18 Distal Radioulnar Joint: Resection Arthroplasty or Prosthetic Arthroplasty

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18.1 Introduction

Arthritis of the distal radioulnar joint (DRUJ), whether it be primary osteoarthritis, post-traumatic or inflammatory, is a difficult condition to adequately manage. This is due to the complexity of the anatomy and biomechanics of the joint and our inability as surgeons to truly replicate those factors in any operation. It is also not a very common pathology to encounter in the clinical setting, and therefore, studies comparing surgical options are relatively few with small numbers.

Resection of the DRUJ was performed as early as 1855 [1]. It provided good pain relief and was the mainstay of management for many years. Over time, it was acknowledged that the rate of longer-term pain, limitation of movement and potential for distal radioulnar convergence was relatively high. This sparked the development of prostheses for the DRUJ in order to enhance stability and function while reducing pain. Prostheses have also evolved from interposition implants to replacement of the ulnar head to total DRUJ replacement. Early results of arthroplasty are somewhat encouraging but studies are lacking in sample size and longevity. Therefore, the management of DRUJ pathology remains controversial.

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18.2 Distal Radioulnar Joint (DRUJ) Anatomy

The DRUJ is composed of the bony articulation between the styloid notch of the distal radius and the ulnar head. There is a significant mismatch in the radius of curvature of these two bony components with the styloid notch having a much greater radius of curvature than that of the ulnar head [2]. There can also be variability in both the sagittal and coronal plane alignment of the joint. In the axial plane, a "flat face" sigmoid notch is present in about 42% of patients and predisposes to instability [3]. With regard to the sagittal plane, differences in the slope of the articular surface of the sigmoid notch in comparison to the long axis of the ulna do not have a direct impact on DRUJ function but are one of the challenges that need to be addressed when considering the use of a prosthesis [3, 4]. Regardless of the morphology of the sigmoid notch or distal ulnar/radial articulation, the bony structures provide little mechanical stability.

Most of the stability of the DRUJ is attributable to the surrounding soft tissue structures, including the triangular fibrocartilage complex (TFCC) [5]. The TFCC is comprised of the dorsal and volar radioulnar ligaments, ulnocarpal ligaments, meniscus homologue, articular disc and tendon sheath of the extensor carpi ulnaris (ECU). The TFCC originates on the distal radius at the styloid notch and inserts at the base of the

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ulnar styloid both dorsally and volarly [6]. Anatomical studies have shown a role not only of the TFCC, but also of the interosseous membrane and pronator quadratus muscle in providing stability to the joint [7, 8]. Interestingly, sectioning of any one of these components in isolation does not result in DRUJ instability, suggesting that there is very much a shared role of all of the soft tissue elements in maintaining stability [7–9]. Therefore, it is important in performing any surgical intervention to the DRUJ; that respect is given to, not only addressing the articular surfaces, but also preserving the soft tissue structures if possible.

18.3 DRUJ Biomechanics

The DRUJ is important in both weight-bearing and forearm rotation. Forearm rotation occurs through an axis of rotation from the centre of the radial head proximally to the centre of the distal ulnar fovea distally. The ulna is constrained proximally in the ulnohumeral joint; therefore, the forearm rotation occurs by rotation of the mobile radius around the fixed ulna [10]. Mismatch between the larger axis of rotation of the shallow sigmoid notch of the radius and the smaller ulnar head results in movement at the DRUJ occurring due to a combination of rotation and sliding. The ulna moves from the dorsal position in pronation to the volar position in supination as well as moving longitudinally relative to the radius.

The distal radius usually takes 80% of the load on axial weight-bearing with the distal ulna taking 20% when the forearm is in neutral position [11, 12]. The percentage of weight-bearing through the ulna varies depending on the position of the forearm (20% axial load through the ulna in neutral position but up to 50% in pronation and ulnar supination) [11, 12]. Load transmission through the ulna also varies depending on the ulnar length [13]. Shortening the ulna by 2.5 mm reduces its axial load to 4%, while lengthening by 2.5 mm increases it to 42% [12]. While ulnar shortening can increase peak pressure within the DRUJ, it may also aid in stability of the DRUJ by increasing TFCC tension [14, 15].

18.4 Management of Distal Radioulnar Joint Arthritis

The DRUJ can be affected by post-traumatic osteoarthritis (OA), primary OA or inflammatory arthropathies. Abnormalities of the joint surfaces can result in painful forearm rotation, limitation in range of movement, tenderness over DRUJ and instability. Given the complexity of the anatomy required to maintain the normal biomechanics of the DRUJ, surgical management is challenging.

As with any other pathology of any other joint in the body, the first step in management should be non-operative. In the case of DRUJ arthritis, conservative management includes activity modification, gentle physiotherapy, splinting, steroid injections and analgesia. When these measures fail, operative intervention is broadly divided into resection arthroplasty or prostheses. There are benefits and complications of each surgical option. The definitive treatment approach should be determined on a patient-to-patient basis by a highly skilled upper limb surgeon.

18.4.1 Resection Arthroplasty

Resection arthroplasty for the DRUJ was first performed in 1855 [1]. Overall, proponents would argue that patient satisfaction rates are relatively high. There are multiple long-term studies [16–18].

Pitfalls of resection procedures are persistent pain, instability of ulnar stump and radioulnar impingement. Opponents to the resection arthroplasty would suggest that these procedures do not reconstruct the complex anatomy of DRUJ.

These complications are relatively high but conversion to ulnar implant is an option.

18.4.1.1 Darrach Procedure

Description and History

Excision of the distal end of the ulna was first described as a technique for open DRUJ dislocation in the 1800s [1, 19]. It was later utilised as a method for addressing distal radial malunions [20–22]. Finally, it was popularised by Darrach

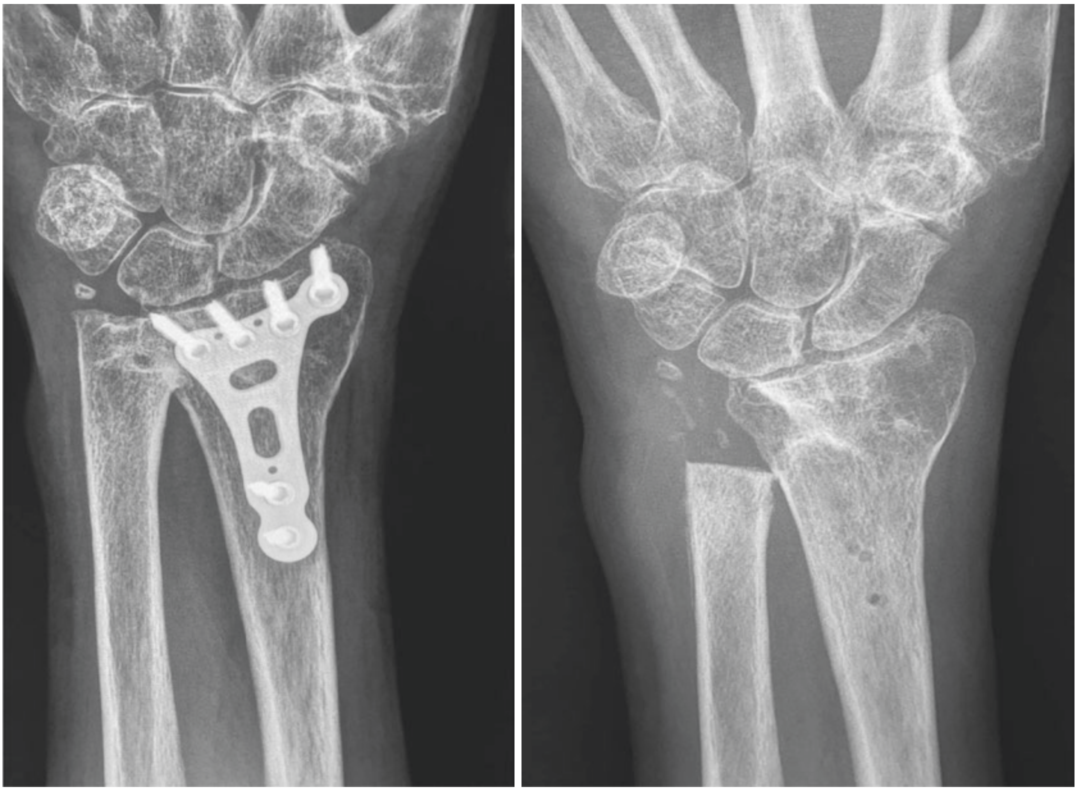

Fig. 18.1 Preoperative (left) and postoperative (right) imaging of Darrach resection arthroplasty

in 1912 as a management for rheumatoid arthritis and post-traumatic DRUJ OA [23].

Darrach's procedure is an excision arthroplasty of the ulnar head through the neck but with attempt at preservation of the ulnar styloid and TFCC attachments (Fig. 18.1).

Intended Benefits

Good longer-term studies exist for resection arthroplasty. Patient satisfaction is high. Range of movement is satisfactory in the longer term. Though radiological follow-up can show a significant percentage of radioulnar impingement, this does not directly correlate with clinical outcomes [16]. Darrach has a role to play particularly in older patients as outcomes in younger more active patients are less favourable.

Potential Complications

There are multiple potential downsides to performing a DRUJ resection arthroplasty. These include instability of the distal ulnar stump, impingement of the stump on the distal radius (radioulnar convergence) and ulnar carpal translation.

Outcomes

Good results are observed in post-traumatic and chronic DRUJ OA [18] as well as after distal radius fracture. Retrospective case series report satisfactory patient outcomes in more than 75% of patients undergoing the Darrach procedure for post-traumatic OA of the DRUJ after distal radius fracture [24].

Multiple studies have shown satisfactory or good long-term outcomes both from objective measures and patient-related subjective outcomes [16, 18].

High levels of postoperative dynamic ulnar convergence are present but do not seem to influence clinical outcomes [16].

Boretto et al. reviewed elderly patients with acute DRUJ instability secondary to concomitant distal ulna and distal radius fractures [25]. They compared open reduction and internal fixation (ORIF) of the distal ulnar fracture to resection of the distal ulna in patients greater than 70 years of age. Overall, there was no significant difference in either objective (active range of movement and grip strength) or subjective measures (pain and Mayo wrist score) between the two groups but complication rates were significantly higher in the ORIF group.

Several methods have been suggested to address the issue of stump instability and radioulnar impingement including the use of a slip of ECU or flexor carpi ulnaris (FCU) to stabilise the stump and interposition soft tissue to reduce impingement pain [17, 26, 27]. There are also reports of the use of Achilles tendon allograft used in the interosseous space to aid stability [28]. None of these alterations to the original described procedure have been shown to be clinically effective.

Studies have shown that the use of an ECU tendon slip to stabilise the remaining stump do not show superiority when compared to cases in which no tendon is used.

Barret et al. describe a technique of performing matched distal ulnar resection in combination with reconstruction of the sixth dorsal compartment and dorsalisation of the ECU tendon in order to improve stability [29]. They looked at 50 wrists in three groups—isolated matched distal ulnar resection (12), distal ulnar resection in combination with total wrist arthrodesis (21) and distal ulnar resection in combination with radius to proximal row arthrodesis (17). The majority of their patients had rheumatoid arthritis. With a mean follow-up of 8.2 ± 5.4 years, 72% of patients were pain-free and 90% would have the procedure performed again. Only two patients (4%) had both clinical and radiological instability with ulnar convergence. This was attributed to an excessively proximal resection of the distal ulna. Two other patients (4%) suffered from ulnocarpal impingement post-op due to a too-distal resection. Range of motion and grip strength were similar across all three groups postoperatively.

Tips

It is important to avoid the dorsal sensory branch of the ulnar nerve on approach. While one can use a strip of ECU or FCU to stabilise the stump, however, these do not bear out in the literature as truly aiding stability and therefore are not performed in our unit.

Rather than a completely horizontal cut, the cut of the distal ulna can be shaped in order to match the opposing surface of the radius. It is important to try to maintain static and dynamic stabilisers of the DRUJ as much as possible—anchor the TFCC to the cut surface of the distal ulna and preserve the interosseous membrane by not cutting too proximally.

Summary

There is very much a role still for distal ulnar resection in treating DRUJ pathology. Rates of radioulnar convergence and persistent stump instability remain high; however, this does not appear to correlate directly with poorer patient outcomes. Several soft tissue methods have been utilised in order to improve stability of the DRUJ post-resection [29] with varying success. Perhaps the most important factor is to be mindful both of the length (not too long—impingement or too short—instability) and shape of the distal ulnar cut as well as an attempt to preserve as much native soft tissue structure as possible.

Similar Procedures

Similar resection arthroplasty procedures include the hemiresection with interposition of the tendon (HIT) first described by Bowers in 1985 [30] and the "matched ulna" resection arthroplasty described by Watson in 1986 [31]. The hemiresection with interposition of the tendon theoretically reduces distal ulna instability as it maintains the ulnar border of the distal ulna and the soft tissue attachments (TFCC). It can be useful for younger patients with intact TFCC. These procedures have comparable outcomes to the Darrach procedure. Additional soft tissue-stabilising procedures do not result in better clinical outcome [32].

18.4.1.2 Sauvé-Kapandji Procedure

Description and History

The Sauvé-Kapandji procedure involves the fusion of the sigmoid notch of the distal radius with the distal ulna along with a more proximal ulnar osteotomy to allow pseudoarthrosis at the ulnar neck. This radioulnar fusion with metaphyseal resection was first described by Kapandji in 1936 [33].

Intended Benefits

There are multiple theoretical benefits of the Sauvé-Kapandji procedure over the Darrach resection. It maintains normal force transmission through the wrist and preserves the ulnar support of the carpus. It allows for the ulna to be shortened if needed and, as long as fusion does occur, results in a stable distal joint. As the distal ulnar attachments are left in situ, the TFCC and distal radioulnar ligaments are preserved.

The Sauvé-Kapandji procedure has been highlighted as an option for inflammatory arthropathy patients as it, theoretically, avoids the distal ulnar instability of a Darrach procedure. It has also been used in younger patients with post-traumatic OA of the DRUJ as it claims to provide better weight-bearing in the joint.

Potential Complications

The potential complications in performing a Sauvé-Kapandji procedure are similar to the Darrach procedure in that ulnar stump instability and radioulnar convergence can still be an issue. Many authors argue that impingement/convergence, present in almost all cases of any kind of resection arthroplasty, is not clinically significant.

As the procedure depends on a successful distal fusion, issues with non-union or delayed union can arise. In addition, the development of a fibrous or osseous union at the ulnar neck pseudoarthrosis site is a concern.

Outcomes

Studies looking at the Sauvé-Kapandji procedure are primarily small in number and retrospective. Overall, the trend suggests that the majority of patients have good pain relief which improves up to 1 year postoperatively, improved grip strength and preservation of movement at the wrist. There is a high rate of successful union at the DRUJ. However, complication rates remain very high.

A group from Switzerland have reported high levels of ulnar instability following the Sauvé-Kapandji procedure [34]. They reported that 6 out of 15 patients, at a mean follow-up of 13 years, required revision surgery for persistent instability of the ulnar stump. They also found that increased ulnar instability (when measured sonographically) was strongly correlated with worse DASH (Disabilities of the Arm, Shoulder and Hand) and PRWE (Patient-Rated Wrist Evaluation) scores as well as lower grip strength and supination torque. There was no significant difference in outcomes between those patients who had soft tissue stabilisation (FCU or retinacular flap) or no soft tissue stabilisation at the time of index surgery. Despite these issues, the pro-supination range in all patients was good. As a result of these findings, this group restricts the use of the Sauvé-Kapandji procedure to only very selected cases.

To minimise ulnar instability, minimal resection of the distal ulna with a very distally based pseudoarthrosis has been proposed. Lluch et al. performed the pseudoarthrosis at the level of the ulnar head and only removed 5 mm of the bone in 70 patients [35]. Despite these adjustments, all patients had ulnar stump instability. However, the instability was painless.

Complication rates following the Sauvé-Kapandji procedure have been reported to be as high as 58% [36] and 63% [37].

Munaretto et al. reviewed 35 patients with a mean follow-up of 49.5 months following the Sauvé-Kapandji procedure [38]. Pain scores were significantly improved postoperatively. Ninety-one percent of the patients had improvement in pain with 64% having complete resolution of pain. However, 9% had either no change or worsening of their pain following the procedure.

The mean grip strength improved in patients. They noted reduced wrist flexion in their patients postoperatively and attributed this to dorsal capsular plication which is performed routinely in their group to aid stability. Otherwise, there was some improvement in pronation, supination and wrist extension which did not reach statistical significance. Again, complication rates were high at 34%. Two cases had persistent ulnar stump instability, one case had persistent DRUJ pain and there was one case of painful heterotrophic ossification which all required re-operation. The other complications were described as "minor", including pin tract infection and prominent hardware. All patients had successful arthrodesis of the DRUJ.

Giberson-Chen et al. retrospectively reviewed 57 patients showing that patient-related outcome measures (QuickDASH score) improved up to 12 months postoperatively for both OA and inflammatory arthritis patients [39]. Interestingly, at 6 weeks postoperatively, QuickDASH scores were worse than those preoperatively for both groups but declined below the preoperative mean by 3 months and continued to improve until 12 months. While QuickDASH scores improved over time from pre- to post-op for OA patients, they remained lower than those for inflammatory arthritis patients at all time points. Supination improved significantly postoperatively, while range of movement in other planes of the wrist was unchanged.

Overall, there was a high revision rate of 21% including removal of hardware and revision osteotomy. Only one patient had ulnar stump instability requiring a revision stabilisation procedure. The group suggests that the low rate of instability of the ulnar stump post-op can be attributed to their surgical technique of a distal site of pseudoarthrosis only just proximal to the DRUJ articulation, thereby preserving soft tissue-stabilising structures such as the periosteum, pronator quadratus and interosseous membrane.

This paper is particularly helpful in counselling patients preoperatively regarding expected outcomes and recovery following the Sauvé-Kapandji procedure. Patients can expect that pain will worsen in the initial postoperative period but improve by 3 months. Functional improvements will continue for up to 12 months. The Sauvé-Kapandji procedure can also improve supination, for those patients with limited preoperative prosuppination, without compromising other wrist movements.

Tips

It can decrease the risk of non-union/delayed union at arthrodesis by ensuring good clearance of soft tissue/periosteum between the styloid notch and distal ulna, debridement down to the bleeding subchondral bone and good alignment + compression at arthrodesis site with the use of a compression screw.

It decreases the risk of fibrous or osseous union at the pseudoarthrosis site by carrying out minimal soft tissue retraction at that site and remove bone debris and periosteum.

By making pseudoarthrosis as close as possible to the head of the ulna, it can minimise ulnar stump painful instability by leaving the smallest bone defect as possible.

Summary

Different types of resection/Sauvé-Kapandji procedure all have similar benefits/perform the same function (no one procedure superior to others), but the rate of post-op pain is high and the range of movement is decreased.

Distal radioulnar convergence and impingement are ongoing issues. Most papers argue that radioulnar convergence does not correlate with clinical symptoms. However, measurement of ulnar stump instability as measured by ultrasound (as opposed to weight-bearing plain films) suggests that stump instability is significantly correlated with poorer outcomes on both objective and subjective measures [34]. Perhaps we are measuring the impingement/convergence inaccurately and should be using ultrasound studies more routinely.

The only statistically significant predictor of poor outcome is a high body mass index (BMI). Patients with raised BMI are found to have higher rates of persistent post-op pain. Other postoperative complications such as limited range of movement and need for revision surgery are not easily predictable. As such, it suggests that resection procedures for the DRUJ are poor options in themselves rather than the technique utilised or the comorbidities of the patients that result in poorer outcome [32].

There is still a role for both the Darrach and Sauvé-Kapandji procedures as surgical options for patients with DRUJ arthritis with careful patient selection, adequate preoperative education as to expected outcomes and correct surgical technique.

18.4.1.3 Comparison of the Darrach Versus Sauvé-Kapandji Procedure

There is paucity of literature directly comparing the outcomes of the Darrach versus Sauvé-Kapandji procedure. Those studies that seek to compare the two procedures are retrospective with small sample sizes. However, those that are out there show comparable long-term outcomes between the two procedures. Both the Sauvé-Kapandji and Darrach procedures have similar outcomes. No significant difference has been shown between the Sauvé-Kapandji and Darrach procedure [32, 36]. However, the Sauvé-Kapandji procedure is more complex and technically more demanding.

When patients less than 50 years of age underwent either the Darrach or Sauvé-Kapandji procedure to address post-traumatic DRUJ arthritis following distal radius fractures, no significant difference in grip strength or ulnar carpal shift was found [36]. Verhiel et al. showed similar outcomes for pain and function between the Darrach and Sauvé-Kapandji groups in post-traumatic DRUJ OA from both distal radius fractures and other causes [40]. Complication rates were higher in the Sauvé-Kapandji group (50% in patients who underwent the Sauvé-Kapandji procedure versus 30% in Darrach cases), but this was not statistically significant.

Yayac et al. reviewed 117 patients with DRUJ OA (post-traumatic, primary and inflammatory arthritis) at a mean follow-up of 70.6 months who underwent either the Darrach, Bowers (distal ulna hemiresection) or Sauvé-Kapandji procedures [32]. Overall, 25.6% of the patients experienced persistent pain postoperatively and 19.7% were limited in their range of movement postoperatively. The patients who underwent the Sauvé-Kapandji procedure were significantly younger than the Bower's hemiresection and Darrach groups (42.4 years versus 60 years). This age difference likely represents surgeon choice. DRUJ arthrodesis provides greater stability which is theoretically beneficial for the younger higher-demand patient. However, there was no significant difference between the groups with regard to pain or function. The study did highlight that patients with a raised body mass index (BMI) were at a significantly increased risk of persistent postoperative pain.

Traditionally, the Darrach procedure is highly utilised in the elderly population, while the Sauvé-Kapandji procedure is used in younger patients or manual labourers. The Sauvé-Kapandji procedure is more technically demanding. Multiple studies have shown that when patients are age-matched, pain, strength, range of movement, patient satisfaction and stump instability do not differ between the two procedures [41]. However, surgical revision rates were significantly higher in the Sauvé-Kapandji group.

Given the lack of superiority of the resection procedures discussed, it is difficult to advise on one rather than another. The traditional thinking that a Sauvé-Kapandji procedure was a better option for younger higher-demand patients as it resulted in greater stability has not been borne out in the current literature. Studies are limited by small numbers and retrospective design. Given that the Sauvé-Kapandji procedure is associated with a higher rate of revision surgery and is a more technically demanding procedure, should we be doing it at all?

Nikkhah et al. have called for a multicentre prospective study to be performed in the UK to determine the role of each operation given that there is no clear superiority of either [42]. Until a properly powered and well-designed study is carried out, the authors cannot advocate for one type of resection procedure over another. However, overall, pain seems to improve in majority of patients regardless of the procedure carried out.

18.4.2 Prosthetic Arthroplasty

The pitfalls of resection arthroplasty of the DRUJ, including persistent pain and radioulnar convergence, stimulated the introduction of prosthetic implant arthroplasty. Theoretically, prosthetic implants maintain more normal joint kinematics. They allow for restoration of the normal axis and rotation of the forearm as well as act to resist tensile and compressive forces across the wrist. The goal of any DRUJ implant arthroplasty is to reestablish the distal pivot joint necessary for the sufficient or adequate tensioning of the IOM allowing optimal transfer of load between the radius and ulna.

DRUJ implants are of three main types: Silastic, ulnar replacement alone and total DRUJ replacement with components on both the radius and ulna. Silastic implants are historical in perspective. Their use was related to significant bone resorption and silicon synovitis. They are no longer used due to high failure rates [43, 44]. The distal ulnar head prosthesis can be a partial or complete ulnar head replacement. In total DRUJ arthroplasty, the device is semi-constrained with components on both the distal radius and distal ulna.

Despite the advances in technology, it remains difficult for any prosthesis to fully address all aspects of the complex DRUJ anatomy and truly restore normal biomechanics. Surgeons should also be aware of the learning curve associated with the use of the newer prosthetic implants.

18.4.2.1 Partial or Complete Ulnar Head Replacement

Description and History

Ulnar head prostheses were introduced to address the limitations of resection arthroplasty at the DRUJ. Their aim was to improve patient's pain and maintain the normal DRUJ biomechanics while addressing the issues of radioulnar convergence and instability seen with resection procedures. They can be utilised when the distal radius sigmoid notch is well maintained and the joint is stable in cases of primary pathology. They are also indicated for use in salvage operations following resection arthroplasty with ongoing distal ulnar stump pain and radioulnar convergence.

In partial ulnar head replacement, the ulnar styloid, and its soft tissue attachments, is left intact. In a complete ulnar head replacement, the entirety of the distal ulna is excised (Fig. 18.2). However, the excision is performed sub-TFCC in order to protect the soft tissues. The complete ulnar head prosthesis is designed with a hole distally to allow the passage of sutures from the ulnar capsule and TFCC to the implant in order to maintain stability from the soft tissues.

Intended Benefits

An ulnar head replacement (UHR) allows for normal weight-bearing through the DRUJ. It aims to restore a normal axis and forearm rotation while resisting the tensile and compressive forces across the wrist joint. By maintaining the soft tissue-stabilising structures around the DRUJ, it also addresses the issue of instability. The benefit of an ulnar head replacement over a resection arthroplasty is to prevent stump pain, radioulnar convergence and instability. Multiples studies have shown that ulnar head replacement is a successful operation, and superior to distal ulnar resection, in restoring normal kinematics of the forearm [45–47].

Potential Complications

Despite adherence to careful surgical technique and repair of soft tissues, instability of the implant can be an issue particularly if the morphology of the native sigmoid notch is quite flat. This can be addressed by a gentle and careful "shaping" of the sigmoid notch at the time of ulnar head implant using a burr.

Sigmoid notch erosion and stress shielding are other concerns with UHR. The metallic ulnar head may erode into the sigmoid notch of the distal radius over time. While the distal ulnar replacement enables normal weight-bearing through the DRUJ, the force transmission on loading passes down the implant stem to the more proximal ulnar diaphysis, thus bypassing the remaining more distal ulnar diaphysis. This can result in stress shielding and osteolysis around the implant.

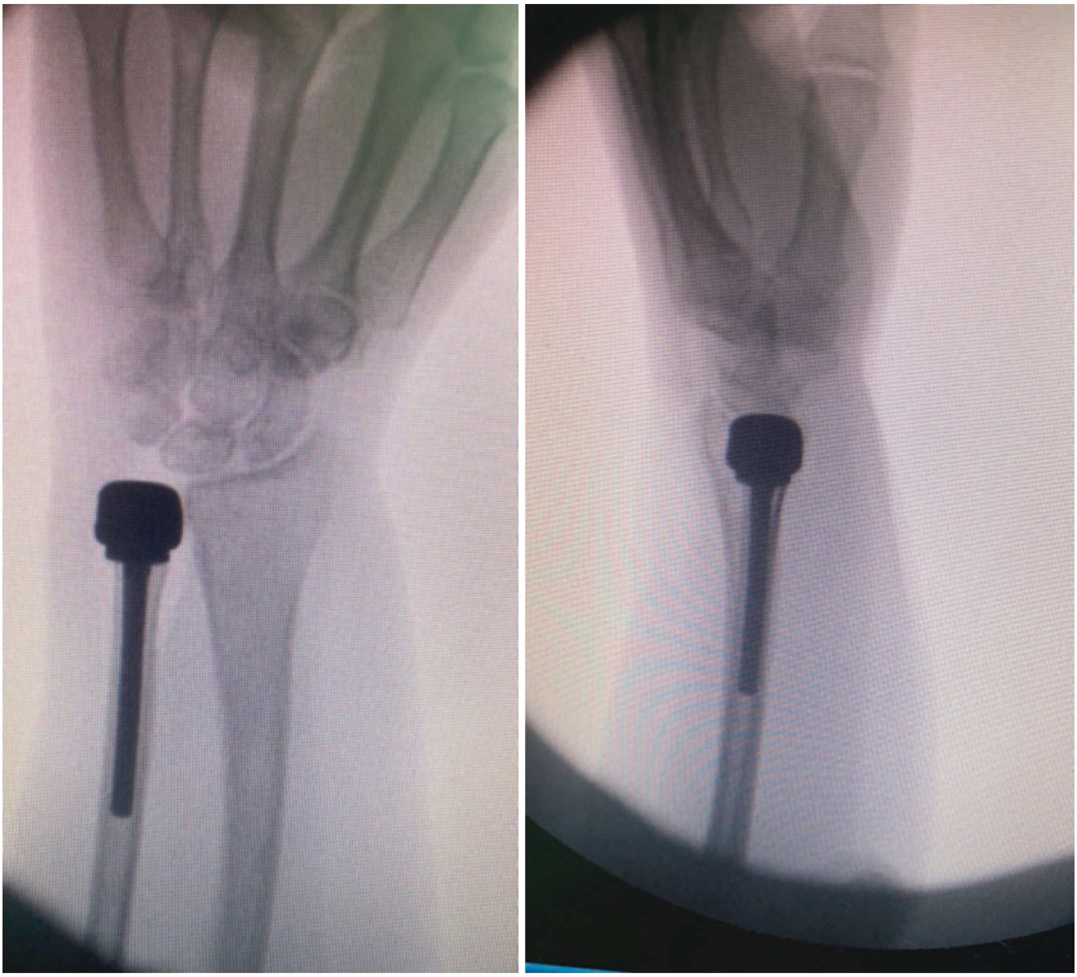

Fig. 18.2 Anteroposterior (left) and lateral (right) images of total ulnar head replacement (UHR)

Stress shielding of the distal ulna can produce significant osteolysis around the implant at short-term follow-up. This has been reported to occur in 90%–100% of patients [48, 49]. Although it is argued that the radiological presence of stress shielding and osteolysis does not directly correlate with clinical outcome [50]. However, one paper does suggest that the presence of a "pedestal" at the tip of the ulnar stem correlates with a worse functional result [51].

Outcomes

In reviewing the outcomes of UHR implants, there are only relatively small studies that are retrospective in nature. However, patient satisfaction and outcomes are generally good.

Baring et al. looked at 10 patients who underwent distal ulnar replacement with mixed aetiologies (primary OA, post-traumatic OA, rheumatoid and failed Darrach procedure) [50]. Nine out of ten patients had developed osteolysis of the distal ulna at a mean follow-up of 48 months. Despite this, the patient-related outcome measures were good. The mean visual analogue scale (VAS) for pain was 2.7 and the mean DASH score was 37. Of the nine patients with osteolysis, eight felt their condition was either "better" or "much better". Though this was a small single-surgeon study with some limitations (no clearly defined preoperative functional or pain measurements and no postoperative measurement of grip strength), it is important in discussing the relevance of stress shielding of these implants. The majority of patients seem to develop distal ulnar osteolysis but the radiological findings do not directly correlate with patient outcomes.

Sauerbier et al. reviewed 25 patients who underwent UHR either as a primary procedure for DRUJ arthritis or as a salvage procedure post resection arthroplasty [48]. There was a statistically significant improvement in pain and pain scores during stress of the DRUJ in both groups. However, patient outcomes were significantly better when the procedure was done as a primary operation rather than as salvage. This may be due to the meticulous maintenance of soft tissue structures when the ulnar head implant in utilised as an index procedure.

Warwick et al. presented their results of 56 UHRs performed in 52 patients with a mean follow-up of 60 months [52]. The mean pain score was 2.2, while the mean DASH score was 18. While there were no preoperative scores recorded to allow a direct evaluation of objective improvement, patient satisfaction was high. Forty-seven of the patients would have undergone the same procedure again. There were five complications reported, of which three required surgical interventions (two-stage revision for infected loosening, impaction grafting for aseptic loosening, tendon transfers for delayed extensor tendon rupture). There were five radiologically confirmed patients with styloid notch erosion, but all of these patients were asymptomatic. Overall, this study reports low pain scores, good function and high patient satisfaction with UHR.

Tips

Regardless of which specific implant is utilised, careful dissection and protection of the TFCC and surrounding soft tissue structures should be a priority. If the corresponding styloid notch of the distal radius is particularly flattened, it can be contoured by gently and carefully using a burr to develop a more "C-shaped" notch to improve stability of the implant.

Summary

There is a lack of robust studies regarding UHRs. However, the small retrospective studies that are available all report high levels of patient satisfaction and improvement in pain postoperatively. The best outcomes are when a UHR is carried out as an index procedure rather than as a salvage procedure after a failed resection. This is likely due to the integrity of the soft tissues.

No significant difference has been documented between partial or total UHR. Partial UHRs show some decrease in range of movement but higher grip strength and rotational force postoperatively when compared to total UHRs, but these differences do not reach statistical significance [53]. As no firm evidence has shown a benefit for total UHR over a partial UHR, we advise that surgeons would use whichever implant they are most familiar and comfortable with.

18.4.2.2 Total DRUJ Arthroplasty

Description and History

While ulnar head replacements were a benefit in restoring normal forearm kinematics in DRUJ pathology, complications such as instability and styloid erosion due to the implant drove the development of a total distal ulnar replacement. The main implant that we refer to in our discussion here is the Scheker or Aptis implant. Schuurman also developed a total DRUJ replacement. While the Schuurman implant has been adapted over time and later designs show superiority over earlier devices, studies have shown better longevity with the Aptis prosthesis when compared to the Schuurman [54, 55]. Most of the current literature available relates to the Aptis implant and it is the prosthesis we use in our unit. The Aptis implant is a semi-constrained, modular implant. It is designed to replace the function of the ulnar head, sigmoid notch of the radius and TFCC. It can be used in inflammatory arthritis, primary OA, post-traumatic OA and congenital DRUJ pathology and has also been shown to be of benefit in failed resection arthroplasty cases (Figs. 18.3 and 18.4).

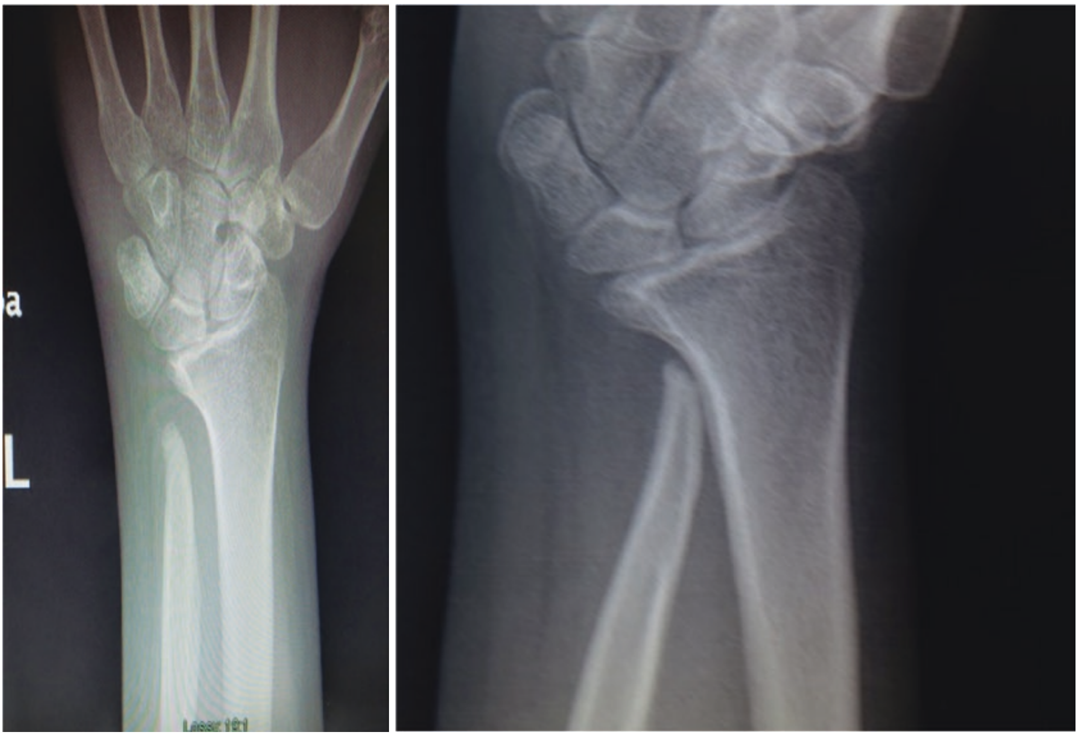

Fig. 18.3 Anteroposterior (left) and lateral (right) preoperative images of patient post-failed Darrach procedure for post-traumatic distal radioulnar joint (DRUJ) osteoarthritis with ongoing significant pain

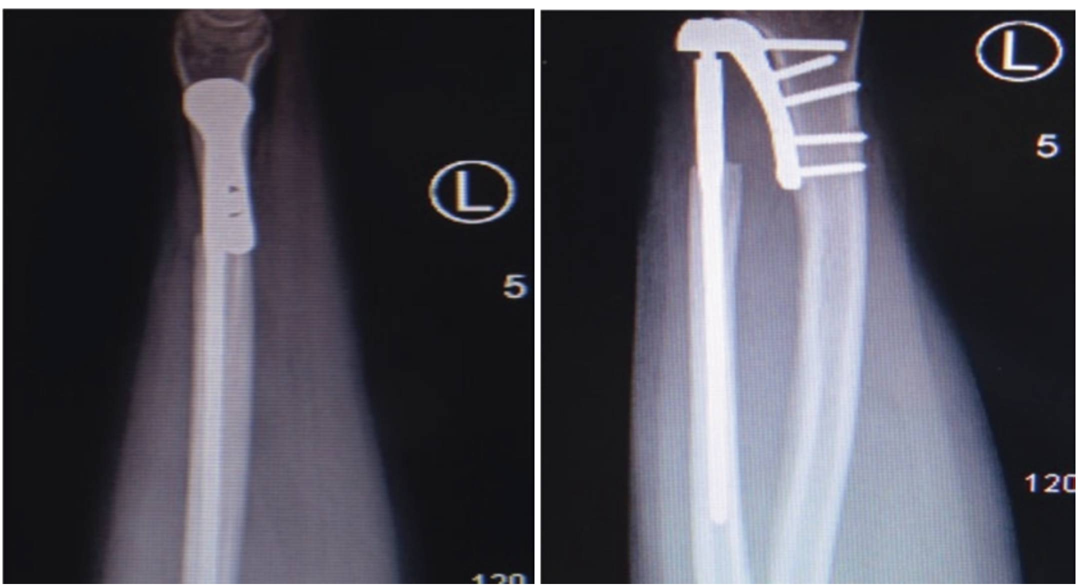

Fig. 18.4 Postoperative images of the same patient following conversion to total distal radioulnar joint (DRUJ)—Scheker prosthesis—with improvement in pain and function

Intended Benefits

The aim of performing a total distal radioulnar joint replacement is to reproduce a stable painless joint and restore normal biomechanics allowing full pronation and supination, radial migration and variable angle of rotation. It has a particularly significant role as a salvage implant for previous failed operations on the DRUJ.

Potential Complications

The total DRUJ arthroplasty theoretically addresses both instability and restores normal biomechanics of the DRUJ but it is not a panacea for all of DRUJ arthritis. It involves significant soft tissue dissection which could lead to injuries of the DRUJ stabilisers. As a semi-constrained device, the Aptis implant attempts to overcome these issues and maintain stability. However, the semi-constrained design may predispose young active patients to loosening over time.

Stress shielding and osteolysis around the ulnar component, similar to UHRs, is another concern. While it has a role as a salvage implant in patients who have failed previous DRUJ operations, concern exists over what options are available if the Aptis itself fails. This is a particular worry in younger patients.

Outcomes

Overall high patient satisfaction rates and good survival are reported with the Aptis implant but high complication rates and high rates of re-intervention are also recorded. There is concern that using this implant in young active patients may predispose to loosening over time given its semi-constrained design. Loosening was reported with early studies [54].

Late complications requiring secondary surgery are very common with the Scheker implant and shown to occur in 21% of patients [55]. Synovitis of the ECU tendon is reported to occur in up to 44% of patients [56]. Other complications include irritation of the superficial radial nerve and first dorsal compartment tenosynovitis which may occur secondary to the length of the radial screws.

The Aptis implant has a wide range of indications for use with good outcomes reported across the board. Galvis et al. report on its benefit in rheumatoid patients [57]. Pain scores and range of movement were both improved postoperatively. Axelsson et al. have reported positive outcomes when the Aptis is used for failed previous DRUJ surgery [58]. DASH scores are significantly improved. Other objective parameters, such as grip strength, are improved but do not reach significance. Significant bone resorption was noted at the distal ulna in most patients but there was no evidence of implant loosening. However, the mean follow-up was only 3.7 years [58].

Frost in 1994 described stress shielding as relating to Wolff's law and bone's structural adaptations or remodelling based on the stresses applied to it [59]. Therefore, if an implant results in force bypassing the bone, the bone will become weaker and less dense as there is no stimulus for continued bone remodelling. This is seen commonly with hip prostheses but can also be present in upper limb prostheses such as humeral stems and even in the distal radius following wrist arthroplasty. While we have noted evidence of stress shielding with the UHRs and total DRUJ replacements, it is not clear whether there is any clinical significance to this finding and whether it can act as a predictor of aseptic loosening in longer-term follow-up.

Rampazzo et al. reviewed the use of the Aptis prosthesis in younger patients [60]. This group looked at 46 arthroplasties performed at a mean age of 32 years with a mean follow-up of 61 months. Both objective and subjective parameters were significantly improved postoperatively, including grip strength, pain scores, DASH scores, PRWE scores and range of movement. The overall survival rate was 96% at 5 years.

Calcagni et al. in Europe reviewed his results of the Aptis implant at both midterm and longer-term follow-up [55, 61]. This group again reported good pain relief and patient satisfaction with significant improvement in strength and weightlifting. There was no significant change in the range of movement. Their overall survival was 80% at 5 years. Calcagni et al. report that, despite it being a "delicate" procedure with careful dissection of soft tissues and the need for a meticulous surgical technique, the learning curve with this implant is quite flat.

Multiple studies have shown very good results with regard to patient satisfaction and functional scores with a mean implant survival of 96%–100% at 5 years [60, 62–64]. However, longer follow-up and assessment are needed to truly assess the outcomes of this implant.

Tips

While the Aptis total DRUJ replacement has very good early results, the surgical technique is somewhat challenging and requires a good deal of soft tissue dissection. We feel that its primary role at present is as a salvage implant as a last option for patients. Therefore, we would suggest attempting other surgical options first. Preoperative planning is important for this implant. It is essential to have high-quality radiological imaging, anteroposterior (AP) and lateral views of the full length of the forearm, in order to plan for the most appropriate implant insertion. Care should be taken to protect soft tissues intraoperatively. It is essential to ensure adequate soft tissue flap to cover the prosthesis and protect the ECU in order to reduce the complications of ECU irritation.

Summary

Overall, 5-year survival rates are good with DRUJ arthroplasty. However, the difficulty then becomes options for revision when the implants do fail. This is particularly relevant in the setting of DRUJ arthritis in a young person.

The National Institute for Health and Care Excellence (NICE) guidelines published in November 2017 suggest that this is a useful prosthesis but that it should be used in very limited setting and by a very small number of surgeons in order to accrue the specialist technique [65].

Even with comprehensive review, very few papers with proper pre−/post-op data are available and very few reached statistical significance. Therefore, it is difficult to comment.

By not addressing the ulnocarpal joint with total DRUJ replacement, we are increasing the axial load to the radiocarpal joint similar to what would occur with an excision arthroplasty.

These need to be added to the National Joint Registry in order to truly calculate accurate preoperative and postoperative outcomes and to compare different prostheses. Without standardised follow-up, early identification of complications and major issues with these implants is very difficult particularly given that they are performed in such small numbers.

Calcagni et al. performed a systematic review of the literature surrounding DRUJ arthroplasty with implants in 2017 [55]. This review highlighted the paucity of data available for review. Very few papers have complete preoperative and postoperative data collection. There are no large studies to reference, and therefore, very few reach statistical significance given the small patient numbers. However, this review did show a patient satisfaction rate of 95% with UHRs and 98% with the Aptis total DRUJ replacement. The UHRs were found to have a 95% survival at or beyond 5 years and the total DRUJ had a survival rate of 98% at or beyond 5 years.

A further systematic review by Moulton et al. in 2017 reviewed both distal ulnar replacements and total DRUJ replacements [66]. Fourteen studies had shown an implant survivor rate of 93% at a mean of 45 months for the ulnar head replacements and 97% survivorship for the total DRUJ prosthesis (primarily Aptis implant) at 56 months.

Certainly the shorter-term results with DRUJ implant arthroplasty are very encouraging but we are somewhat cautious with the use of these implants in younger patients given the lack of long-term outcome data. We feel that a prospective multicentre trial is needed in order to most accurately assess the outcomes in these implants.

18.4.3 Authors' Preferred Treatment Methods

In general, we prefer a Darrach procedure in older less-demanding patients. It is a relatively straightforward procedure with overall high satisfaction rates. As a local group, we do not tend to do Sauvé-Kapandji procedure as we feel that, in our hands, the high complication rates and rates of revision surgery outweigh the benefits. In the younger patient, we would tend to favour an ulnar head replacement. We have found that some of these implants are becoming increasingly difficult to obtain and to have adequate surgical rep support as larger companies take over smaller ones and drop these from their portfolio as they are utilised in a much smaller volume than other upper limb implants. In cases of prior failed surgery as a salvage operation or for that subset of patients with concomitant DRUJ arthritis and instability, we favour a Scheker total DRUJ prosthesis.

While the newer implants for either ulnar head or total DRUJ replacements show good outcomes in the short term and hold great potential, there is certainly an added cost issue with their use. In the current age of careful resource utilisation, each surgeon needs to decide what is best for their patient based on the resources available in their unit as well as their own surgical expertise while still maintaining a focused individualised optimal patient care.

18.4.4 Conclusions

It is difficult to propose an algorithm to aid with treatment options in DRUJ arthritis. It remains an area of great controversy. We would recommend that surgeons decide management options on a case-by-case basis dependent on both patient factors (i.e. BMI, function, age) and joint factors (stability, congruency, morphology).

We need robust, prospective long-term studies to assess the true outcome of these procedures. These are all done in such a small number; it is difficult to reach statistical significance. Our understanding may always be somewhat limited as a result.

The authors hesitate to suggest a rigid algorithm of management for these cases. There is definite potential for the prostheses; however, their complication rate is high and the number of studies, long-term follow-up and rigid pre- and post-op data are limited. Prosthetic replacement of the DRUJ is not something for the "casual" hand surgeon to undertake. If done, they should be carried out in very specialist centres by a very small number of surgeons in order to improve the learning curve of any newer technology.

It is perhaps one of those conditions where arthritis in a young patient does not have an easy management option and conservative measures should be employed first at all costs.

We think it is important when considering any of the surgical options for DRUJ arthritis that we counsel patients appropriately. Most of these options (resection and prosthesis) will provide pain relief and functional improvement. However, when we discuss supposedly "good" outcomes, we must emphasise to our patients that no surgical procedure offers 100% pain relief in all patients. Functional range of movement is still considered flexion/extension of 40°/40°, radial-ulnar deviation combined of 40° [67] and pronation/supination of 50°/50° [68]. These may be very disappointing figures for some young and active patient's, particularly in this contemporary age where the use of computer keyboards or smart phones requires a greater degree of pronation [69].

In this age, particularly with younger patients, expectations are high. It is important to explain what we interpret as "good" results.

References

1. Malgaigne J. Traites des fractures et des luxations. Paris; 1855.
2. af Ekenstam F. Anatomy of the distal radioulnar joint. Clin Orthop Relat Res. 1992;275:14–8.
3. Tolat AR, Stanley JK, Trail IA. A cadaveric study of the anatomy and stability of the distal radioulnar joint in the coronal and transverse planes. J Hand Surg. 1996;21:587–94.
4. Sagerman SD, Zogby RG, Palmer AK, Werner FW, Fortino MD. Relative articular inclination of the distal radioulnar joint: a radiographic study. J Hand Surg. 1995;20:597–601.
5. Stuart PR, Berger RA, Linscheid RL, An KN. The dorsopalmar stability of the distal radioulnar joint. J Hand Surg. 2000;25:689–99.
6. Palmer AK, Werner FW. The triangular fibrocartilage complex of the wrist—anatomy and function. J Hand Surg 1981;6:153–162.
7. Cole DW, Elsaidi GA, Kuzma KR, Kuzma GR, Smith BP, Ruch DS. Distal radioulnar joint instability in

distal radius fractures: the role of sigmoid notch and triangular fibrocartilage complex revisited. Injury. 2006;37:252–8.
8. Watanabe H, Berger RA, Berglund LJ, Zobitz ME, An KN. Contribution of the interosseous membrane to distal radioulnar joint constraint. J Hand Surg. 2005;30:1164–71.
9. Gofton WT, Gordon KD, Dunning CE, Johnson JA, King GJ. Soft-tissue stabilizers of the distal radioulnar joint: an in vitro kinematic study. J Hand Surg. 2004;29:423–31.
10. af Ekenstam F, Hagert CG. Anatomical studies on the geometry and stability of the distal radio ulnar joint. Scand J Plastic Reconstruc Surg. 1985;19:17–25.
11. Palmer AK, Werner FW. Biomechanics of the distal radioulnar joint. Clin Orthop Relat Res. 1984;187:26–35.
12. Palmer AK, Werner FW, Glisson RR, Murphy DJ. Partial excision of the triangular fibrocartilage complex. J Hand Surg. 1988;13:391–4.
13. Nygaard M, Nielsen NS, Bojsen-Moller F. A biomechanical evaluation of the relative load change in the joints of the wrist with ulnar shortening: a 'handbag' model. J Hand Surg Eur. 2009;34:724–9.
14. Nishiwaki M, Nakamura T, Nagura T, Toyama Y, Ikegami H. Ulnar-shortening effect on distal radioulnar joint pressure: a biomechanical study. J Hand Surg. 2008;33:198–205.
15. Nishiwaki M, Nakamura T, Nakao Y, Nagura T, Toyama Y. Ulnar shortening effect on distal radioulnar joint stability: a biomechanical study. J Hand Surg. 2005;30:719–26.
16. Grawe B, Heincelman C, Stern P. Functional results of the Darrach procedure: a long-term outcome study. J Hand Surg. 2012;37(2475–80):e1–2.
17. Tulipan DJ, Eaton RG, Eberhart RE. The Darrach procedure defended: technique redefined and long-term follow-up. J Hand Surg. 1991;16:438–44.
18. Jochen-Frederick H, Pouyan Y, Khosrow BA, Christoph H, Berthold B, Ulrich K, et al. Long-term functional outcome and patient satisfaction after ulnar head resection. J Plastic Reconstruct Aesthetic Surg. 2016;69:1417–23.
19. EM M. Three cases illustrating luxation of the ulna in connection with Colles' fracture. Medical Records 1880;17:305–308.
20. L VL. Zur behandlung fehrerhaft gehlilter bruche der karpalen radiusepiphuse. Centralblatt fur Chirurgie 1887;14:265–269.
21. C L. Zur Fraser der derangement interne des kniegelenks. Deutsche Medizinische Wolhenschrift 1840;16:169–170.
22. Buck-Gramcko D. On the priorities of publication of some operative procedures on the distal end of the ulna. J Hand Surg. 1990;15:416–20.
23. Darrach W. Anterior dislocation of the head of the ulna. Ann Surg. 1912;56
24. Coulet B, Onzaga D, Perrotto C, Boretto JG. Distal radioulnar joint reconstruction after fracture of the distal radius. J Hand Surg. 2010;35:1681–4.
25. Boretto JG, Zaidenberg EE, Gallucci GL, Sarme A, De Carli P. Comparative study of internal fixation of the ulna and distal ulna resection in patients older than 70 years with distal radius and distal metaphyseal ulna fractures. Hand. 2019;14:540–6.
26. Breen TF, Jupiter JB. Extensor carpi ulnaris and flexor carpi ulnaris tenodesis of the unstable distal ulna. J Hand Surg. 1989;14:612–7.
27. Sotereanos DG, Gobel F, Vardakas DG, Sarris I. An allograft salvage technique for failure of the Darrach procedure: a report of four cases. J Hand Surg. 2002;27:317–21.
28. Allende C. Allograft tendon interposition and brachioradialis tendon stability augmentation in revision surgery for failed Darrach distal ulna resections. Tech Hand Upper Extremity Surg. 2010;14:237–40.
29. Barret H, Lazerges C, Chammas PE, Degeorge B, Coulet B, Chammas M. Modification of matched distal ulnar resection for distal radio-ulnar joint arthropathy: analysis of distal instability and radio-ulnar convergence. Orthop Traumatol Surg Res. 2020;106:1597–603.
30. Bowers WH. Distal radioulnar joint arthroplasty: the hemiresection-interposition technique. J Hand Surg. 1985;10:169–78.
31. Watson HK, Ryu JY, Burgess RC. Matched distal ulnar resection. J Hand Surg. 1986;11:812–7.
32. Yayac M, Padua FG, Banner L, Seigerman DA, Beredjiklian PK, Aita DJ, et al. Treatment outcomes in patients undergoing surgical treatment for arthritis of the distal radioulnar joint. J Wrist Surg. 2020;9:230–4.
33. M SLaK. Nouvelle technique de traitement chirurgical des luxations recidivantes isolees de l'extremite inferieure du cubitus. J Chirurgie (Paris). 1936;47:589–94.
34. Reissner L, Schweizer A, Unterfrauner I, Estermann L, Nagy L. Long-term results of Sauve-Kapandji procedure. J Hand Surg Eur. 2021;46:626–31.
35. Lluch A. The sauve-kapandji procedure. J Wrist Surg. 2013;2:33–40.
36. George MS, Kiefhaber TR, Stern PJ. The Sauve-Kapandji procedure and the Darrach procedure for distal radio-ulnar joint dysfunction after Colles' fracture. J Hand Surg. 2004;29:608–13.
37. Carter PB, Stuart PR. The Sauve-Kapandji procedure for post-traumatic disorders of the distal radio-ulnar joint. J Bone Joint Surg Br. 2000;82:1013–8.
38. Munaretto N, Aibinder W, Moran S, Rizzo M. Sauve-Kapandji remains a viable option for distal radioulnar joint dysfunction. Hand. 2020 Nov;22:1558944720966725.
39. Giberson-Chen CC, Leland HA, Benavent KA, Harper CM, Earp BE, Rozental TD. Functional outcomes after Sauve-Kapandji arthrodesis. J Hand Surg. 2020;45:408–16.
40. Verhiel S, Ozkan S, Ritt M, Chen NC, Eberlin KR. A comparative study between Darrach and Sauve-Kapandji procedures for post-traumatic distal radioulnar joint dysfunction. Hand. 2021;16:375–84.

41. Roulet S, Williot A, Sos C, Mazaleyrat M, Marteau E, Laulan J, et al. Comparison of subjective outcomes of Darrach and Sauve-Kapandji procedures at a minimum 2 years' follow-up. Orthop Traumatol Surg Res. 2021;107(5):102974.
42. Nikkhah D, Rodrigues J, Dejager L. Do patients really do better after the Sauve-Kapandji procedure when compared to the Darrach procedure? A systematic review. J Hand Surg Eur. 2011;36(7):615.
43. Sagerman SD, Seiler JG, Fleming LL, Lockerman E. Silicone rubber distal ulnar replacement arthroplasty. J Hand Surg. 1992;17:689–93.
44. McMurtry RY, Paley D, Marks P, Axelrod T. A critical analysis of Swanson ulnar head replacement arthroplasty: rheumatoid versus nonrheumatoid. J Hand Surg. 1990;15:224–31.
45. Gordon KD, Dunning CE, Johnson JA, King GJ. Kinematics of ulnar head arthroplasty. J Hand Surg. 2003;28:551–8.
46. Berger RA, Cooney WP 3rd. Use of an ulnar head endoprosthesis for treatment of an unstable distal ulnar resection: review of mechanics, indications, and surgical technique. Hand Clin. 2005;21:603–20.
47. Masaoka S, Longsworth SH, Werner FW, Short WH, Green JK. Biomechanical analysis of two ulnar head prostheses. J Hand Surg. 2002;27:845–53.
48. Sauerbier M, Arsalan-Werner A, Enderle E, Vetter M, Vonier D. Ulnar head replacement and related biomechanics. J Wrist Surg. 2013;2:27–32.
49. Herzberg G. Periprosthetic bone resorption and sigmoid notch erosion around ulnar head implants: a concern? Hand Clin. 2010;26:573–7.
50. Baring TK, Popat R, Abdelwahab A, Ferris B. Short- to mid-term results of ulna head replacement as both a primary and revision implant. J Clin Orthop Trauma. 2016;7:292–5.
51. Kakar S, Swann RP, Perry KI, Wood-Wentz CM, Shin AY, Moran SL. Functional and radiographic outcomes following distal ulna implant arthroplasty. J Hand Surg. 2012;37:1364–71.
52. Warwick D, Shyamalan G, Balabanidou E. Indications and early to mid-term results of ulnar head replacement. Ann R Coll Surg Engl. 2013;95:427–32.
53. Estermann L, Reissner L, Rosskopf AB, Schweizer A, Nagy L. Clinical, radiological and patient-rated outcome comparison between total and partial ulnar head implants. J Hand Surg Eur. 2021:17531934211048406.
54. Schuurman AH, Teunis T. A new total distal radioulnar joint prosthesis: functional outcome. J Hand Surg. 2010;35:1614–9.
55. Calcagni M, Giesen T. Distal radioulnar joint arthroplasty with implants: a systematic review. EFORT Open Rev. 2016;1:191–6.
56. Savvidou C, Murphy E, Mailhot E, Jacob S, Scheker LR. Semiconstrained distal radioulnar joint prosthesis. J Wrist Surg. 2013;2:41–8.
57. Galvis EJ, Pessa J, Scheker LR. Total joint arthroplasty of the distal radioulnar joint for rheumatoid arthritis. J Hand Surg. 2014;39:1699–704.
58. Axelsson P, Sollerman C. Constrained implant arthroplasty as a secondary procedure at the distal radioulnar joint: early outcomes. J Hand Surg. 2013;38:1111–8.
59. Frost HM. Wolff's law and bone's structural adaptations to mechanical usage: an overview for clinicians. Angle Orthod. 1994;64:175–88.
60. Rampazzo A, Gharb BB, Brock G, Scheker LR. Functional outcomes of the Aptis-Scheker distal radioulnar joint replacement in patients under 40 years old. J Hand Surg. 2015;40(1397–403):e3.
61. Fuchs N, Meier LA, Giesen T, Calcagni M, Reissner L. Long-term results after semiconstrained distal radioulnar joint arthroplasty: a focus on complications. Hand Surg Rehab. 2020;39:186–92.
62. Sander AL, Ebert F, Marzi I, Frank J. Outcome after implantation of the Aptis total distal radioulnar joint replacement prosthesis. Handchirurgie, Mikrochirurgie, plastische Chirurgie : Organ der Deutschsprachigen Arbeitsgemeinschaft fur Handchirurgie: Organ der Deutschsprachigen Arbeitsgemeinschaft fur Mikrochirurgie der Peripheren Nerven und Gefasse. 2015;47:306–11.
63. Bizimungu RS, Dodds SD. Objective outcomes following semi-constrained total distal radioulnar joint arthroplasty. J Wrist Surg. 2013;2:319–23.
64. Kachooei AR, Chase SM, Jupiter JB. Outcome assessment after Aptis distal radioulnar joint (DRUJ) implant arthroplasty. Arch Bone Joint Surg. 2014;2:180–4.
65. Excellence NIfHaC. Total distal radioulnar joint replacement for symptomatic joint instability or arthritis 2017. Available from: https://www.nice.org.uk/guidance/ipg595.
66. Moulton LS, Giddins GEB. Distal radio-ulnar implant arthroplasty: a systematic review. J Hand Surg Eur. 2017;42:827–38.
67. Ryu JY, Cooney WP 3rd, Askew LJ, An KN, Chao EY. Functional ranges of motion of the wrist joint. J Hand Surg. 1991;16:409–19.
68. Valone LC, Waites C, Tartarilla AB, Whited A, Sugimoto D, Bae DS, et al. Functional elbow range of motion in children and adolescents. J Pediatr Orthop. 2020;40:304–9.
69. Sardelli M, Tashjian RZ, MacWilliams BA. Functional elbow range of motion for contemporary tasks. J Bone Joint Surg Am. 2011;93:471–7.