., Ian K.Y Lo, Stephen S Burkhart, "Double-row arthroscopic rotator cuff repair: re-establishing the footprint of the rotator cuff", with permission from Elsevier

aspect of the bone bed just medial to the "drop-off" of the greater tuberosity. Special care must be taken to ensure an adequate bone bridge between the medial and lateral anchors and that each anchor is inserted at a proper deadman's angle. Depending on the size of the tear, medial and lateral row could require one or two anchors. Sutures are passed through the rotator cuff tendon starting from the medial row of anchors; the medial sutures are tied in a mattress fashion over the tendon. The lateral row of anchors are tied later and passed in a simple suture fashion (Fig. 9) [106].

Important achievements in arthroscopic rotator cuff surgery are represented by the repair of large and retracted lesions. The first repairs, in which the tendon was simply re-attached to the bone in a "tendon-to-bone" or "direct-lateral" fashion, failed for excessive tissue tension if the lesion was too large or the margin to re-attach was too far from the footprint.

Already in 1994, Burkhart suggested that "to cover the hole in the cuff" at all costs was not a correct imperative in every rotator cuff repair. In fact, the biomechanical function of the rotator cuff is to provide a stable fulcrum to the deltoid muscle in the abduction of the humeral shaft, and this can be obtained also with a deficient supraspinatus [24]. This justifies the concept of "partial repair", a repair of subscapularis and infraspinatus tendons, without supraspinatus repair, which is enough to restore a force couple that stabilizes the humeral head [26, 28] and permits return to daily activities in pseudo-paralytic shoulders with long-term patient satisfaction (Fig. 10) [139].

Other advancements in treatment of large lesions are represented by the concepts of "margin convergence" and "interval slide".

Margin convergence is a repair technique in which the margins of a large U-shaped or L-shaped rotator cuff lesion

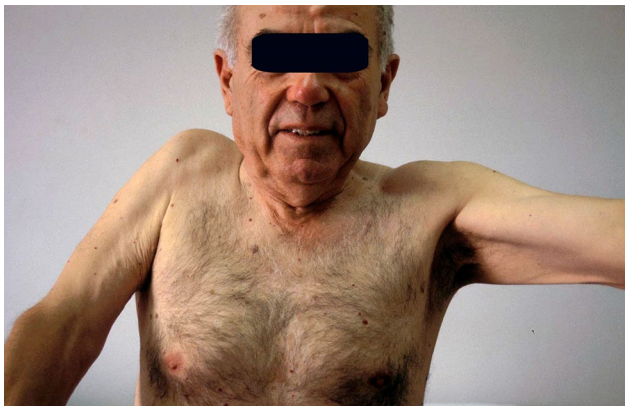

Fig. 10 Pseudo-paralytic shoulder after massive rotator cuff tear: a disabling situation which can be solved by arthroscopic partial repair or by implantation of a reverse shoulder prosthesis

are tied together with a side-to-side suture; this permits the advancement of the free margin closer to the anatomical insertion, hence permitting to perform a tendon-to-bone repair with less strain (Fig. 11) [27].

The anterior "interval slide" consists in the detachment of the supraspinatus from the superior capsule and from the coracohumeral ligament in order to obtain a better tendinous mobilization; although already used in open surgery, Tauro [164] described the arthroscopic application of this technique first in 1999. A posterior interval slide, consisting in detaching the supraspinatus from the infraspinatus and the posterior capsule, was described later (Fig. 12) [119].

These repair variations for large tears can all be performed regardless of the fixation technique chosen.

Various modified double-row techniques have been developed, in order to reproduce the results of the open transosseous technique, which until late years was considered the gold standard for rotator cuff repair [49, 130, 134].

The "suture-bridge" or "transosseous-equivalent" technique was developed to increase the footprint contact area using a double-row-like suture construct, to mimic the anatomical results of open transosseous repair. This technique consists in creating a medial row of anchors, placed at the articular margin, with sutures passed in a mattress configuration. The lateral fixation points are placed 1 cm distal–lateral to the lateral edge of the tuberosity footprint insertion; the anchors have to be placed as far anteriorly and posteriorly as possible to maximize the pressurized contact area. In general, the medial and lateral fixation implants are placed at points where drill holes would be placed for a traditional open transosseous technique. After the medial row is repaired, the sutures are not cut, but the limbs are then used to create suture bridges over the tendon [134].

Transosseous repair was one of the most appreciated open repair techniques, because of the possibility to recreate the footprint anatomy. The possibility to combine these biomechanical premises with a minimally invasive surgical approach has raised the attention of numerous surgeons. The use of "giant needles", which were passed in through skin, deltoid muscle, torn tendon, humeral bone and out through the lateral cortical surface, deltoid and skin was the first attempt to imitate the open transosseous repair in arthroscopy [63, 133]. Later, surgical devices to perform arthroscopic transosseous repair without suture anchors were developed [37, 112], and the first promising results of arthroscopic transosseous repairs, performed with different systems, have been published (Fig. 13) [16, 102]. Combinations of medial suture-anchor fixation and lateral transosseous fixation have also been attempted and recently described as "arthroscopic surface-holding" repair [161, 170].

Suture anchors

A wide variety of suture anchors has been developed for the fixation of tendons to bone.

Suture anchors vary in size, shape, composition, method of insertion and fixation, radiopacity and holding strength [10]. New anchors continue to be released

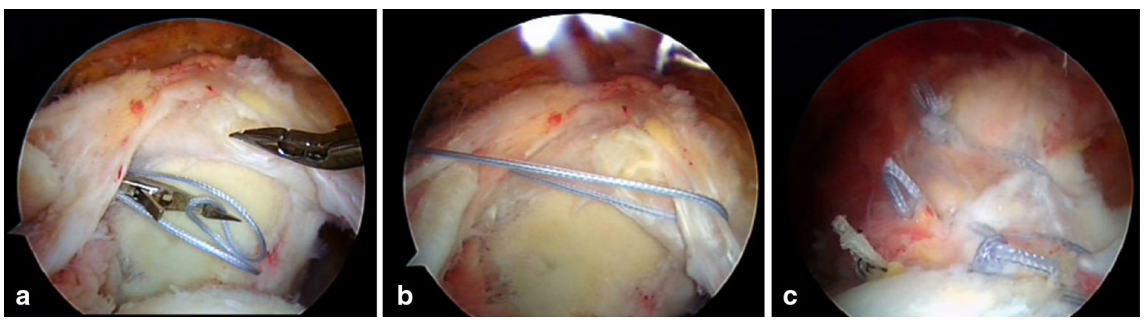

Fig. 11 Side-to-side suture: UHMWP wires are passed from the anterior to the posterior border of the lesion (**a**). Once the knots are tied, the free margin of the lesion advances (**b**), thus permitting to repair the tendon to the bone without excessive tension (**c**)

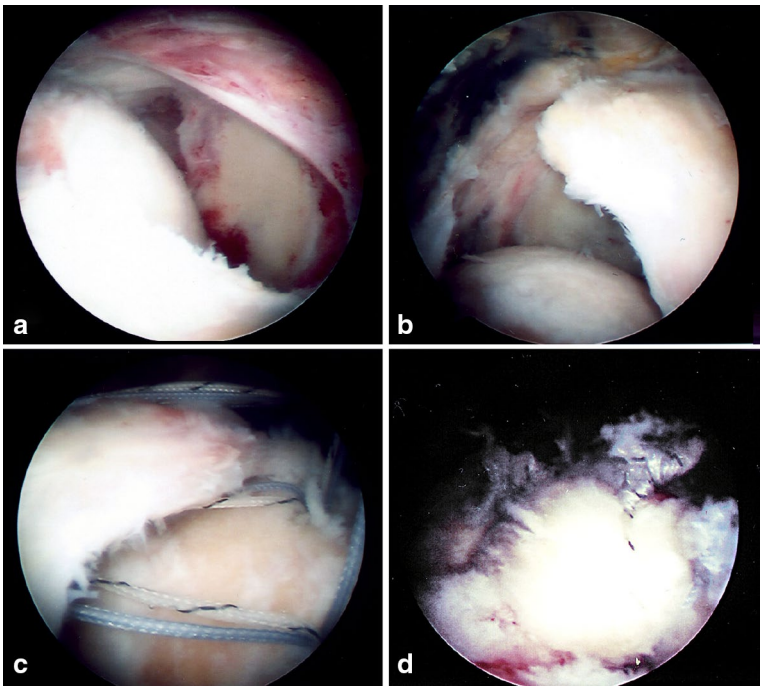

Fig. 12 Posterior interval slide to repair a C4 lesion (**a**): the supraspinatus tendon is detached from the infraspinatus and from the posterior capsule (**b**); UHMWP wires are passed through the lesions borders (**c**). Tension-free tendon-to-bone repair (**d**)

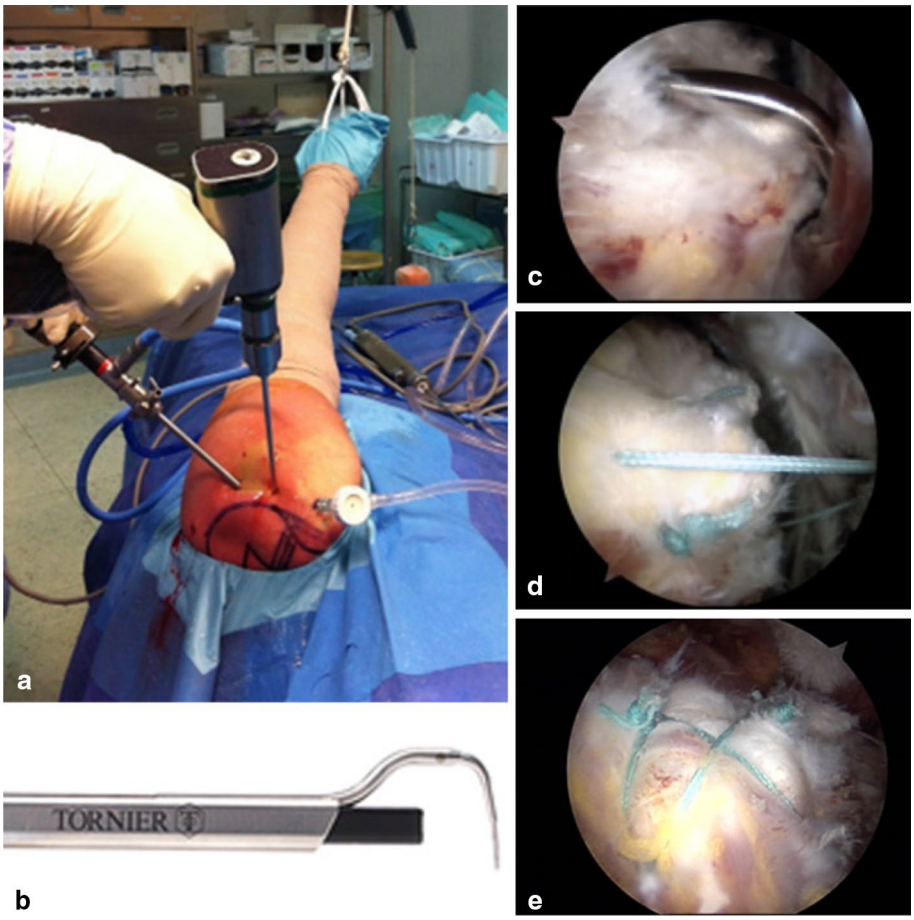

Fig. 13 Arthroscopic transosseous repair. The transosseous tunnels are drilled (**a**) with the help of an aiming device (**b**, **c**) (ArthroTunneler™, Tornier N.V., Amsterdam, The Netherlands); sutures are then passed through the tunnels and through the free margin of the lesion (**d**) and tied in a X-box modified suture that maximizes the tendon-bone contact surface (**e**)

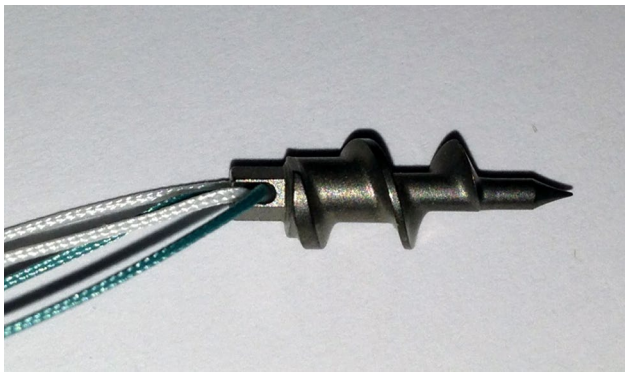

Fig. 14 A Corkscrew® Suture Anchor (Arthrex, Inc Corporate, Naples, FL, USA), a double-loaded, fully threaded, screw-in suture anchor, one of the first titanium anchor available for RCR

as older designs are replaced by newer ones easier to handle, with improved mechanical properties and with a lower rate of failure for anchor pull-out and suture cut-out. Suture breakage represented a failure reason in the past, but has been nowadays overcome by newer, extremely strong ultra-high molecular weight polyethylene (UHMWPE)-containing sutures [12].

For what concerns anchors' insertion and fixation, several strategies have been adopted: partially threaded, fully threaded or double threaded screw-in anchors are opposed to non-screw push-in anchors. In cadaveric biomechanical studies, threaded screw-in anchors provided superior pull-out strength when compared to push-in or hook-type anchors, especially in osteoporotic bone [11, 166].

The most frequent material used for anchors manufacture in the past 20 years has been metal (stainless steel or titanium, Fig. 14); however, new materials have been used in the last decade, like polyglycolic acid, poly-L-lactic acid, polyetheretherketone, tricalciumphosphate and hydroxyapatite. These non-metallic anchors should be easier to deal with in case of revision and are used in paediatric applications; some of them are biodegradable and may offer anchor resorption and bone integration [9].

Failure of these bio-anchors is mostly caused by eyelet breakage, as opposed to anchor pull-out which represents the most relevant failure reason in metallic anchors. However, it should be emphasized that although tendon-to-bone repair failure can occur, the weakest point of a repair is the suture–tendon interface [12].

Suture-based anchors, which are composed only of ultra-high molecular weight polyethylene, have also been developed [13].

Double-loaded and triple-loaded suture anchors represent a solution to achieve excellent footprint restoration also with a reduced number of fixation points [47, 137].

Sutures and knots

Suture wires have evolved from weak materials like catgut or polyester to stronger polydioxanone or UHMWPE-containing wires, and this allowed to overcome the problem of suture breakage previously described [14].

The knot-tying techniques evolved as well and new suture configurations were proposed to better restore the footprint anatomy [117]. All knots rely on two principles for their effectiveness and their ability to securely hold and approximate tissue. The first concept is loop security, which is defined as the ability of the length of suture passed through the tissue to maintain the initial tension and length as the knot is delivered and tightened. The second, knot security, is the ability of the completed knot to resist slippage.

Two basic types of knots exist: non-sliding and sliding knots. Sliding knots are constructed outside the cannula and delivered to the tissue with a knot pusher, while non-sliding knots are performed at the tissue [86, 117]. New knots have been suggested and tested in vitro and over twenty different choices are nowadays available [17, 42].

Other techniques

Although arthroscopic repair represents the most widely used approach to treat rotator cuff lesions, other strategies have been described.

Musculotendinous transfer, which was presented as experimental technique in 1982 by Robert Cofield (subscapularis transfer) [39] and 1988 by Christian Gerber (latissimus dorsi transfer) [69], has gained a relevant role in a selected subgroup of patients.

Transfers of latissimus dorsi and pectoralis major tendons have been shown to consistently improve pain; however, functional benefits are unpredictable [129]. Trapezius tendon transfer may be an alternative in patients with massive postero-superior rotator cuff tears and has been used with conflicting results to repair irreparable subscapularis tears [73].

Latissimus dorsi tendon transfer is the most frequent transfer performed to treat massive irreparable postero-superior cuff tears. It can be performed as open as well as arthroscopic procedure and is indicated in young and non-osteoarthritic patients either as a primary procedure or after the failure of a previous surgical treatment of massive irreparable postero-superior rotator cuff tears [68, 70, 75, 124].

Kilinc et al. [99] proposed the idea to use a non-invasive subacromial spacer for articular distraction and better visualization of the footprint. Few years later, a biodegradable subacromial balloon was developed to restore joint mechanics and provide pain relief in patients with

massive irreparable tears. This technique was associated with improvement in shoulder function and low rate of complications, and it may be an alternative to reverse arthroplasty for old patients with massive, painful, irreparable tears [151, 152].

Shoulder arthroplasty is considered the last option to treat irreparable rotator cuff tears.

Shoulder resurfacing and anatomical hemiarthroplasties were the first attempts to solve this problem and were used since the late 1970s [7, 126]; humeral head replacement with maintenance of the coracoacromial arch was the treatment of choice and could provide pain relief and modest gains in motion [51]. Large heads specifically designed for cuff tear arthropathy could slightly improve the results of anatomical hemiarthroplasty.

An important advancement in treatment of cuff tear arthropathy was represented by the development and introduction of the reverse total shoulder prosthesis in 1987 [74]. For its biomechanical characteristics, this implant can provide excellent results without the rotator cuff and is therefore now considered an attractive strategy to treat irreparable tears in old patients [22].

Results of rotator cuff repair

Many studies do not show any significant outcome difference between rotator cuff repair techniques.

Open rotator cuff repair has been shown to result in good to excellent outcomes in terms of functional improvement (75–95 % of patients) and pain relief (85–100 %) [2, 41, 60, 62, 79, 84, 88, 145].

Arthroscopic rotator cuff repair has also showed good results, not only after short time, but also at long-term follow-up. In fact, although high-level evidences are lacking, arthroscopic rotator cuff repair appears to be an effective and safe option to treat the symptoms of rotator cuff tears and to provide durable successful clinical results after more than 5 years [23, 48, 49, 76, 77, 94, 95, 110, 136, 139, 157, 158].

For what concerns the difference between open and arthroscopic repairs, Duquin published in 2010 a systematic literature review which analysed the structural healing of 1,252 repairs collected from 23 studies. No significant difference in re-tear rates between open transosseous and single-row arthroscopic repair methods or between arthroscopic and non-arthroscopic approaches for any repair method and any tear size were observed; the author therefore concluded that the surgical approach has no significant effect on re-tear rate. Pain relief, range of motion, return of strength or other functional criteria were not investigated [54].

The same study showed that re-tear rates were significantly lower for double-row repairs when compared to open transosseous or single-row arthroscopic repair. A possible explanation for this finding is the improved biomechanical performance of double-row repairs; alternatively, the fact that lesions amenable to a double-row technique are inherently more mobile and the fact that surgeons who perform a double-row repair need to perform more extensive releases to create sufficient mobility, may be two factors which diminish tension on the repair and therefore reduce re-tear risk [54].

Mini-open and arthroscopic procedures were compared by Morse, who published in 2008 a meta-analysis of clinical trials comparing the results of the two approaches for rotator cuff repairs. He reported no difference in functional outcome scores or complications between the arthroscopic and mini-open repair groups. The ability to perform transosseous fixation is considered a possible advantage of mini-open surgery, although the author points out that new suture-anchor designs have allowed obtaining stronger fixation than transosseous tunnels. Stiffness and higher infection rate are advocated as potential drawbacks for mini-open surgery [123].

Five years later, Shan analysed 12 comparative studies and confirmed that there were no differences in function outcome and re-tear rate between all-arthroscopic and mini-open repair groups. Pain scores and the incidence of adhesive capsulitis were also analysed, and no difference was reported [153].

Several other studies analysed the difference between single-row and double-row repair. Saridakis in 2010 reviewed six studies of level III or higher and showed no significant difference between the single-row and double-row groups within each study in terms of post-operative clinical outcomes. However, the authors noted that in one study, patients with large to massive tears who had double-row fixation performed better in terms of the American Shoulder and Elbow Surgeons and Constant scores. Moreover, there appeared to be a benefit in terms of structural healing when an arthroscopic rotator cuff repair was performed with double-row fixation, as opposed to single-row fixation [150].

Mascarenhas published in 2014 a systematic review of eight overlapping meta-analyses regarding single- and double-row techniques. This paper is the one with the highest level of evidence currently available. Six out of eight meta-analyses found no differences between single-row and double-row rotator cuff repair for patient outcomes, whereas two favoured double row for tears greater than 3 cm [111]. Three high-quality reviews with concurring results were selected by the authors to represent the current best available evidence [36, 120, 173]. These studies all concluded that rotator cuff repair performed with double-row technique provided statistically significant improvement in structural healing when compared to single-row repair,

although the differences in patient outcomes were not clinically significant.

For what concerns arthroscopic transosseous and surface-holding repairs, although encouraging results have been reported with different techniques [16, 37, 65, 66, 102, 112, 161], no randomized controlled trials have been published to date. Two biomechanical studies have suggested that arthroscopic transosseous rotator cuff repairs are similar in strength, stability and biomechanical properties to arthroscopic suture-bridge repairs [101, 162].

Scaffolds

Scaffold devices were first used in the late 1970s as experimental repair techniques; Julius S. Neviaser was the first to report the use of a freeze-dried graft from a cadaveric rotator cuff to augment a repair [128]. Ozaki et al. [131] reported the use of polyester as well as polytetrafluoroethylene (Teflon) grafts to repair massive rotator cuff tears in 1986, showing good tolerance and improved functionality in 23 out of 25 patients in a non-controlled case series.

In the clinical setting of a weak tendon-to-bone repair, first-generation scaffold augmentation off-loaded the repair and mitigated the poor construct properties but did not improve tissue healing [8]. Therefore, investments were made in order to develop new scaffolds, with improved mechanical and biological characteristics, which could promote rapid and effective biological healing while protecting the tendon from excessive mechanical load. Currently, three types of scaffold devices exist: extracellular matrix (ECM)-based structures, synthetic patches and hybrid scaffolds.

ECM-based scaffolds currently approved by the Food and Drug Administration are obtained either from human, porcine or bovine dermis, porcine small intestinal submucosa and equine pericardium [143]. The removal of donor cells from the ECM is critical for the acceptance by the host. This approach postulates that supporting the repair biologically would enable self-healing and implants are characterized by excellent cell biocompatibility in vitro. ECM-based scaffolds are proposed to target the intrinsic cell populations by providing a temporary, collagen-based matrix as a substrate [82, 169].

Numerous synthetic scaffolds have been manufactured, using different materials. Poly-L-lactic acid, poly(urethanurea) and polycarbonate poly(urethanurea) are those currently available on the market, and new materials are constantly being investigated [3]. The duration and importance of the host response to a synthetic scaffold is dictated by its biomaterial composition, morphology (size, shape, porosity and roughness) and biological and mechanical factors at the implantation site. Devices made from aliphatic polyesters (poly-L-lactide, polycaprolactone, polyhydroxybutyrate) typically degrade over a period of several months [118], while devices derived from non-biodegradable polymers such as polycarbonate polyurethane and Teflon are expected to persist for the life of the patient. Hybrid scaffolds are ECM-based devices reinforced with synthetic materials [143].

The last generation of synthetic, degradable and biomimetic scaffolds (not yet released for clinical use) is being developed to improve the host response to the implant: a new manufacturing technique called electrospinning allows to create devices, the structure of which mimics the orientation of collagen fibrils, and to incorporate in the scaffold structure biological components, such as stem cells, matrix proteins, growth factors, or to create mineral gradients. These scaffolds have exhibited excellent cellular response and biocompatibility in vitro and higher mechanical properties and lower immune response in animal models [82, 121, 148, 149].

Despite the growing clinical use of scaffold devices for rotator cuff repair, numerous questions remain to be clarified or addressed: clinical well-conducted human studies are lacking, and little data describing the complications or adverse events are available. Moreover, controversies remain about precise indication and technique, mechanism of action and efficacy of different devices [108, 143].

Biological enhancement of rotator cuff repair

Recently, a report by McElvany highlighted that, although the number of relevant articles published per year increased dramatically over time, the clinical and anatomical results did not show improvement. This study showed that the development and introduction of novel surgical techniques is not related to an improvement of results, and novel biological strategies to enhance rotator cuff healing should be investigated [115].

To enhance tendon tissue regeneration, new biological solutions including growth factors, platelet-rich plasma (PRP) and stem cells are being investigated.

The use of PRP as a biological solution to improve rotator cuff tendon healing has gained popularity over the last several years. PRP is a whole blood fraction containing high platelet concentrations that, once activated, provide a release of various growth factors which participate in tissue repair processes (Fig. 15) [61].

In vitro studies on the effect of PRP on human tenocytes from rotator cuff with degenerative lesions showed that growth factors released by platelets may enhance cell proliferation of tenocytes and promote the synthesis of extracellular matrix [87, 91].

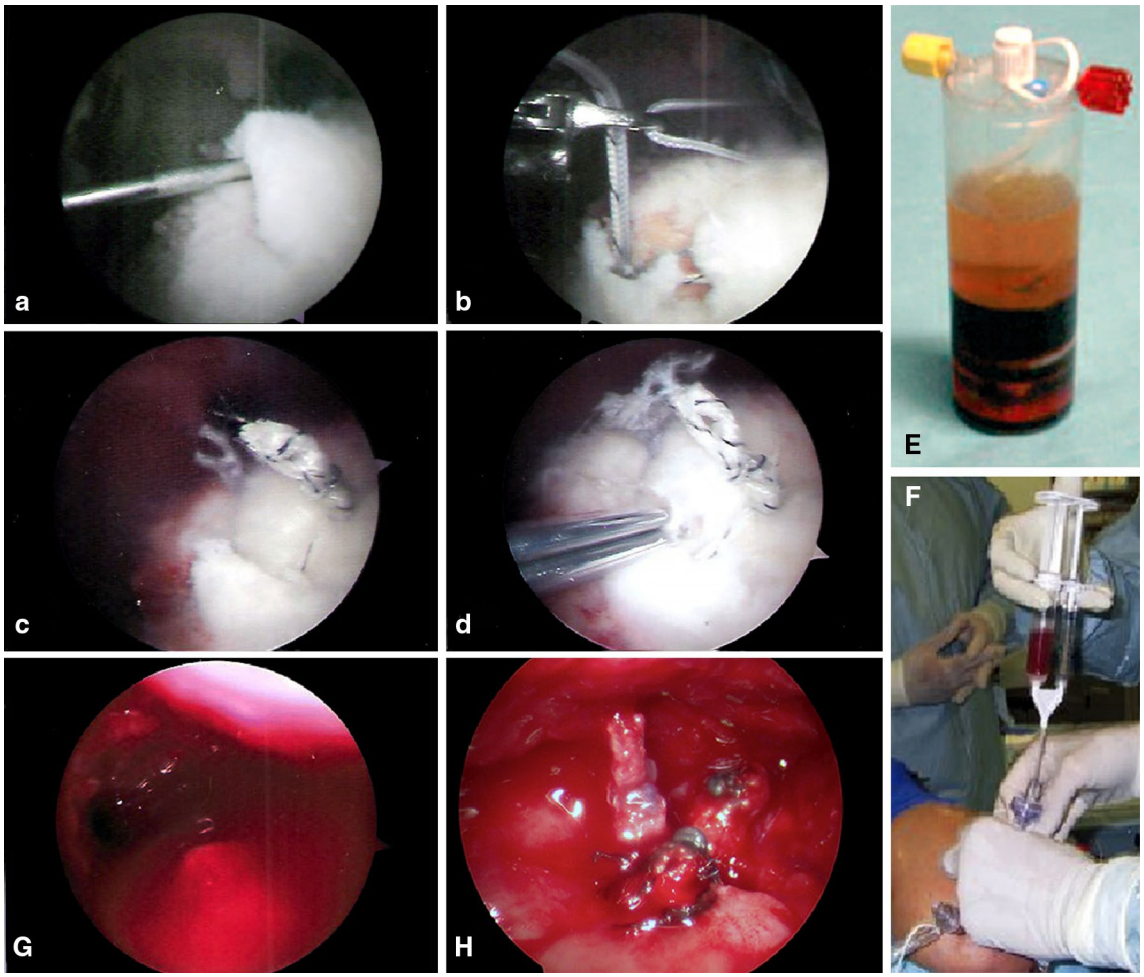

Fig. 15 Local application of PRP after rotator cuff repair. A supraspinatus lesion is identified (**a**) and tendon-to-bone repair is performed (**b**, **c**). Once the lesion is repaired, (**d**) PRP previously prepared with a commercial kit (GPS® II, Biomet Biologics, Warsaw, IN, USA) (**e**) is injected in a dry condition (**f**, **g**); at the end of the procedure, the repaired lesion is covered with PRP (**h**)

The first report of a clinical use of PRP in rotator cuff surgery was published by Pietro Randelli in 2008; his group proved PRP application to be a safe and effective technique, the results of which appeared to be stable with time [142]. In the next years, conflicting results on the effectiveness of PRP use in rotator cuff tendon repair were produced, making it now difficult to draw definitive conclusions.

The clinical studies published to date have different experimental designs with a level of evidence that varies from 1 to 4 [6, 14, 19, 33, 35, 78, 90, 92, 140, 144, 146, 174]. Moreover, there are differences in PRP formulations in terms of growth factor concentration and catabolic enzyme content [159]. Experimental protocols present differences among the trials concerning volume of autologous blood collected, speed and time of centrifugation, method of administration, activating agent, the presence of leucocytes, final volume of PRP and final concentration of platelets and growth factors. The surgical technique (transosseous equivalent, single- or double row) and the rehabilitation protocol (standard or accelerated) were not the same among different studies. Although a PRP classification system exists, which is based on whether white blood cells are present and whether PRP is used in an activated (ex vivo activation with thrombin and/or calcium) or un-activated form (in vivo activation via endogenous collagen), not all studies indicate it [52]. Moreover, PRP can be administrated either with a simple injection or in a fibrin-matrix clot.

A recent systematic review shows a significant difference when a stratified analysis is performed to analyse the results of small and medium lesions of the rotator cuff. The rate of re-injury was 7.9 % among patients treated with PRP, compared to 26.8 % of those treated without PRP [34].

Cell-based approaches have also been suggested to enhance tendon healing. Bone marrow is a well-known

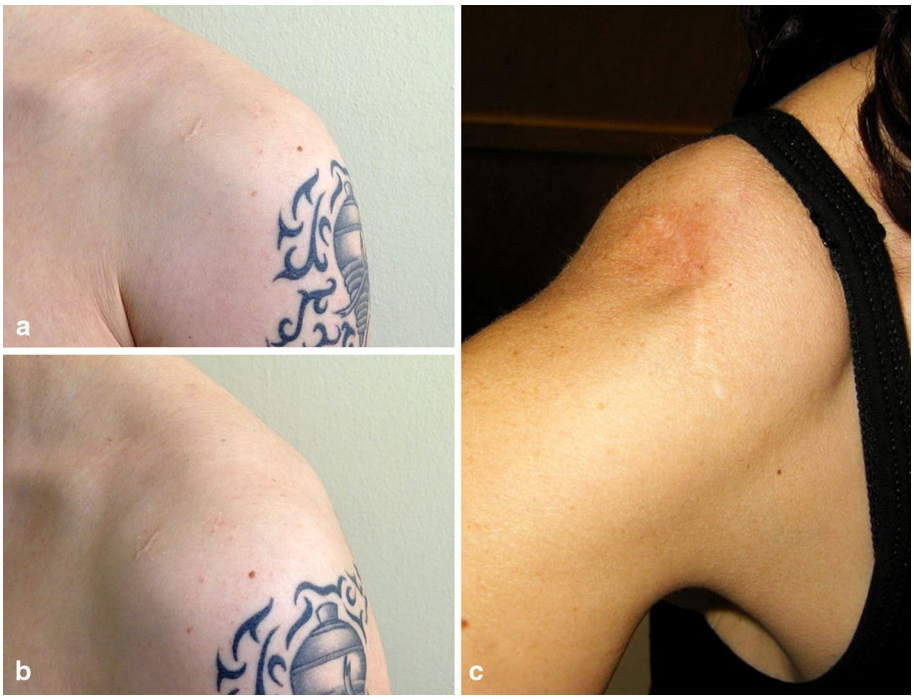

Fig. 16 Comparison of the scars after arthroscopic (**a**, **b**) and open (**c**) rotator cuff repair. Note the deltoid atrophy, a possible post-operative complication of open RCR (**c**)

source of mesenchymal stem cells (MSCs); recently, ex vivo human studies have isolated and cultured distinct populations of MSCs from rotator cuff tendons, long head of the biceps tendon, subacromial bursa and glenohumeral synovial [141, 167, 168]. Stem cells could represent a promising solution for rotator cuff tear repair due to a triple action mechanism: direct participation in repair response, stimulation of local cells via paracrine signalling and immunomodulatory activity [71, 113, 114].

A single clinical study has been conducted on stem cell-based therapies for rotator cuff healing, proving the injection of bone marrow mononuclear cells extracted from the iliac crest to be safe [55].

Clinical research regarding the use of MSCs in shoulder surgery is very limited. Further basic and clinical investigations are required to find a routine strategy for the use of stem cell-based therapies in shoulder surgery.

Discussion

Important advancements have been achieved in shoulder surgery during the last century. The transition from open to arthroscopic surgery has allowed us to perform rotator cuff repairs with smaller skin incisions, reduced inflammatory response and less post-operative morbidity and complications (Fig. 16) as well as to easy combine procedures extremely demanding with an open approach (Fig. 17). However, although technical advancement in surgical repair has been significant, there is little evidence that the results of rotator cuff repair are improving over time. An interesting meta-analysis by McElvany highlights that, although the number of relevant articles published per year increased dramatically over time, the clinical and anatomical results did not show improvement. Not only this report showed that there is little evidence that the results of rotator cuff repair improved, but it is also pointed out that patients with failed rotator cuff repairs can experience outcomes comparable with those after successful repairs [115].

Furthermore, patients with failed rotator cuff repairs can experience outcomes comparable with those after successful repairs, also at long-term follow-up [136, 157]. No important clinical differences were found also in a meta-analysis of 861 patients who underwent rotator cuff repair, regardless of the structural integrity of the repair, with the only significant exception of greater elevation strength in patient with intact repair [147].

Among arthroscopic surgeons, debate is constantly being conducted upon the best fixation strategy between single-row, various double-row constructs and, newly, arthroscopic transosseous fixation.

The currently available highest evidence shows superiority of double-row technique in terms of structural healing when compared to single-row repair, although the differences in patient outcomes are not clinically significant.

For researchers, the knowledge of history is a fundamental tool to identify pearls and pitfalls of previous techniques; this avoids repeating errors already made by our predecessors and permits to improve current techniques, not only creating new devices, but also using modern

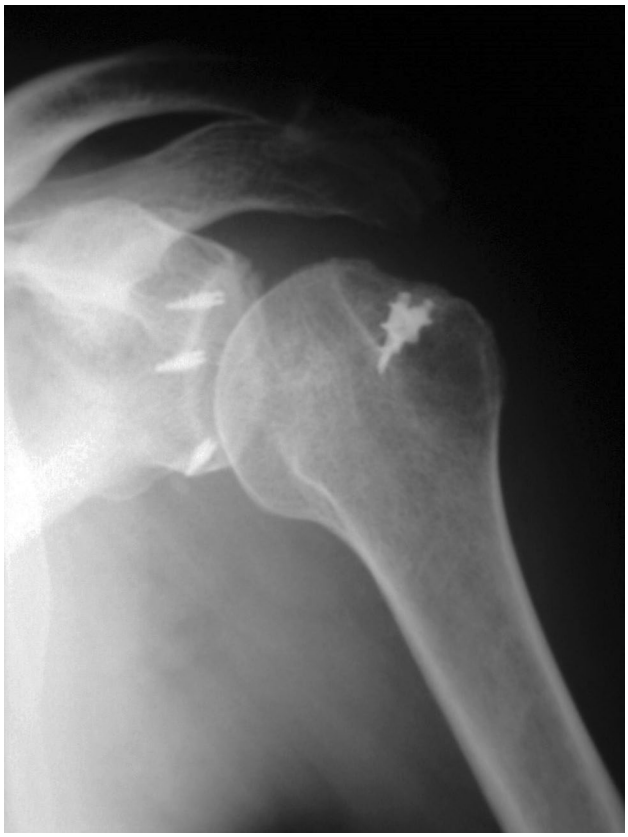

Fig. 17 Shoulder radiograph showing results of combined arthroscopic RCR with two suture anchors and Bankart lesion repair with three glenoid anchors

technologies to rediscover ancient, well-performing techniques, at that time dismissed because technically demanding. The development of arthroscopic transosseous fixation is an interesting example of this progression: the open transosseous repair, once considered the "gold standard", was substituted by anchor repairs, which were minimally invasive but could recreate anatomy in a less-precise fashion; hence suture-anchor technique evolved from single row to double row to transosseous equivalent in order to imitate the anatomical results of open transosseous repairs. No wonder then, that the possibility to return to the previously hailed transosseous technique with an arthroscopic approach is raising great expectations.

Regenerative approaches have been investigated to augment tendon healing after arthroscopic cuff repair. Growth factors have been extensively analysed in vitro, showing promising results and clinical trials using PRP have showed decreasing re-tear rate after small and medium rotator cuff tears repair. Cell-based approaches have also been suggested to enhance tendon healing; however, clinical research regarding the use of mesenchymal stem cells in shoulder surgery is very limited. Further basic and clinical investigations are required to define routine procedures for the use of these cells in shoulder surgery.

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