Biomechanics of the Rheumatoid Wrist Deformity

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Introduction

Rheumatoid arthritis (RA) is a common systemic inflammatory disease that is associated with progressive disability, significant morbidity, early death, and significant socioeconomic costs [1]. Although it can affect any synovial joint, the wrist is the most frequently involved. Chronic synovitis and pannus expansion result in degradation of articular cartilage and bone, ligamentous laxity, and significant deformity. This in part follows a predictable pattern of change and therefore targeted early operative intervention can be achieved, ranging from arthroscopic synovectomy to complete wrist arthrodesis.

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Multiple Ring Concept of the Wrist Stability

The wrist has three synovial spaces: the radiocarpal, midcarpal, and distal radioulnar joint (DRUJ). However, there are four articulating joints because the ulnar-carpal articulation should not be ignored. Another way to conceptualize the joints of the wrist is to consider it as a series of conjoined rings, which operate in concert with each other. This forms the basis of the “multiple ring concept of the wrist.” The structure, stability, and borders of the rings are defined by the intrinsic ligamentous attachments. The sites where the rings are linked form major stability points of the carpus. The wrist joint is unique in that it provides movement in all three planes and must provide a stable platform for the function of the hand in all positions in space. The rings provide stability, while allowing transmission and dissipation of force throughout the range of motion. This is particularly important at the extremes of motion, where the stability is threatened. Disruption of these ligaments creates instability within the ring, which can then impart a *global* instability to the wrist.

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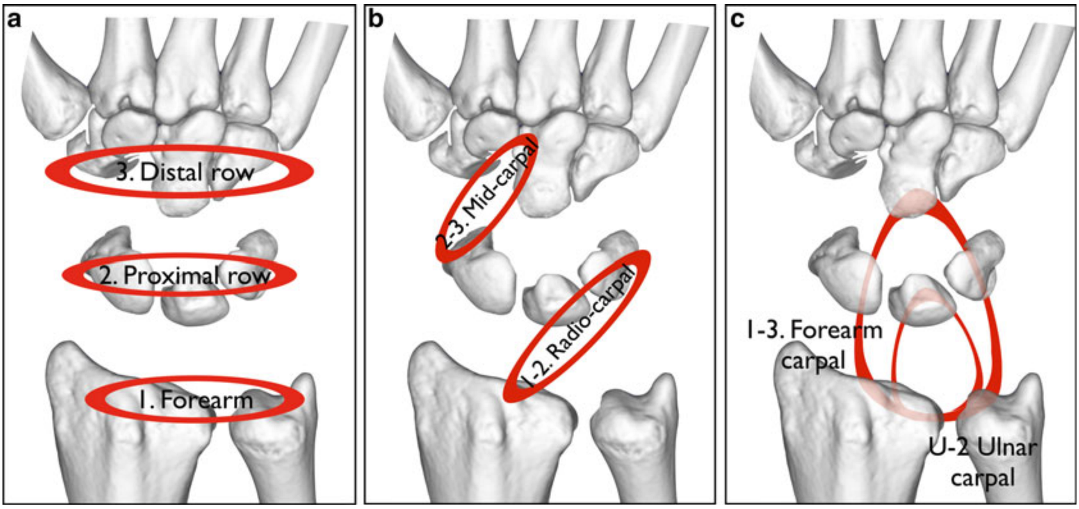

Fig. 8.1 Multiple ring concept of the wrist: (**a**) rows of rings; (**b**) inter-row rings, radiocarpal and midcarpal; (**c**) arcuate carpal rings, greater and lesser. Published with permission of © Dr. Gregory Bain 2015. All Rights Reserved

Rows of Rings

There are three rows of rings of the wrist: the DRUJ, proximal carpal row, and distal carpal row (Fig. 8.1a).

1. The DRUJ ring is stabilized by the radioulnar ligaments, with failure causing DRUJ instability.
2. The proximal carpal row is stabilized by the dorsal intercarpal ligament and the volar scaphotriquetral ligaments. Failure examples include scapholunate and lunotriquetral instability.
3. The distal carpal row is stabilized by the volar and dorsal interosseous ligaments, failure of which causes axial instability.

Inter-row Rings

These are the rings that link and provide stability between the individual rows (Fig. 8.1b, c).

1. The radiotriquetral ring, which has been referred to as the Kuhlman's sling [2], includes the dorsal radiocarpal ligament and the volar radiotriquetral ligament, preventing ulnar translocation.
2. The scaphoid-trapezium-trapezoid (STT) ring is a simple hinge joint, consisting of the scaphotrapezoid and scaphocapitate ligaments. Failure of the STT ring causes midcarpal instability.
3. The **lesser arcuate ring** consists of the ulnar-lunate and radiolunate ligaments, which stabilizes the lunate to the forearm to prevent volar subluxation of the carpus.
4. The **greater arcuate ring** consists of the radioscaphocapitate and the ulnar capitate ligaments, which stabilizes the distal carpal row to the forearm, to prevent distraction of the wrist (Fig. 8.1c).

Variability in Carpal Morphology

Finally it should be noted that there can be significant variation in the morphology of carpal bones, which can affect the movement at the joints. At the midcarpal joint, the lunate type [3] has been shown to alter the pattern and range of motion at the radiocarpal joint (Fig. 8.2) [4]. Variations have also been identified in the morphology of the capitate [5], triquetrohamate joint [6], and scaphoid [7], which also have an effect on the carpal motion.

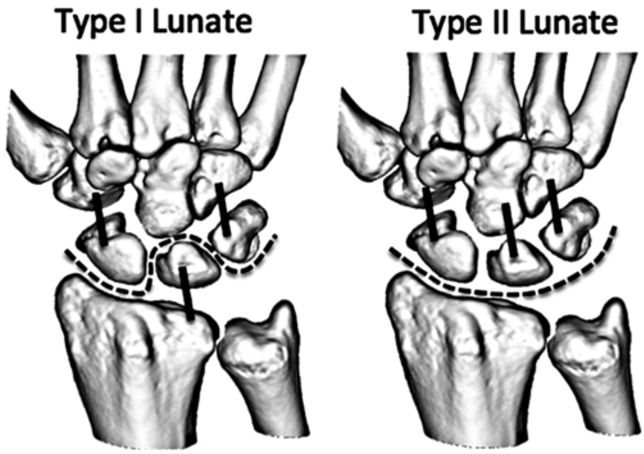

Fig. 8.2 Effect of lunate morphology on plane of motion during wrist flexion/extension. Note that the type of lunate morphology significantly affects the plane of motion of the wrist (*dotted lines*) and those joints with a restricted motion (*solid bar*). Reproduced from The Effect of Lunate Morphology on the 3-Dimensional Kinematics of the Carpus JHS (Am) 20154, Copyright G I Bain

Pathophysiology: Rheumatoid Arthritis at the Wrist

Rheumatoid arthritis (RA) is a common autoimmune disease characterized by synovial inflammation and hyperplasia, autoantibody production, cartilage and bone destruction, as well as many other systemic features. Although the exact cause is unknown, the pathogenesis has been well described.

Adrian Flatt reported that there are three stages in the rheumatoid process [8]:

1. *Synovitis*, which typically occurs at the sites of capsular attachments
2. *Destruction* of the periarticular cartilage, which is often at the bare areas and capsular attachments
3. *Deformity*, which is due to the osseous and ligamentous destruction

Synovitis

Synovitis occurs when leukocytes infiltrate the synovial compartment, causing a profound reorganization of synovial architecture and an expansion of synovial inflammatory tissue or pannus. The change in the architecture of the synovium, caused by complex change in immune-modulated signaling pathways and cytokines, eventuates in chronic inflammation of the joint. This causes a loss of the lubricating effects of the synovium and, together with the activation of fibroblasts, permits the growth of hyperplastic synovium or pannus [9]. The hyperplastic synovium is the major contributor to cartilage and joint damage in RA.

Joint Destruction

Cartilage

The joint destruction that occurs is a result of both chronic inflammation and mechanical forces. The normal wrist joint is a synovial joint with a negative pressure environment and well-hydrated articular cartilage. In RA, there is destruction of the articular cartilage at the pannus-cartilage junction. The cartilage is degraded by invasion of synovial cells and immune cells causing chondrolysis and collagen breakdown, frequently at the edge of the joint capsule.

Bone

Bony erosion also occurs rapidly in RA, affecting 80 % of patients 1 year after diagnosis [10]. The chronic inflammatory state results in hyperemia and increased bone resorption with increase in the activity of osteoclasts, without a compensatory increase in osteoblasts. Osteopenia and osteoporosis are later sequelae as the arthritis creates a painful joint, with disuse osteopenia, creating further bone loss. Areas of high contact pressure will develop bony eburnation and osteophytes, similar to degenerative osteoarthritis. These may result in sharp bone edges that may lead to joint capsule breach and tendon rupture. Examples include the Mannerfelt lesion and extensor tendon ruptures over the ulnar head.

Ligaments

The concept of "pseudo-laxity" is of major importance (Fig. 8.3). Pseudo-laxity occurs with a loss of the height of the articular cartilage, which creates a *relative* lengthening of ligament. This results in a greater and pathological range of movement and contributes to the joint instability and abnormal joint mechanics.

The expansive synovium also creates laxity of the *intrinsic and extrinsic ligaments* in the wrist, by both mechanical force and chronic inflammation. The growing pannus in the wrist joint puts mechanical strain on the ligaments, stretching them beyond the point of elastic compliance (elastic modulus). The chronic inflammatory pannus also degrades the ligaments directly by similar cellular mechanisms described above. Laxity of the ligaments in the wrist results in an altered and pathological range of movement about the joint, creating increased articular contact pressures and contributing further to degradation of cartilage and bone (Fig. 8.4).

Load and Articular Contact Pressure

In the rheumatoid wrist, there are also abnormal joint contact pressures and a loss of efficiency of synovial fluid. In a finite element analysis, Bajuri and colleagues simulated advanced RA wrist changes such as cartilage and bone destruction, dislocation, and carpal collapse and assessed the change in load born by the carpus [11]. The authors demonstrated a three times increase in contact pressures at all articulations and a loss of the uniform distribution of stress, owing largely to a loss of articular cartilage. They further stipulated that bony erosion contributed to the increased contact pressure, via articulation with sharper edges. This can be explained by the principle that a constant force (F) with a decreased surface area of contact (A) results in increased pressure (P):

$$P = F / A$$

Bajuri and colleagues also showed a shift in the load bearing of the wrist from the radius to the ulna as the carpus collapses and slides down the distal radius (Fig. 8.5). The alteration in load modeled by the authors is based on the common carpal deformities found in the RA wrist.

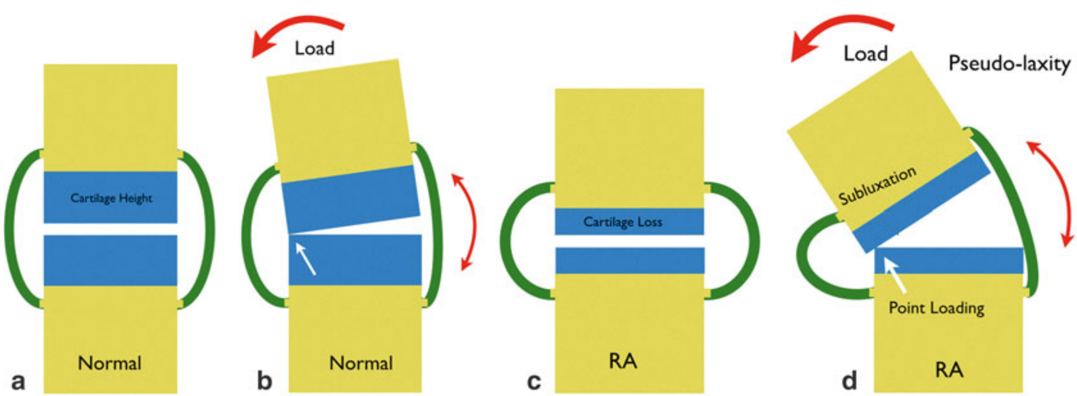

Fig. 8.3 Pseudo-laxity. In the normal joint (**a**) the articular cartilage height is seen as "joint space" on the X-rays. With loading (**b**) the joint will tilt until the collateral ligament is tight. In RA there is loss of articular cartilage (**c**), which is seen as "joint space narrowing" on plain radiographs. The collateral ligaments are the normal length but are relatively lax. With loading (**d**) the joint will tilt until the collateral ligament is tight. The loss of articular cartilage allows the joint to tilt further, which appears to be joint laxity (pseudo-laxity). Note the other effects including abnormal loading and a tendency to joint subluxation. Published with kind permission of © Dr. Gregory Bain 2015. All Rights Reserved

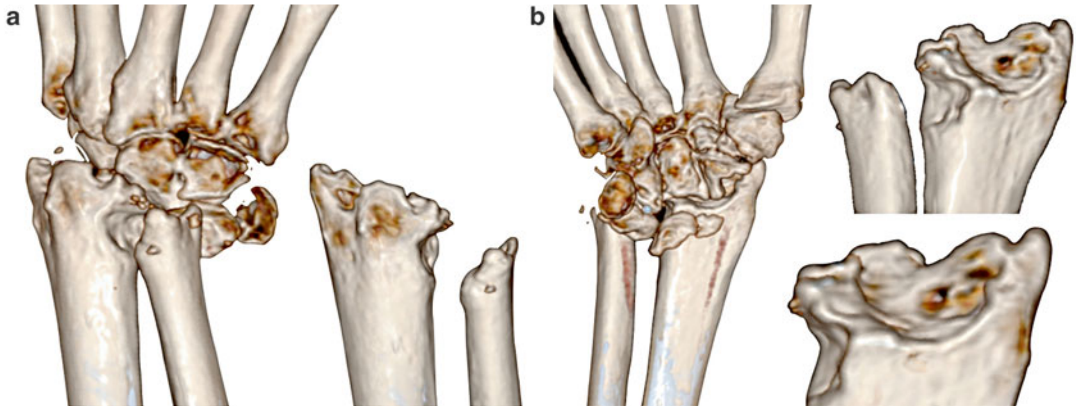

Fig. 8.4 Erosive arthropathy of the wrist. (**a**, **b**) Dorsal aspect of the wrist, demonstrating that the distal ulnar is dislocated dorsally and the carpus is dislocated in a volar, ulnar, supination, and proximal direction. Note the extensive erosion of the sigmoid notch. Published with kind permission of © Dr. Gregory Bain 2015. All Rights Reserved

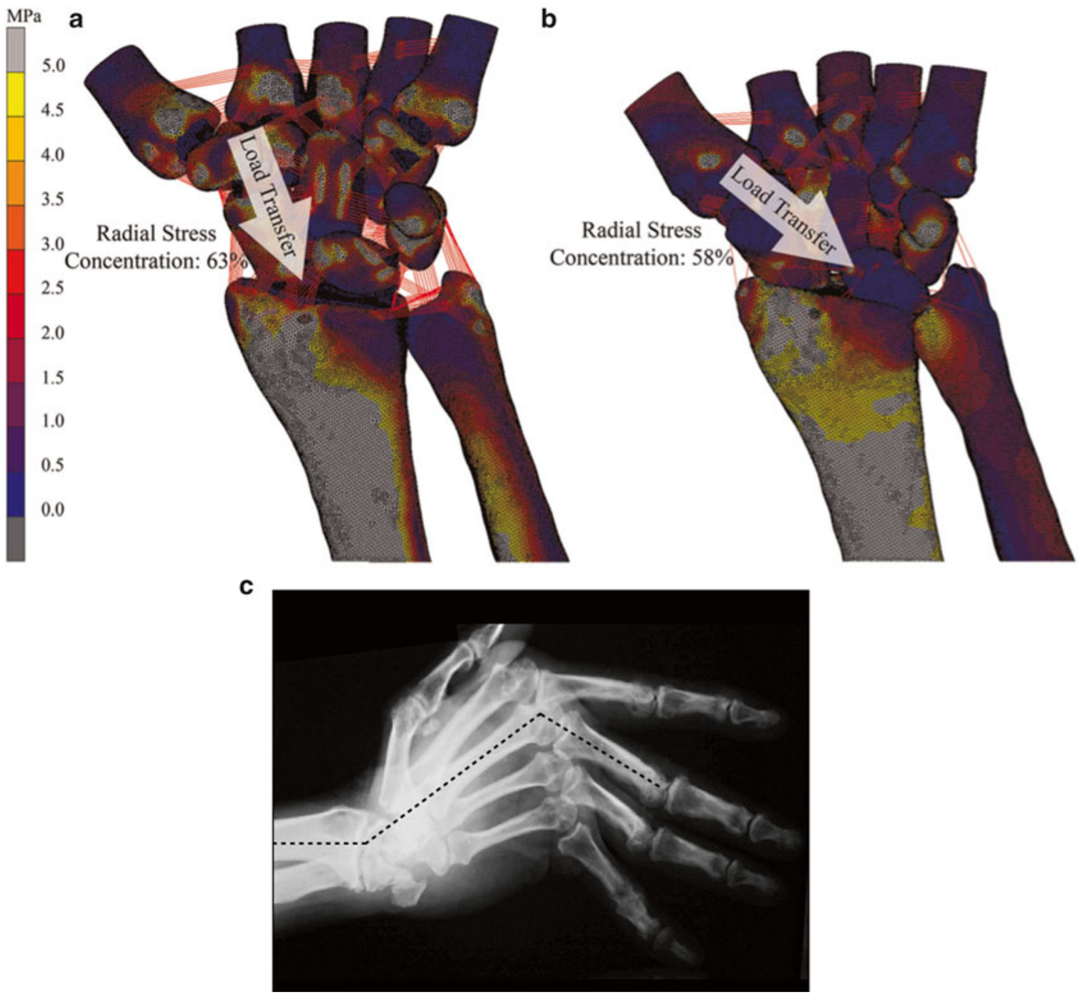

Fig. 8.5 Von Mises stress distribution for the palmar aspect of the (**a**) healthy model and (**b**) RA model (Used with permission from MN Bajuri et al. J Engineering in Medicine, 2012 [11]). (**c**) Characteristic "*Z*" deformity of the hand. Ulnar translocation and radial deviation of the wrist are commonly associated with ulnar drift of the fingers (Published with kind permission of © Dr. Gregory Bain 2015. All Rights Reserved)

Deformity

In the rheumatoid wrist, ligamentous laxity and destruction of articular cartilage and bone eventuate in joint instability and significant deformity. The most important factor in the deforming process is the laxity of ligaments. Of all the ligaments in the wrist, the loss of palmar and dorsal radiotriquetral ligaments and palmar radiolunate ligaments has been described as the most crucial [5].

Adjacent joints may compromise each other, producing a characteristic "*Z*" deformity (Fig. 8.5b). Ulnar translocation and radial deviation of the wrist are commonly associated with ulnar drift of the fingers. When performing multiple MCP joint arthroplasties in RA, we use the ECRL to ECU transfer as a prophylactic reconstructive procedure to correct the other side of the "*Z*" deformity, thereby reducing the incidence of recurrent ulnar drift deformity.

Radiocarpal Deformity

Due to the degradation of articular cartilage and ligamentous laxity, the carpus as a whole tends to translocate in the direction of the articular slope of the radius. The distal radius has a mean radial inclination of 24° and volar tilt of 11° [12]. Carpus tends to "slide" down the slope of the distal radius, which is potentiated by the force of the flexors and extensors of the wrist and fingers. Resultantly, the most common deformity is that the carpus translocates in an *ulnar*, *volar*, *supination*, and *proximal* direction [12, 13]. This carpal translocation may also result in tendon imbalance and leads to secondary deformity such as ulnar deviation of the fingers.

In the coronal plane, there is loss of the radiocarpal alignment with the carpus translocating in an ulnar direction. This deformity has been described to be due to destruction of the articular disk and the internal ligamentous structures of the radiocarpal joint [14]. The scapholunate ligament is prone to weakening from the synovitis, leading to flexion of the scaphoid and an increase in the scapholunate angle, promoting collapse of the radial column [15]. Unhinged from the scaphoid, the lunate translocates in a volar direction and dorsiflexes. Videos 8.1 and 8.2 show a patient with advanced rheumatoid changes of the wrist with volar, ulnar, and proximal translocation of the carpus. Video 8.1 demonstrates the laxity of ligaments at the wrist created by rheumatoid changes. Video 8.2 shows the pronounced effect of rheumatoid changes on the range of movement in the flexion/extension axis at the wrist.

These findings have been recently modeled using three-dimensional CT scan reconstructions. Arimitsu and colleagues studied carpal kinematics using three-dimensional CT scans of patients with advanced RA of the wrist [12]. They confirmed that the centroids (center of volume) of each carpal bone shifted in an ulnar, volar, and proximal direction along the slope of the surface of the distal radius (Fig. 8.6).

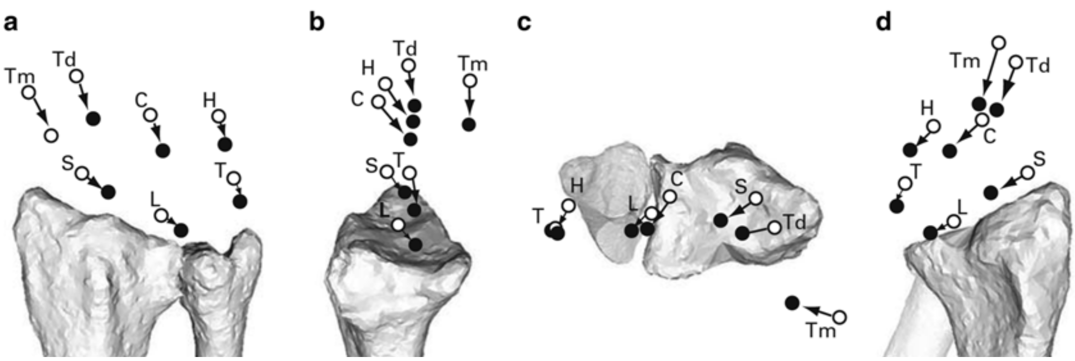

Fig. 8.6 Diagrams showing centroid translocation from (**a**) a dorsal view, (**b**) ulnar view, (**c**) distal view, and (**d**) radiopalmar view. All the centroids translocated in an ulnar, proximal, and volar direction (Used with permission from Aramitsu et al., J Bone Joint Surg Br. 2007 [12])

Distal Radioulnar Joint

The DRUJ is often the first compartment of the wrist involved in the rheumatoid process. The static restraints are the triangular fibrocartilaginous complex (TFCC) and interosseous membrane, and the dynamic restraints are the extensor carpi ulnaris (ECU) tendon and the pronator quadratus muscle. Destruction of the distal radius and the adjacent ligaments, and collapse and translation of the carpus, predispose to the *ulnar-carpal abutment*. The destruction of the TFCC by the synovitic process destabilizes the DRUJ articulation and causes the ulnar head to move dorsally [13]. The extrinsic stabilizers are inadequate to resist the natural collapse pattern, and what follows is the sequence of events leading to *caput ulnae syndrome* (Backdahl 1963) [16].

Video 8.3 gives some insight into the etiology of tendon ruptures. The sigmoid notch of the distal radius has a sharp hardened area of bone due to abnormal loading and erosion from the synovitis in the DRUJ.

As the forearm rotates, the sharp hard bone of the sigmoid notch sculptures the ulnar head, like a chisel sculptures wood on a lathe. Interestingly, it can be appreciated that as they push into each other, they subsequently sharpen each other. Once the ulnar head develops a sharp ridge around its head, it can then have an effect on other adjacent structures. In this case, as the forearm rotates, the sharp edge of the ulna head cuts through the dorsal capsule and then subsequently through the extensor tendons. It is our experience that tendon ruptures only occur with abrasion from sharpened bone (or metallic implants). Tendon ischemia and synovial invasion may weaken the tendon and predispose it to injury. But it is the sharp bone that divides the tendon.

Treatment of Rheumatoid Arthritis Wrist Deformity

Synovectomy

In the early stages of synovitis, prior to the development of significant destruction or deformity, a synovectomy can be a useful treatment option. Though the standard has been open synovectomy, which allows for inspection of all compartments and the extensor tendons, arthroscopic synovectomy is also being performed with success [17, 18]. The arthroscopic approach has the advantage of reduced joint capsule and ligament damage, allowing for earlier mobilization and reduced hospital stay [19]. It has been shown that if the procedure is performed before joint destruction occurs, the natural history can be improved, although disease progression can still occur [20–22]. Recent studies have demonstrated that there can also be benefits for patients who have later stages of the disease (e.g., Larsen stage III) [23].

Radiocarpal Joint

An intact midcarpal joint and localized pathology within the radiocarpal joint are common findings in the early stages of the RA wrist [24]. As we have seen, the carpus tends to translocate in proximal, volar, and ulnar directions, causing radial deviation of the radiocarpal joint. In these cases, partial wrist fusion may be beneficial to relieve pain and prevent instability and deformity, while maintaining a functional range of motion [25].

Radiolunate Fusion

Radiolunate (RL) fusion is a well-established technique that was developed from the observation that spontaneous radiolunate ankylosis will stabilize the joint, minimize further joint deterioration, and improve pain. Chamay and colleagues demonstrated that surgical fusion of the radiolunate joint served as a block to further carpal translocation [13]. Several authors have reported successful outcomes [26, 27], whereas others have reported a high incidence of radiolunate nonunion [13, 15]. A surgical prerequisite is that the adjacent joints (radioscaphoid and midcarpal) are free of disease. Unfortunately the radioscaphoid joint is often involved [25].

Radioscapholunate Fusion

If the radioscaphoid joint is involved in the inflammatory process, then a radioscapholunate (RSL) fusion is indicated. Like the RL fixation, an absolute prerequisite for RSL fusion is a functional midcarpal joint to maintain painless movement. The long-term outcomes of RSL fusion have demonstrated a high complication rate and a range of motion of 33–40 % of the normal wrist [28–31]. There is an increasing trend to perform a distal scaphoidectomy to increase range of movement at the midcarpal joint [31, 32].

Authors' Technique: RSL Fusion

In cadaveric studies, we have also demonstrated that excision of the triquetrum improves the range of ulnar deviation and extension [32]. We have also performed this technique in a clinical series with good results [33]. The excision of the triquetrum provides good bone graft for the fusion mass and minimizes the risk of ulnar-carpal impaction (Fig. 8.7).

The authors' technique is to debride the articulation between the distal radius and the reciprocal articular surfaces of the scaphoid and the lunate. Two 1.1 mm *K*-wires are advanced between the scaphoid and the lunate with the distal articulation in view, ensuring that it is perfectly reduced. *K*-wires are then passed from the proximal pole of the scaphoid and the lunate into the distal radius. This will often provide adequate stability but if there is concern, then pin plates or locking plates can be used. Cancellous bone graft harvested from the excised triquetrum and distal pole of the scaphoid is then packed around the fusion sites. Alternatively, memory staples may be placed between the distal radius and proximal pole of the scaphoid and between the distal radius and lunate to achieve a stable fixation with compression. Following the stabilization, the position is confirmed to be satisfactory with the aid of fluoroscopy.

Distal Radioulnar Joint

For patients with rheumatoid arthritis involving the DRUJ, there are several surgical options. The standard was traditionally the Darrach procedure, which is resection of the distal 1–2 cm of the ulna [34]. However, this is most often complicated by instability of the proximal stump as the TFCC is destabilized. Alternatives to the Darrach procedure include

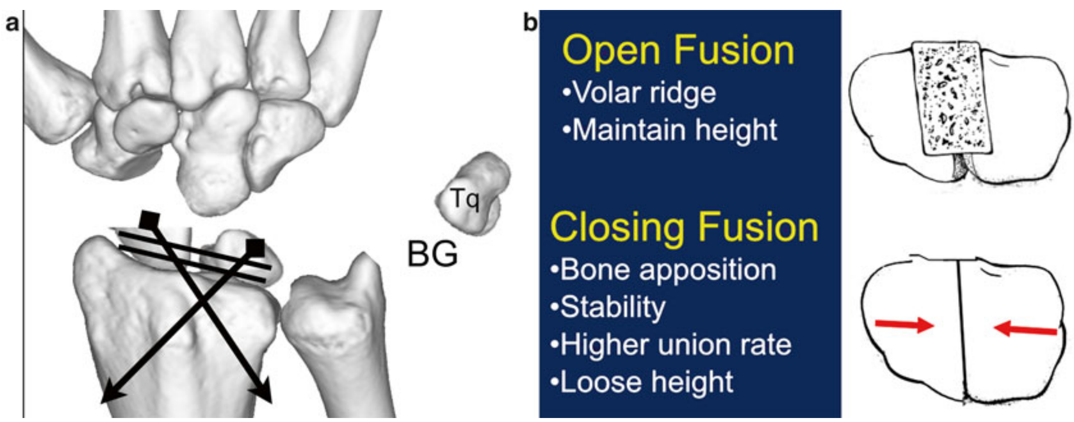

Fig. 8.7 (**a**) The authors' preferred technique for RSL fusion. The distal scaphoid excision increases radial deviation and flexion. Excision of the triquetrum increases ulnar deviation and extension, provides excellent bone graft, and prevents ulnar-carpal impaction. The scaphoid and lunate are anatomically reduced under direction vision and held with the 2×1.1 mm *K*-wires. The proximal row is then stabilized to the radius with cannulated screws or *K*-wires. (**b**) The authors utilize a closing fusion technique, as it provided greater stability, increases the contract area, and is therefore more likely to lead to a successful fusion (Published with kind permission of © Dr. Gregory Bain 2015. All Rights Reserved)

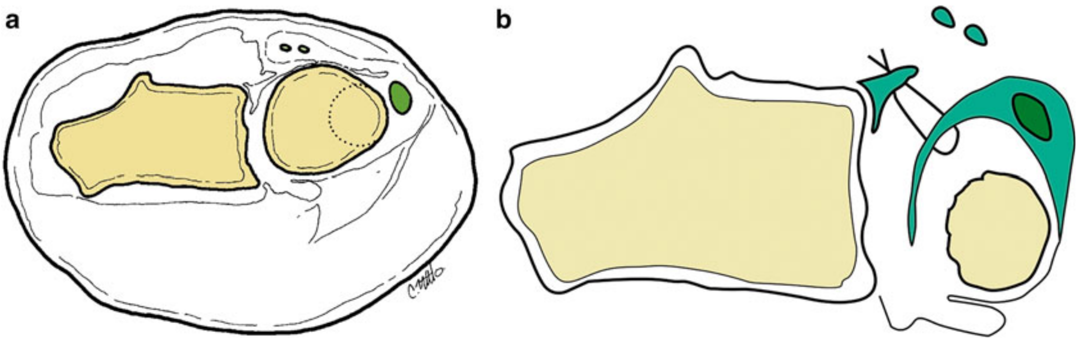

Fig. 8.8 Matched hemi-resection of the distal ulna. Note how the capsular-retinacular flap acts as an interposition and brings the captured ECU tendon over the top of the distal ulna to provide stability. From Bain, Roth et al. *J Hand Surg* 1995 [38], reproduced with permission

the hemi-resection techniques described by Bowers in 1985 and Watson in 1986 [35, 36]. These procedures seek to preserve the TFCC by resecting the ulnar articular cylinder while maintaining the shaft, styloid, and TFCC. If DRUJ instability is considered a problem, some surgeons prefer a Sauvé-Kapandji procedure, as it will stabilize the DRUJ. Unfortunately the instability will continue but is just transferred more proximally [37].

Authors' Technique: Matched Hemi-resection

For patients with rheumatoid arthritis involving the DRUJ, with an unstable and deformed distal ulna, the authors' preferred technique is the matched hemi-resection developed by the late Dr. Jim Roth [38]. The extensor retinaculum is divided over the fifth extensor compartment. The dorsal radioulnar joint capsule and the adherent infra-tendinous portion of the extensor retinaculum are divided 1 mm from their attachment to the sigmoid notch. No attempt is made to separate the dorsal capsule from the retinaculum, and the ECU is not removed from the retinacular flap. An oblique osteotomy of the distal ulna is performed and the distal ulna shaped to match the contour of the distal radius throughout forearm rotation. Care is taken to ensure that there is adequate resection and no impingement between the ulnar and radius and the ulnar styloid and carpus.

The joint is also examined with intraoperative fluoroscopy throughout supination and pronation. The ulnar-based retinacular flap is undermined from the adjacent ulna and tendons, allowing it to be mobilized and used as an interposition graft (Fig. 8.8). The technique helps to stabilize the distal ulna, as the ECU tendon is stabilized over the top of the distal ulnar stump. The ulnar-based retinacular flap is sutured to the 1 mm stump. The supra-tendinous portion of the retinaculum is repaired distally to prevent bowstringing of the extensor digiti minimi tendon.

Case Discussion: Arthroplasty of the Wrist

The case presented in Fig. 8.4 and Videos 8.1, 8.2, 8.3, 8.4, 8.5, 8.6, 8.7, and 8.8 is a complex total wrist arthroplasty case, as the long-term dislocation makes it difficult to reduce the new articulation. As a consequence, we set out to perform an arthroplasty, but if an adequate reduction could not be obtained, we would revert to an arthrodesis. To decompress the joint, we excised more of the carpus than usual and shortened the radius and ulna. We could then insert the trial prosthesis but it was tight, and the wrist had a fixed flexion deformity of approximately 20°.

After shortening of the radius by an extra few millimeters, excising of the volar wrist capsule, and fractional lengthening of the FRC and FCU, we were able to reduce the joint and obtain extension with the trial prosthesis in situ. We consider at that point an arthroplasty was a viable option,

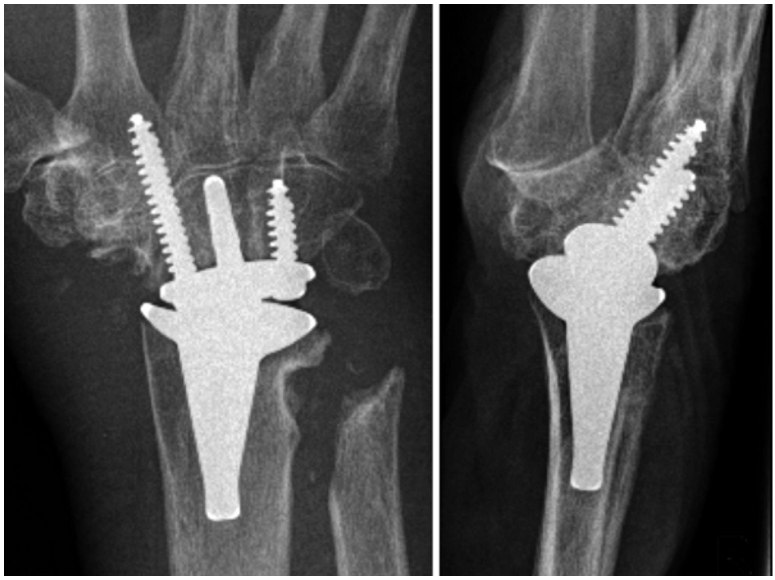

Fig. 8.9 Postoperative radiographs of total wrist arthroplasty. The radius and ulnar have been shortened and the anterior capsule excised with fractional lengthening of FCR and FCU, and the prosthesis is well seated in the radius. The wrist is maintained in extension until the soft tissues have stabilized. The distal ulna was managed with a matched hemi-resection

and a definitive prosthesis was inserted. The wrist could be extended to 20° but would naturally assume a posture in 20° of flexion. As the wrist had been in the flexion posture for some years, we were concerned that with the usual early active motion rehabilitation, she may never extend the wrist and be left with a permanent fixed flexion deformity. We therefore applied a volar slab and held the wrist in the extension arc for 4 weeks, followed by a resting extension splint at night for 3 months. She has subsequently maintained functional motion of the wrist (Fig. 8.9).

Case Discussion: Arthroplasty of the DRUJ

Arthroplasty of the DRUJ is beyond the scope of this manuscript; however, an interesting case worthy of discussion is a 35-year-old lady with RA who had painful dorsal instability of the DRUJ and attrition ruptures of the extensor tendons (Fig. 8.10a, b). The patient was still active, so an ulnar head replacement was preferred to a matched hemi-resection. However the dorsal sigmoid notch was eroded, so it would not contain the ulnar head. A dorsal sigmoid notch osteoplasty redirected the sigmoid notch, so that it would contain the ulnar head arthroplasty (Fig. 8.10c). The patient has maintained a functional range of motion.

Conclusion

The pathological process of rheumatoid arthritis in the wrist joint results in significant pain and loss of function. The chronic inflammation causes articular cartilage loss, pseudo-laxity, true ligamentous laxity, joint destruction, and deformity. Targeted surgical intervention can stabilize the joint, halt the progression of disease, and alleviate the symptoms, while maintaining an adequate range of motion.

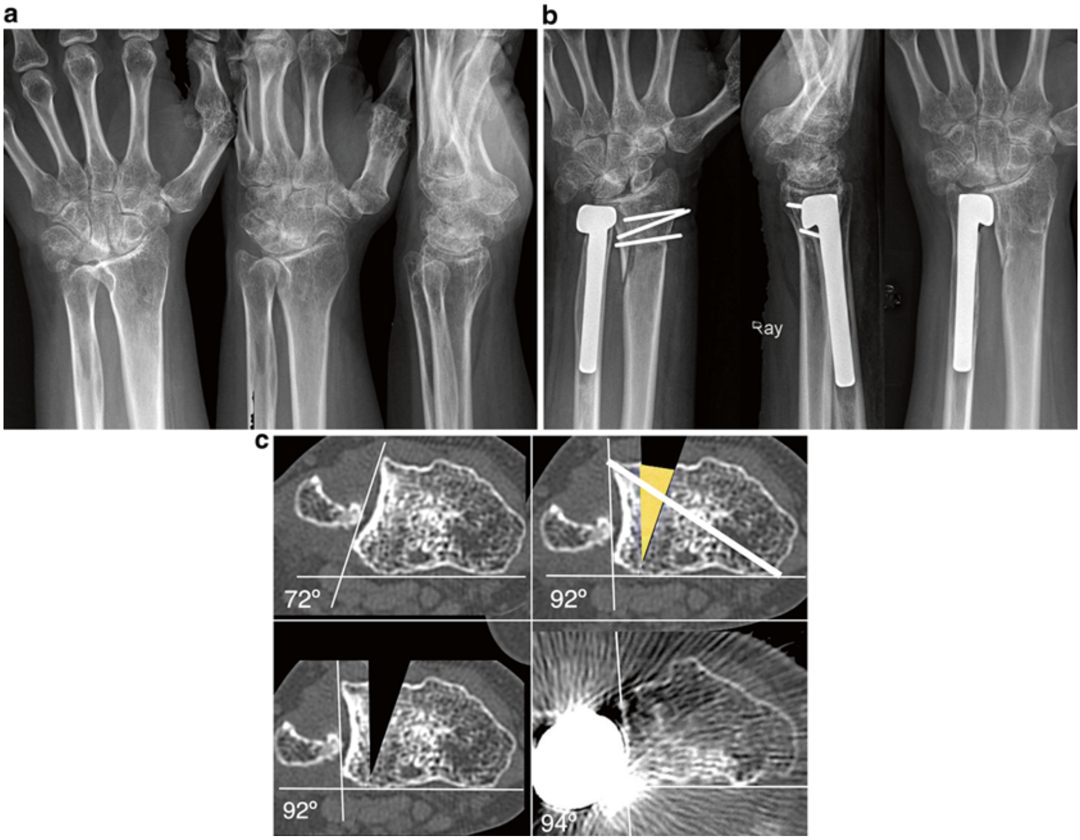

Fig. 8.10 Rheumatoid arthritis with advanced DRUJ destruction, managed with sigmoid notch osteoplasty. (**a**) At time of surgery, the dorsal aspect of the sigmoid notch was clearly eroded and would not contain the native head or a trial ulnar component. A dorsal sigmoid notch osteoplasty was performed with the aim of stabilizing the component. (**b**) The ulnar head arthroplasty is well contained due to the sigmoid notch osteoplasty. Note that on the lateral view the ulnar head is now reduced. (**c**) Sigmoid notch osteoplasty. (i) Preoperative CT scan with abnormal shaped sigmoid notch. (ii) The aim was to perform a 200 sigmoid notch osteotomy, to better contain the ulnar head. (iii) The osteotomy is supported with bone graft and stabilized with *K*-wires. (iv) Follow-up CT scan demonstrates that the osteotomy united and that the ulnar prosthesis remained stable. We have added the measured angles but do acknowledge sampling and interpretation errors. However the important point is that the osteotomy did unite and contained the ulnar head and allowed her to return to functional activities. Published with kind permission of © Dr. Gregory Bain 2015. All Rights Reserved

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