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Scaffolds in the management of massive rotator cuff tears: current concepts and literature review

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- Injuries to the rotator cuff (RC) are common and could alter shoulder kinematics leading to arthritis. Synthetic and biological scaffolds are increasingly being used to bridge gaps, augment RC repair and enhance healing potential. Our review evaluates the clinical applications, safety and outcome following the use of scaffolds in massive RC repair.
- A search was performed using EBSCO-Hosted Medline, CINAHL, Cochrane and PubMed using various combinations of the keywords 'rotator cuff', 'scaffold', 'biological scaffold', 'massive rotator cuff tear' 'superior capsular reconstruction' and 'synthetic scaffold' between 1966 and April 2018. The studies that were most relevant to the research question were selected. All articles relevant to the subject were retrieved, and their bibliographies hand searched.
- Synthetic, biosynthetic and biological scaffolds are increasingly being used for the repair/reconstruction of the rotator cuff. Allografts and synthetic grafts have revealed more promising biomechanical and early clinical results than xenografts. The retear rates and local inflammatory reactions were alarmingly high in earlier xenografts. However, this trend has reduced considerably with newer versions. Synthetic patches have shown lower retear rates and better functional outcome than xenografts and control groups.
- The use of scaffolds in the treatment of rotator cuff tear continues to progress. Analysis of the current literature supports the use of allografts and synthetic grafts in the repair of massive cuff tears in reducing the retear rate and to provide good functional outcome. Though earlier xenografts have been fraught with complications, results from newer ones are promising. Prospective randomized controlled trials from independent centres are needed before widespread use can be recommended.

Keywords: massive cuff tear; rotator cuff; scaffolds

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Introduction

The rotator cuff (RC) plays a significant role in shoulder biomechanics and is predisposed to injury and degenerative changes because of its location and blood supply.[1] The prevalence of RC tears is 34% in the general population and is more prevalent in the elderly population (54% in those > 60 years of age).[2,3] A study on the natural history of RC tears has shown that asymptomatic rotator cuff tears will become symptomatic and that the size of the tear will progress with time.[4] Massive RC tears could alter glenohumeral kinematics leading to humeral head migration, cuff tear arthropathy and pseudo paralysis of the shoulder.[4,5] Surgical management of massive cuff tear is challenging and the re-rupture rate has been reported in the literature as between 11%[6] and 94%.[7]

To reconstruct the RC and to optimize tendon healing, various scaffolds have been in use (Table 1). Though outcomes following the use of biological[8,9] and synthetic scaffolds[10,11] were encouraging in preclinical studies, the results were not replicated in human studies.[12–15] In spite of the growing clinical use of scaffold devices for tendon repair, there are numerous questions related to their design, indication for surgical applications, safety, mechanism of action, and outcomes that remain to be clarified or addressed. The aim of this review is to investigate the current state of knowledge in the field of biomaterials for augmentation and/or repair of the rotator cuff.

Materials and methods

A comprehensive search was performed using EBSCO Hosted Medline, CINAHL, Cochrane and PubMed between 1966 and April 2018, using various combinations of the keywords 'rotator cuff', 'scaffold', 'biological scaffold', 'massive rotator cuff tear', 'superior capsular reconstruction' and 'synthetic scaffold' over the years. The studies that were most relevant to the research question were selected. All articles relevant to the subject were retrieved, and their bibliographies hand searched for further

Table 1. Commercially available scaffolds for rotator cuff repair

Scaffold	Supplier	Composition
Synthetic		
X-Repair	Synthasome (San Diego, CA, USA)	Poly-L-lactic-acid
LARS Ligament	LARS (Arc-sur-Tille, Burgundy, France) Dacron Xiros (Leeds, UK)	Polyethylene Terephthalate
Poly-Tape	Neoligaments (Leeds, UK)	Polyethylene Terephthalate
Mersilene mesh	Ethicon, Inc. (Somerville, NJ)	Polyethylene Terephthalate
Integraft	Hexcel Medical (Dublin, CA)	Carbon fibre tow
Teflon	Dupont Company (Wilmington, DE)	Polytetrafluoroethylene
Marlex	C.R. Bard (Mullayhill, NJ)	High-density polyethylene
Repol Angimesh	ANGIOLOGICA BM Srl (Pavia, Italy)	Polypropylene
BioFiber	Tornier (Edina, MN)	Poly (4-hydroxybutyrate)
Biosynthetic		
BioFiber-CM	Tornier (Edina, MN)	Poly (4-hydroxybutyrate) + bovine collagen
Biological		
Restore	Depuy (Warsaw, IN)	Porcine small intestine submucosa
Zimmer Collagen Repair Patch	Zimmer (Warsaw, IN)	Porcine dermis
Conexa	Tornier (Edina, MN)	Porcine dermis
Biotape	Wright Medical Technology, Inc. (Arlington, IN)	Porcine dermis
Permacol	Medtronics (Mansfield MA)	Porcine dermis
OrthoADAPT	Pegasus Biologics, Inc. (Irvine, CA)	Native equine pericardium
BioBlanket	Kensey Nash Corporation (Exton, PA)	Bovine dermis
Tutopatch	Tuto-gen Medical GmbH (Neunkirchen am Brand, Germany)	Bovine pericardium
Tissue Mend	Stryker Orthopedics (Mahwah, NJ)	Foetal bovine dermis
GraftJacket	Wright Medical Technology (Arlington, TN)	Human dermis
Allopatch HD	MTF Sports Medicine (Edison, NJ)	Human dermis
Arthroflex	Arthrex (LifeNet Health, Virginia Beach, VA)	Human dermis

Table 2. Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Massive rotator cuff tear	Tendinopathy/other disorders with intact tendon or ligament
Synthetic and/or biological scaffolds	Expert opinion, letter to editors, case reports and literature review
Rotator cuff repair using scaffolds – augmentation and bridging	Experimental studies on animals
Clinical studies in human beings	Non-anatomical rotator cuff repair/reconstruction – superior capsular reconstruction, tendon transfers, balloon spacers etc.

references in the context of biomaterials for repair of the rotator cuff. The search was limited to articles in English (including the articles where an English translation was available), which had been peer reviewed. Grey literature was searched on the internet and the System for Information on Grey Literature in Europe (SIGLE). Strict inclusion and exclusion criteria were followed (Table 2) in including the study for review.

Results

In the literature search 8607 studies were identified related to rotator cuff injuries, of which 145 were related to the use of biological/synthetic scaffolds in the repair of torn rotator cuffs. Of the 145 studies, 30 were related to the use of biological scaffolds, one compared biological and synthetic, and the remainder were related to the use of synthetic scaffolds. After applying strict inclusion and exclusion criteria to the selected studies, 27 studies (18 biological; eight synthetic; one biological versus synthetic) were selected for the review (Fig. 1).

Biological scaffolds

Numerous studies have been published in the literature describing the role of biological scaffolds (Table 3) in the treatment of rotator cuff injuries in humans, the results are less promising than those of animal studies.

Xenografts

Porcine small intestine submucosa – Restore graft (Depuy, Warsaw, IN). This graft is a circular implant consisting of ten non-cross-linked layers of porcine small intestine submucosa (SIS), 0.8 mm to 1.0 mm thick and with a diameter of 63 mm.[16] It is more than 90% collagen with approximately 5% to 10% lipids and a small amount of carbohydrate. The layers are obtained from specific

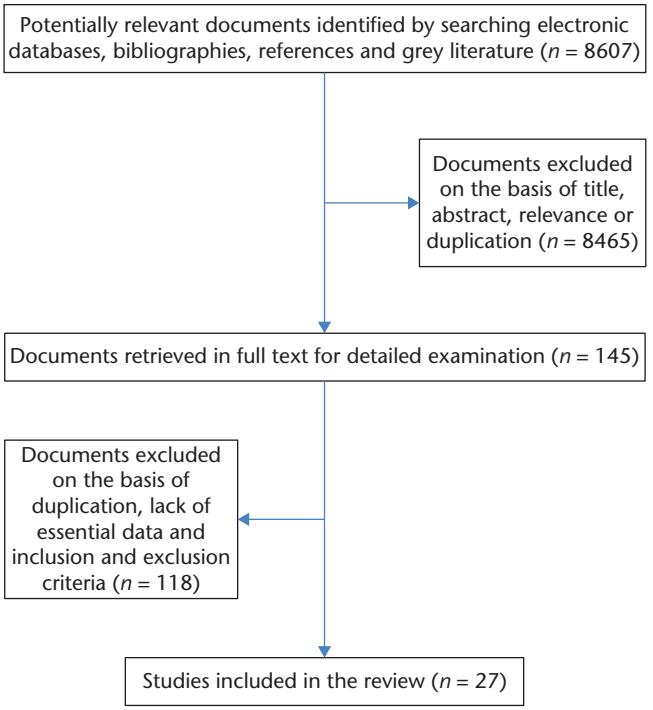

Fig. 1 Flow diagram

pathogen-free swine. The inner mucosa and muscular layers are manually removed. Individual sheets are then cleansed and disinfected with peracetic acid and ethanol, and do not contain viable cells. Ten individual layers are oriented at approximately 20° relative to each other and laminated together under a vacuum press to produce a 1-mm-thick isotropic graft with sufficient strength and mechanical properties. Electron beam sterilization is performed after packaging. Each lot is tested for bacterial endotoxins and mechanical strength. The implant is packaged dry and requires soaking for 5 min to 10 min before use.[16]

Metcalf et al[17] first reported the use of Restore SIS as an augmentation device in the repair of the rotator cuff. In their study, 12 patients underwent repair of their massive chronic rotator cuff tear using Restore graft. At a two-year follow-up using magnetic resonance imaging (MRI) scans, graft incorporation was found in 11 patients. In one of the 12 patients, mechanical failure was observed within 12 weeks with complete resorption of the graft. In their study there was no evidence of local or systemic rejection or infection in any patient. The mean postoperative University of California, Los Angeles (UCLA) score was 19.9 on a scale of 1–35; a significant improvement ($P < .01$) over the preoperative score (9.9). However, shoulder function remained below normal in these patients. This study established improved postoperative outcomes for patients managed with Restore graft augmentation compared with their preoperative condition. However, the lack of a control group in his study makes it difficult to conclude that the functional improvements in the study were the result of augmentation.

Sclamberg et al[15] evaluated 11 patients both clinically and with MRI at six to ten months after repair of large or massive rotator cuff tears augmented with Restore. MRI showed a retear in ten of the 11 patients. Though the pain improved in seven out of the 11 patients, there was no increase in the range of motion. The preoperative and postoperative shoulder scores were the same and the function did not improve after surgery.

The only prospective randomized controlled study that compared Restore graft augmentation and no augmentation was performed by Iannotti et al.[13] In this study they randomized 30 shoulders with chronic two-tendon rotator cuff tears (nine with large tears and 21 with massive tears of the rotator cuff) that were completely repairable with open surgery to be managed with either augmentation with porcine SIS or no augmentation. The rotator cuff healed in four of the 15 shoulders in the augmentation group compared with nine of the 15 in the control group ($P = 0.11$). The authors concluded that augmentation of the surgical repair of large and massive chronic rotator cuff tears with porcine SIS did not improve the rate of tendon healing or the clinical outcome scores. On the basis of their investigation, the authors do not recommend using porcine SIS to augment repairs of massive chronic rotator cuff tears performed with the surgical and postoperative procedures described in their study.

A study by Malcarney et al[12] on 25 patients using the Restore graft showed severe postoperative inflammatory reaction in four out of 25 patients. At a mean of 13 days all the four patients had open debridement and failure of repair is also noted. Though this study was designed as a prospective randomized controlled trial (RCT), it was aborted because of this complication. Walton et al[18] followed up ten tendons repaired with Restore and compared 12 tendons repaired without augmentation by the same surgeon. The groups were matched for gender, mean age, and mean size of the rotator cuff tear. MRI at two years showed retears in six of the ten tendons repaired with Restore and in seven of the 12 non-augmented tendons. Interestingly the patients with augmentation had less strength than the controls and had more impingement in external rotation, a slower rate of resolution of pain during activities, more difficulty with hand behind the back activities, and a lower rate of sports participation.

This material is now not used in Europe for rotator cuff repairs. In the USA, though the FDA has initially approved the material for clinical use, the use of this implant was stopped due to serious adverse effects[12,13,18] and is not recommended by American Academy of Orthopaedic Surgeons (AAOS).[19]

Table 3. Biological scaffolds used in rotator cuff repair

Study, year	Scaffold used	Technique*	Sample size/follow-up	Outcome	Adverse events
Xenografts					
Metcalf et al, 2002[17]	Restore	Open augmentation	12/24 months	UCLA score improved from 9.9 to 19.9 (P < .01) MRI scan at 2 years – 11 incorporation with thick tendon, one complete resorption of graft	No complications
Sclamberg et al, 2004[15]	Restore	Open bridging and augmentation	11/6–10 months	ASES score improved from 60.3 to 58.4 (P = –0.7) MRI scan – retears in 10/11 patients	No complications
Iannotti et al, 2006[13]	Restore	Open augmentation	Augmented (A) 15, Non-augmented (NA) 15/12–26 months	PENN score 83 points in augmented and 91 in non-augmented group (P = –0.07) MRA four out of 15 healed in augmented group; nine out of 15 healed in NA group	Three patients in augmentation group developed erythema, swelling and discharge
Malcarney et al, 2005[12]	Restore	Open bridging and augmentation	25	RCT aborted because of serious postoperative complications	Four patients developed overt inflammatory reaction in a mean of 13 days postoperatively.
Walton et al, 2007[18]	Restore	Open bridging and augmentation	A 15, NA 16/25 months	Mean activity pain score 9.9 augmented vs. 4 control (P < 0.01). Augmented group had less strength in internal rotation (P < 0.01), less supraspinatus strength (P < 0.1) and exhibited more impingement symptoms in external rotation (P < 0.05) MRI – 6 out of 10 in augmented and 7 out of 12 in control group had retorn the tendons.	Four patients with severe inflammatory reaction that required reoperation and removal of xenograft in the early postoperative period
Phipatanakul and Petersen, 2009[14]	Restore	Open bridging and augmentation	11/26 months	Mean UCLA and ASES scores improved from 13.9 and 36.3 to 25.7 and 71.8 postoperatively (P < .01) MRA (8)/ surgery (1) – 6 failed to repair	One infection and two local skin reactions
Soler et al, 2007[21]	Zimmer Collagen Repair Patch	Mini-open bridging	4/3–6 months	Early failure in all four cases MRI – all four failed with extensive inflammatory reaction	Florid inflammatory reaction and two cases ended up with reverse total shoulder replacement
Badhe et al, 2008[22]	Zimmer Collagen Repair Patch	Mini-open bridging	10/12 months	Constant–Murley score improved from 41 to 62 (P = .0003), pain, abduction power and range of movement improved postoperatively (P < .05) USS and MRI – two failures out of ten	No complications
Gupta et al, 2013[24]	Conexa	Mini-open bridging	26/24–40 months	Mean ASES improved from 62.7 to 91.8 (P = .0007) and SF-12 scores improved from 48.4 to 56.6 (P = .044) USS – 16 intact, five partially intact, one complete tear	No complications
Neumann et al, 2017[23]	Conexa	Mini-open bridging	61/24–63 months	Pain score decreased from 4.0 to 1.0 (P = .001), Forward flexion, external/internal rotation and strength of supra and infraspinatus significantly increased postoperatively (P < .001) USS – 56 intact, two partially intact and three completely torn	No complications
Allograft					
Burkhead et al, 2007[27]	GraftJacket	Open augmented	17/14 months	UCLA scores improved from 9.06 to 26.12 (P < .001), MRI (11)/CT arthrogram (1) – three failures to repair	No complications
Bond et al, 2008[28]	GraftJacket	Arthroscopic bridging	16/12–18 months	UCLA score increased from 18.4 to 30.4 (P = .0001), Constant–Murley score increased from 53.8 to 84.0 (P = .0001). MRI scans 13 patients had full incorporation of graft	No complications
Wong et al, 2010[29]	GraftJacket	Arthroscopic bridging	45/24–68 months	UCLA score increased from 18.4 to 27.5 (P < .001); final follow-up ASES score was 84.1. No radiological evaluation	Deep wound infection in an immunocompromized patient
Barber et al, 2012[30]	GraftJacket	Arthroscopic augmentation	A 22, NA 20/12–38 months	ASES (P = .035), Constant–Murley score (P = .008), UCLA score (P = .43) significantly better in augmented group MRI – intact cuff in 17 out of 20 in augmented group and six out of 15 in non-augmented group	Augmented – one bursitis; NA – cellulitis (2); bursitis (1); post-traumatic fibrosis (1); Biceps tendon rupture (1)

(continued)

Table 3. (Continued)

Study, year	Scaffold used	Technique*	Sample size/follow-up	Outcome	Adverse events
Gupta et al, 2012[31]	GraftJacket	Mini-open bridging	24/29–40 months	Mean ASES improved from 66.6 to 88.7 (P = .0003) and SF-12 scores improved from 48.8 to 56.8 (P = .03) USS (19) – 14 fully intact, 5 partially intact	No complications
Pandey et al, 2017[32]	GraftJacket	Mini-open bridging vs. partial repair	13 each arm/2 years	Constant–Murley score increased from 41.2 to 83.9 in allograft group vs. 43.1 to 70.8 in partial repair group, OSS increased from 14.9 to 43.9 in allograft group vs. 17.8 to 37.1 in partial repair group. The allograft group showed greater significant improvement than the partial repair group (P < .01) USS – retear four patients	No complications
Sharma et al, 2018[33]	GraftJacket	Mini-open bridging	22 (two single layers of Graft Jacket)/ 18–24 months	OSS improved from 22 to 45.5 (P = 0.00148), 95% patients would recommend the surgery to their family or friends No radiological assessment	One frozen shoulder and another patient with persistent pain ended up with two arthroscopies and finally a reverse total shoulder replacement
Agrawal, 2012[34]	Allopatch HD	Arthroscopic augmentation	14/12–24 months	Constant–Murley score increased from 49.72 to 81.07 (P = .009). Pain score improved from 13.57 to 7.73 (P = .008). Flexilevel Scale of shoulder function improved from 53.69 to 79.71 MRI – 12 structurally intact, two partial tears	No complications

Note. UCLA, University of California, Los Angeles Score; ASES, American Shoulder and Elbow Surgeon; MRA, ; OSS, Oxford Shoulder Score; PENN, ; RCT, randomized controlled trial; MRI, magnetic resonance imaging; USS, ; CT, computed tomography.
*Arthroscopic vs. open; augmentation vs. bridging gap.

Acellular porcine dermis marketed as Permacol (Tissue Science Laboratories, Covington, GA, USA), Zimmer Collagen Repair Patch (Zimmer, Warsaw, IN, USA), and Conexa (Tornier, Inc.,. Edina, MN, USA). Acellular porcine dermis is a cross-linked collagen sheet of 1.5 mm thickness.[20] The graft is processed in various stages to make it acellular, and the graft is cross-linked with hexamethylene diisocyanate. The patch is hydrated and could be stored at room temperature.

Soler et al[21] used the Zimmer Collagen Repair Patch as a bridging device to repair massive rotator cuff tears in four older patients (aged 71 years to 82 years). At between three and six months postoperatively, the graft began to fail and the patients showed signs and symptoms of re-rupture, with signs of inflammation. MRI scans showed inflammatory changes, resorption of the graft, fluid pooling in the sub-deltoid bursa and loss of continuity of the remaining graft material. Histology of the tissues retrieved revealed necrotic fibrinous material on a background of chronic inflammation.

Badhe et al[22] prospectively evaluated ten patients with extensive rotator cuff tears treated with the Zimmer Collagen Repair Patch. All patients experienced significant pain relief, and improvement in abduction power and range of motion. Nine out of ten patients were happy with the outcome after surgery. Ultrasound imaging at the final follow-up identified intact grafts in eight and disrupted grafts in two patients. A recent study by Neumann et al[23] utilizing Conexa showed promising results at a mean follow-up of 50.3 months (range, 24 months to 63 months). Ultrasound evaluation demonstrated intact repair in 91.8% (56 of 61) of the patients. In addition, the patients had significant improvement in their pain score from 4 to 1 (P < .001), range of motion – forward flexion from 140.7° to 160.4° (P < .001), external rotation at 0° of abduction from 55.6° to 70.1° (P = .001), and internal rotation at 90° of abduction from 52.0° to 76.2° (P < .001) – supraspinatus strength increased from 7.7 to 8.8 (P < .001) and infraspinatus strength increased from 7.7 to 9.3 (P < .001) and the average Modified American Shoulder and Elbow Surgeons Score postoperatively was 87.8. In both the studies the authors suggested the possibility of cellular contaminants in the earlier xenografts causing tissue reactions. Similar results with good functional outcome were reported by Gupta et al[24] and Giannotti et al.[25]

Allografts

GraftJacket (Wright Medical Technology, Inc., Arlington, Tennessee) is a commercially available acellular dermal matrix obtained from tissue-bank human skin.[26] The skin is processed with a patented technique that removes epidermal and dermal cells, and it is then freeze dried to avoid the formation of ice crystals and to retain the native extracellular architecture and vascular channels. As it is rendered acellular during processing, it lacks many of the disadvantages typical of standard allograft tissue. The resulting patch is an acellular tissue, made of collagen types I, III, IV, VII, elastin, chondroitin sulphate, proteoglycans, and fibroblast growth factor. This graft has an intact basement membrane complex and preserved vascular

channels to allow rapid infiltration of fibroblasts and vascular tissue, with minimal host inflammatory response.[16] It is recommended for tendon repairs, ligament augmentation, capsular reinforcement and periosteal covering. It is commercially available in several forms. With an average thickness of 1.0 mm, it is available in 5 cm by 5 cm and 5 cm by 10 cm sheets. With an average thickness of 1.5 mm, it is available in 4 cm by 7 cm or 5 cm by 5 cm sizes. With an average thickness of 2.0 mm, it is available in a 4 cm by 7 cm size. It is packaged dry. Before use, the GraftJacket needs to be hydrated for at least 10 min to 15 min.[16]

Burkhead et al[27] used GraftJacket allografts for the augmentation of massive rotator cuff tears in 17 patients. At a mean follow-up of 24 months three out of 17 failed; however, the tear sizes were smaller than in the preoperative MRIs. UCLA scores improved from 9.06 to 26.12 ($P < .01$). There were no adverse events and the range of movements improved postoperatively.

Bond et al[28] treated 16 patients with massive, contracted, immobile rotator cuff tears with arthroscopic implantation of a GraftJacket allograft. At mean follow-up of 26.7 months, 15 of 16 patients were satisfied with the procedure. The mean UCLA score increased from 18.4 preoperatively to 30.4 postoperatively. The mean pain score improved from 4.6 to 9.8 postoperatively. The mean Constant–Murley score increased from 53.8 to 84.0 ($P = .0001$); improvements were noted in pain, forward flexion and external rotation strength. MRI scans showed full incorporation of the graft into the native tissue in 13 patients. There were no complications related to the use of the grafts. The study by Bond et al[28] was updated by Wong et al[29] in 2010. Forty-five patients who had GraftJacket allografts were followed up for 24 months to 68 months and the preoperative UCLA scores improved from 18.4 to 27.5 ($P < .0001$). Except for a deep wound infection in an immunocompromised patient, no other major complications were reported.

A prospective randomized controlled trial by Barber et al, compared the use of GraftJacket for augmentation (Group 1) of chronic two-tendon tears versus no augmentation (Group 2).[30] There were 22 patients in Group 1 and 20 in Group 2, with a mean age of 56 years. At a mean follow-up of 24 months (range, 12 to 38 months) the ASES (American Shoulder and Elbow Surgeons) score improved from 48.5 to 98.9 in Group 1 and from 46.0 to 94.8 in Group 2. The scores in Group 1 were statistically better than those in group 2 ($P = .035$). The Constant–Murley score improved from 41.0 to 91.9 in Group 1 and from 45.8 to 85.3 in Group 2. The scores in Group 1 were statistically better than those in Group 2 ($P = .008$). The UCLA score improved from 13.3 to 28.2 in Group 1 and from 15.9 to 28.3 in Group 2 ($P = .43$). The repairs were found intact in 85% of the augmented group in comparison to the 40% of the non-augmented group by gadolinium-enhanced magnetic resonance arthrogram at one or two years of follow-up ($P < .01$). No adverse events related to the GraftJacket were observed. The results show significantly better functional outcome and a significantly better healing rate in patients with augments compared with non-augmented rotator cuff repairs. These studies support further investigation of non-cross-linked dermis scaffolds for the treatment of rotator cuff tears. Similar results with no major complications were replicated in a study by Gupta et al.[31] In their study at an average follow-up of three years, the mean pain level reduced from 5.4 to 0.9 ($P = .0002$), mean ASES and SF-12 scores improved from 66.6 to 88.7 ($P = .0003$) and 48.8 to 56.8 ($P = .03$) respectively. Besides this, ultrasound scans revealed fully intact rotator cuffs in 76% of the patients. Pandey et al compared the outcome between 13 patients who had partial cuff repair and 13 patients with partial repair and gap bridged with a GraftJacket.[32] At a minimum follow-up of two years, Constant–Murley score increased from preoperative scores by 27.7 points in the partial repair group and 42.8 points in the GraftJacket group ($P<0.01$). The Oxford Shoulder Score (OSS) also improved by 19.3 points in the partial repair group and 29 points in the GraftJacket group ($P<0.02$). Ultrasound scan (USS) evaluation at two years showed a 30% (four patients) retear rate. Sharma et al utilized GraftJacket to bridge the gap in massive cuff tear repairs in 20 patients.[33] At a follow-up of 18 months to 24 months, the OSS improved from 22.0 to 45.5 ($P = 0.00148$). The authors did not evaluate the integrity of repair radiologically.

Tissuemend HD (human dermis) was used in 14 patients with recurrent massive cuff tears.[34] Follow-up evaluation with MRI between one and two years demonstrated complete healing in 85.7% of the patients. All the patients in this study had significant improvement in Constant–Murley scores from 49.72 (range 13–74) to 81.07 (range 45–92) postoperatively ($P = 0.009$), the Flexilevel Scale of Shoulder Function improved from a preoperative mean of 53.69 to a postoperative mean of 79.71 ($P = 0.003$), scapular plane abduction improved from a preoperative mean of 113.64° to 166.43° postoperatively ($P = 0.010$), pain score improved from a preoperative mean of 7.73 to 13.57 postoperatively ($P = 0.008$) and strength improved from a mean of 1.73 kg preoperatively to a mean of 7.52 kg postoperatively ($P = 0.006$).

Synthetic scaffolds

Encalada-Diaz et al[35] evaluated the Biomerix RCR Patch made of polycarbonate polyurethane, as an augmentation device in open repair of full thickness rotator cuff tears. Ten patients with a mean tear size of 20 mm (supraspinatus or infraspinatus tendon) had the surgery. At the one-year follow-up, significant improvement in

outcome scores was reported, with ultrasound and magnetic resonance imaging demonstrating a 10% failure rate. Again, as with other studies, the lack of a control group for comparison makes it difficult to determine the precise benefit of the graft, particularly in limiting repair failures. The authors also acknowledge that the mean tear size in the series represents a small- to medium-sized tear, which may not necessitate repair augmentation as commonly as a large or massive tear.

The other synthetic material utilized for rotator cuff repair is Gore-Tex patch WL (Gore-Tex Soft-Tissue Patch (Gore-Tex, W. L. Gore & Assoc. Inc., Flagstaff, Arizona). It is composed of the inert biomaterial polytetrafluoroethylene.[36] It features a microporous structure allowing for host tissue incorporation. It is elastic and resembles a dense sponge rubber. Hirooka et al[37] in a retrospective clinical study evaluated the functional outcome after using Gore-Tex patches in 28 patients with rotator cuff tears. In a mean follow-up of 72 months good improvements in pain relief, range of motion and muscle strength were noted. However, three of the 28 patients needed revision surgeries for recurrent tear. Audenaert et al[38] used Mersilene mesh (polyethylene terephthalate), in 41 patients, the preoperative Constant–Murley score improved significantly from an average of 25.7 to 72.1 ($P < 0.001$). In addition, 74% of the patients had good pain relief and 77% could carry out overhead activities.

Ozaki et al[39] presented the first series of massive cuff lesions treated with polyester grafts (Marlex (CR Bard, Cranston, Rhode Island) and Teflon (CR Bard, Haverhill, Massachusetts; WL Gore, Flagstaff, Arizona)) in 1986. Although the authors concluded that satisfying results were obtained, no standardized scoring system was utilized to evaluate the patients. Two other studies utilized carbon fibre for reconstruction of the cuff.[40,41] This use was discontinued due to potential problems with fragmentation and reactive synovitis.

A recent study by Nada et al[42] showed promising results at a follow-up of 36 months following RC repair using LARS Ligament. All their patients had significant improvement in pain, function and range of motion ($P < 0.001$). MRI scans at final follow-up confirmed intact tendon/bands in 15 out of 17 patients. Ciampi et al[43] compared the functional outcome and structural integrity after cuff repair in 152 patients with posterosuperior massive rotator cuff tears (control group = 51; Tutopatch = 49; polypropylene patch augmentation = 52). Ultrasound assessment at one year showed a retear rate of 41% in the control group, 51% in the Tutopatch group, and 17% in the polypropylene patch augmentation group. At three-year follow-up the polypropylene group had significant better functional outcomes than the control and Tutopatch groups.

Ranebo et al assessed 12 patients at a mean follow-up of 18 years following rotator cuff interposition repair with Dacron (DuPont, Wilmington, DE, USA).[44] The mean Constant–Murley score at a minimum follow-up of 17 years was 46 ($SD = 25$) and the mean Western Ontario Rotator Cuff index score was 59 ($SD = 20$). Nine out of 12 patients developed cuff tear arthropathy and three needed arthroplasty.

Discussion

Rotator cuff repair using scaffolds is gradually gaining momentum and its application is expanding.[19,45] The proposed advantages of scaffolds are to improve the biology of repair by providing a scaffold for host tissues to infiltrate and remodel, as well as to reduce the mechanical forces that act at the repair site, to help with tissue healing and to prevent recurrent tears.[19,45]

Animal studies using Restore, Zimmer Collagen Repair and GraftJacket have shown positive outcomes with good host tissue integration, remodelling and improvement in biomechanical properties.[46–48] Besides, these studies did not show any tissue rejection or adverse host tissue response. Though similar results were found for synthetic scaffolds, these were not replicated in clinical studies.[19] The disadvantage with animal models are that the injuries are acute, unlike in humans where the cuff tears are chronic and postoperative restrictions and therapy are not possible in the animal model.[11]

Porcine small intestine submucosa was the earliest biological scaffold that was used in rotator cuff repair. Promising results from animal studies were not replicated in humans, with some studies exposing the increased rerupture after repair and tissue oedema due to host tissue response.[13,15,18] Polymerase Chain Reaction (PCR) analysis of the Restore graft demonstrated residual porcine DNA, and implantation in mice and rabbits confirmed host tissue response in the form of inflammatory changes and lymphocyte infiltration.[49] This is in contrast to earlier studies where the Restore graft was considered as a scaffold devoid of cells.[17] The earlier studies advised against using Restore for rotator cuff repair due to poor functional outcomes and serious complications.[12,13,18]

Zimmer Collagen Repair Patch (porcine dermis) has mixed results, with a study reporting serious complications.[20] All four patients in this study experienced failure of graft and significant host tissue response. A similar report finding was reported following the use of Zimmer Collagen Repair Patch after trapeziectomy.[50] Recent studies did show promising results, probably following improvement in the graft properties by making it DNA free.[21,24] Currently there are no randomized controlled trials to evaluate the safety of this scaffold and further clinical trials are needed before its widespread use.[20,21,50]

However, with the newer porcine dermal xenografts (Conexa), the results are promising; with newer technologies the matrix is made acellular without porcine DNA. In

these studies the results are comparable to human acellular dermal matrix.[23,24] In the current literature there were no clinical studies evaluating functional outcome of Tissue Mend (foetal bovine dermis) or OrthADAPT (equine pericardium).

Studies have consistently shown promising results for the use of GraftJacket for rotator cuff repair.[28–34] Unlike other biological scaffolds, no serious host tissue response has been reported. Besides, GraftJacket has better mechanical properties that other biological scaffolds.[51]

The ultimate strain of a normal rotator cuff is 1978 +/- 301 N[52] and the same in available scaffolds are GraftJacket (229 N), Zimmer Patch (128 N), Tissue Mend (76 N), and Restore (38 N).[51] Though the synthetic scaffolds have a higher mean load to failure (Leeds-Keio Ligament, 780 +/- 200 N and LARS Ligament, 998 +/- 148 N), they are still below the ultimate strain of rotator cuff.[45] The retear rate is proportional to the mechanical strength of the graft. A recent review has shown an overall retear rate of 25% with scaffolds, with xenograft having the highest rate of retear at 44%, followed by allograft (23%) and synthetic graft (15%).[53] The results are similar to our review and the retear rates appear far lower than those of conventional repair methods for massive cuff tears.[6,7]

The role of scaffolds is to improve the biological and mechanical properties of repair and to degrade and be replaced by host tissue. Valentin et al[54] have shown that in animals, the Restore patch was completely degraded in around 112 days and the remaining biological scaffolds either partially degrade (GraftJacket, Cuff Patch and Tissue Mend) or do not degrade at all (Zimmer Patch). This is worse with synthetic scaffolds. Studies have shown the presence of scaffolds in knee joints after 15 years and also poor host tissue integration.[55,56] The only exceptions among synthetic scaffolds are made from aliphatic polyesters which do degrade, the remaining do not, irrespective of the time of implantation.[20,45,57] There is a significant gap in the literature about the sequence of events after implantation of scaffolds in the shoulder. Further research is needed to assess healing, scaffold degradation and host tissue response.[58] This will impact on postoperative rehabilitation and will help optimize tissue healing.

Smith et al[59] assessed the mechanical properties of seven commercially available scaffolds for rotator cuff repair and compared those with the supraspinatus tendon. All of them were subjected to scanning electron microscopy, tensile testing, rheometer testing and scanning probe microscopy. The testing showed that none of the available scaffolds have micro or macro mechanical properties similar to the supraspinatus tendon.

Scaffolds do improve the strength of the repair and reduce the retear rate in patients with massive rotator cuff tears.[6,7,53] Though the retear rate is better than for conventional repair, it is still high. Further studies to assess the bone and scaffold junction healing and the role of its use in young active patients are desirable.

Conclusion

Several biological and synthetic scaffolds are available on the market for the repair of massive rotator cuff injuries and their use continues to expand. Rotator cuff reconstruction with human dermal allograft is associated with good functional and structural outcomes. Xenografts have higher retear rates and have shown less improvement in patient-reported outcomes, strength and range of motion than synthetic grafts and allografts. Though the earlier versions of xenografts were associated with severe inflammatory reactions, the recent ones appear safer and have demonstrated radiological and functional outcomes similar to allografts. The synthetic grafts have the lowest retear rates and did not exhibit any tissue reactions or osteolysis. Prospective, randomized controlled trials by independent units comparing the various scaffolds are needed to establish clear recommendations. The incorporation of techniques of tissue engineering, gene therapy and nanotechnology could improve the mechanical properties and biocompatibility of the scaffolds.

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