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Review Article

Total Wrist Replacement: State of the Art, Challenges and Pitfalls: A Comparative Review

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Abbreviations: TWR: Total Wrist Replacement; TWA: Total Wrist Arthrodesis; PPOA: Painful Pancarpal Wrist Ostoeoarthritis; DRF: Distal Radius Fracture; DASH: Disability of Arm, Shoulder and Hand; PRWE: Patient-rated Wrist Evaluation; ADL: Activities of Daily Living; DRUJ: Distal Radioulnar Joint; CMCJ: Carpometacarpal Joint; UHR: Ulnar Head Replacement; USO: Ulnar Shortening Osteotomy; PE: Polyethylene; UTW: Universal Total Wrist; TCMJ: Thumb Carpometacarpal Joint; SLAC: Scapholunate Advanced Collapse;SNAC: Scapho-nonunion Advanced Collapse; PROMs: Patient-reported Outcome Measures; PPO: Periprosthetic Osteolysis; PEEK: Polyetheretherketone

Abstract

Background: Total wrist replacement (TWR) as motion-preserving procedure continues to be critically discussed in the literature, although the complication rates have been significantly reduced with the current 3rd generation designs compared with older types. Possible reasons for this are often also a lack of knowledge about the currently available evidence, the complication management, and the lack of practical experience by the surgeons.

Methods: Based on an extended review of literature and own experience, the aim of this article is to give practicable insights for the clinician on: (1) biomechanical fundamentals, (2) differences in design, survivorship and functional outcome between the recent types, (3) possible pitfalls, and (4) failures and salvage options.

Results: The goal of TWR is that the overall wrist motion is maintained respectively improved despite it works with a locked midcarpal joint. Regarding survivorship and functional outcome the Maestro is (was) being superior over all other types that is (was) based on features in design. There is no scientific evidence as to why the Maestro was withdrawn from the marketplace by the company. For assessment of instability and/or impingement the use of dynamic radiographs is recommended. The problem of TWR is unchanged failure of the carpal components primarily based on mechanical dysbalance, and secondarily followed by metal and/or polyethylene wear, but surgical revision of asyptomatic periprosthetic osteolysis without safe radiagraphic signs of loosening is only required in not more than 20% of cases. For a failed TWR, revision TWR or conversion to total wrist arthrodesis are viable salvage options.

Conclusion: The knowledge about recent evidence and features in design of the available types, exact assessment of radiographic findings, presence of technical skills by the surgeons, and observance of the patient's expectations are the basic requirements for a successful TWR.

Introduction

Total wrist replacement (TWR) is the motion preserving alternative to total wrist arthrodesis (TWA) for the first-line treatment of painful panacarpal wrist osteoarthritis (PPOA) for both rheumatic and non-rheumatic conditions (post-traumatic, primary PPOA, Kienböck's disease, Gout), for the second-line treatment after a failed previously performed partial motion preserving procedure, for the first-line treatment of highly comminuted distal radius fractures (DRF) in single cases, and it can be useful as motion restoring procedure for patients who are unsatisfied after TWA and explicitly want wrist motion again (Figures 1-10) [1-14]. The goal of all modern 3rd generation TWR types (or 4th generation types if the Silicone implants are considered to be the 1st generation) compared to partial wrist fusion or proximal row carpectomy is the fact that wrist motion in summary is not impaired despite it works with a locked midcarpal joint [15].

Adams et al. [16] demonstrated impressively that in young healthy subjects limited wrist motion inevitably leads to statistically significant worsening of their ratings in Disability of Arm, Shoulder and Hand (DASH) and Patient-rated wrist evaluation (PRWE). In TWA patients, the lowest scores in activities of daily living (ADL) were found for perineal hygiene, using a screw driver, trouble using the hand in tight spaces such changing spark plugs on the family car, and followed by writing, drinking from a glass, turning a door knob, combing hair, and using a hammer (i.e. „dart-thrower's" motion) [17]. Nearly all patients with TWA after a failed TWR reported in mid- to long-term outcomes, if given the chance, they would have a procedure again which is able to maintain wrist motion [18,19]. A comparative study (TWR vs. TWA) at a mean-time follow-

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up of 68 months revealed that patients with TWR rated their self-reported outcomes significantly better than patients with TWA for both in DASH (29 vs. 38, p value 0.41) and PRWE (31 vs. 73, p value 0.01) [20]. Noted that not more than 60% of the maximum wrist capacity is needed to maintain functional wrist motion for ADL [21].

Limited or complete wrist or distal radioulnar joint (DRUJ) motion with or without pain is subsequently followed by impaired power and performance both in elbow and shoulder [16,22,23]. This pattern can be compensated by increased activities of trunk and shoulder muscles (upper trapezius and deltoideus) or using the other unaffected hand or both hands more often but over a not clearly known time [24-26]. The question is: are elderly patients with their age-related overall muscle degeneration able for this compensation mechanism, and if yes, how long, and what about the number of subsequently following functional disorders in elbow and shoulder in patients with longstanding impaired wrist motion?

The aim of this article content is to give practicable insights (tips and pitfalls) based on recent evidence and personal experience with the use of the ReMotion and Maestro implants over a period of 14 years.

Shortcomings and features in design

Historically, TWR utilizing older designs were associated with high complication rates especially due to mechanical failure of its carpal components, thus, it was mainly indicated for older patients with rheumatoid arthritis. With introducing of the recent 3rd generation TWR types Universal2 with it further development Freedom (Integra / Smith & Nephew, USA), ReMotion (stryker, USA) and both Maestro types with a higher modularity than the other implants (Zimmer Biomet, USA, withdrawn from the marketplace by the company in 2018) at the beginning of the 21st century the complication rates could be significantly decreased compared to the older types (0.1 - 2.9% vs. 0.2 – 8.1%), and there are no longer any significant differences compared to TWA (7% vs. 10%), but regardless of that TWA is performed nearly five times more frequently than TWR in USA [27-29]. Noted that Reigstad et al. [30] reported complication rates after first-line TWA with 60.5% at a long-term follow-up that is higher than previously assumed.

However, the main problem of the 3rd generation types is unchanged the long-term survivorship of its carpal component [6]. The simplification of the wrist by replicating contour and kinematics to a single radiocarpal articulation out of the physiological radio- and midcarpal joint leads to an unphysiological divergence between the center for extension-flexion and ulnar-radial deviation in the capitate that is followed by opposing rotational/translational contact pattern at the surface of both TWR components; and the circumduction ellipsis consisting of the coupled motion between the extension-flexion and ulnar-radial deviation arcs becomes smaller associated with the inability to obtain completely circumduction and the “dart thrower’s” motion as well as stress distribution like in a normal wrist [31-34].

The development of the semi-constrained resurfacing low-friction 3rd generation types (metal-on-polyethylene (PE) gliding), introduced by Menon in 1998 with the Universal total wrist (UTW) [35], with its anatomically shaped ellipsoidal articulations like a normal wrist and fixation of the carpal components with a central peg into the capitate (i.e. biaxial-anatomical) was the logical consequence in order to enhance stability compared to prior ball-and-socket types as well as to reduce the inacceptable high failure rate of the biaxial-physiological design (Biax). The Biax had an ellipsoidal articulation too but fixation of the carpal component with a peg into the 3rd metacarpal that often led to a breakthrough by the tip of the peg on the dorsal aspect [36,37]. The rationale behind this specific complication is the anatomically predetermined longitudinal/transversal concavity of the metacarpus/carpus to volar that makes the dorsal cortices significantly less resistant to long-lasting load peaks ("Wolff’s law" 1892: bone trabeculae were arranged in response to the stress lines resulting in bone reinforcement at the pressure side and bone resorption at the tension side) [38]).

If a TWR is being considered, pre-operative evaluation of concomitant injuries or disorders at the DRUJ and/or thumb carpometacarpal joint (TCMJ) should be done (Figures 1,2,6,8,9). It is recommended to preserve the ulnar head because it serves as a cantilever for the entire wrist [7,8,12,39]. If the ulnar head is removed, as commonly done for rheumatic patients, there is potential risk for instability of the entire wrist or a TWR [40-42]. Dislocation of a TWR was mainly a concern with the older types observed in up to 9% of cases, but it may also occur with the recent 3rd generation types by iatrogenic injury of the volar extrinsic stabilizers of the wrist (radioscaphocapitate and long radiolunate ligaments) or insufficient restoration of resection-related loss of carpal height potentially leading to ligamentous instability of the entire wrist (Figure 3), and a suggested instability can often only be verified under dynamic test conditions [1,43]. One disadvantage of the UTW and Universal2 was/is that the DRUJ can be mechanically compromised by the radial component, caused by the required oblique resection in ulnar direction at the joint surface for placement of it (in contrast to the ReMotion and Maestro), that often required an ulnar head resection. Noted as well that pre-existing pronounced ligamentous instability presented as volar dislocation of the wrist in rheumatic patients is to be considered as contraindication for TWR [44].

Regarding the placement of the two fixation screws for the carpal components there is a consensus in the literature that, in order to avoid micromotions at the screw-bone-interface as potential risk factor for loosening, the ulnar-sided screw should be placed only into the hamate whereas the radial-sided screw can be placed into the 2nd metacarpal with crossing the carpometacarpal joint (CMCJ) II [1]. This consensus is based on the predetermined joint anatomy which reveals a higher stability in the CMCJs II/III (i.e. stable amphiarthroses) compared to the CMCJs IV/V [45,46]. If a placement of the ulnar-sided screw into the 4th metacarpal would become necessary then the CMCJ IV arthrodesis should be considered with the use of bone graft. A potential advantage of the Maestro is (was) the possibility for use of a carpal plate involving a scaphoid augment associated with complete removal of the entire scaphoid that provides a stable support onto the bases of the trapez/trapezoid and may avoid the fusion of the surrounding carpal bones (Figures 1,3,6B1/2,10) [47].

In decision making TWR vs. TWA the patient’s expectations and experiences must be considered. Larsson et al. [26] found that living with unbearable constant pain and the desire to be free from it is the breakpoint for the patients to undergo extensive wrist surgery, and patients who had either a TWR or a TWA as a first-line treatment experienced more pain relief after surgery than patients who had undergone several previous

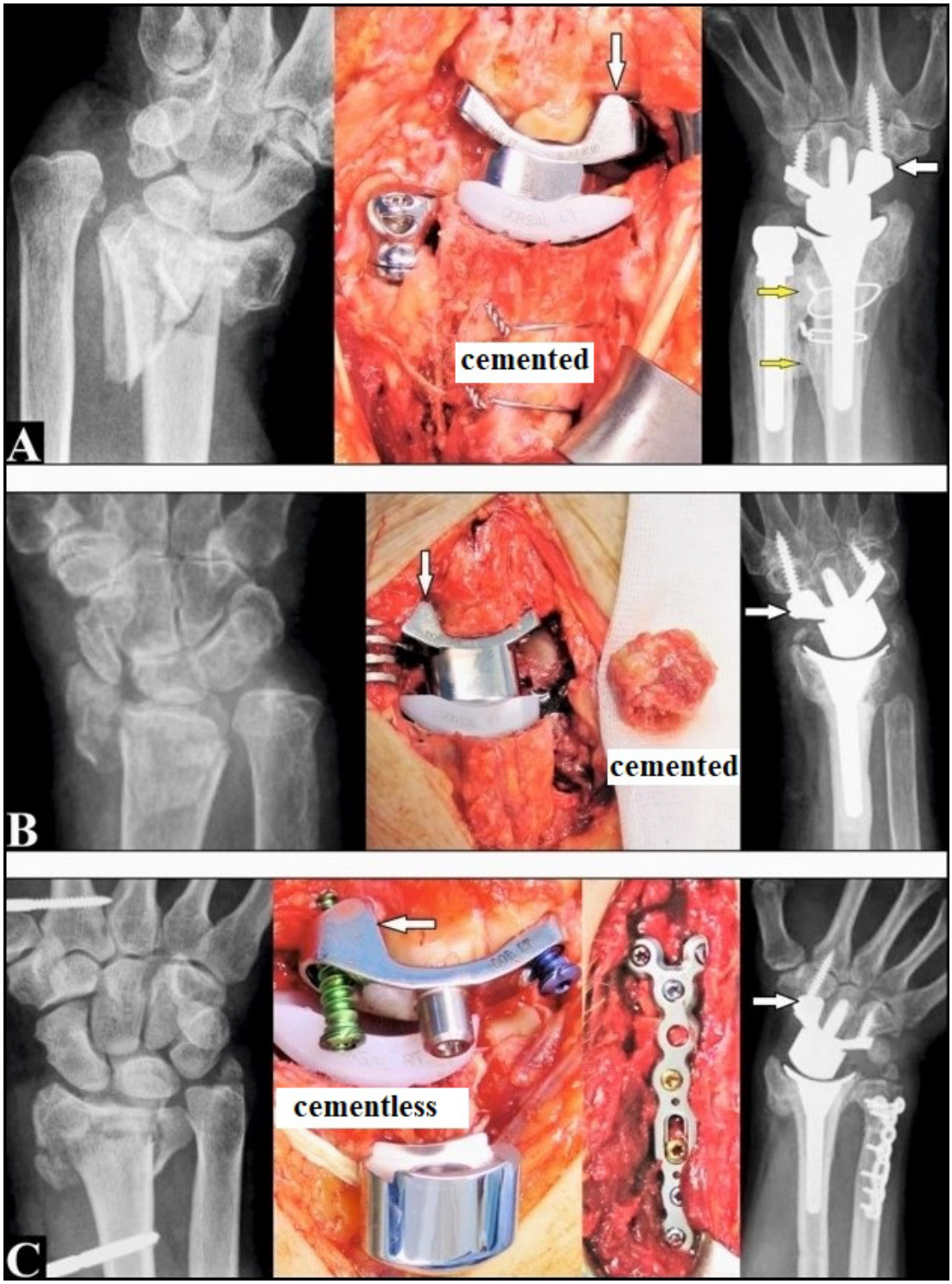

Figure 1. ***(All three patients received the 2nd Maestro type (locking screws for fixation the carpal components with scaphoid augments after removal of the entire scaphoid (white arrows) [14]):*** *(A) This 79-year-old female sustained a left highly comminuted DRF with pronounced impaction of the distal radius metaphysis associated with poor osteoporotic bone stock. The primary cemented TWR combined with ulnar shortening and a cementless UHR utilizing the uHead prosthesis was performed. The course was complicated by development of distal radioulnar synostosis (two yellow arrows) that led to restriction of the supination-pronation motion arc, the forearm was completely fixed in 90° neutral position. (B) This 84-year-old female sustained a right highly comminuted DRF with impaction of the distal radius associated with poor osteoporotic bone stock as well. The primary cemented TWR combined with the Darrach procedure was performed. (C) This 56-year-old male sustained a left highly comminuted DRF with impaction of the distal radius metaphysis associated with good bone stock. The primary cementless TWR combined with an ulnar shortening osteotomy (USO) utilizing a 2,5 mm locking titanium plate was performed. Note the locking green colored polyaxial and blue colored monaxial fixation screws for the carpal plate.*

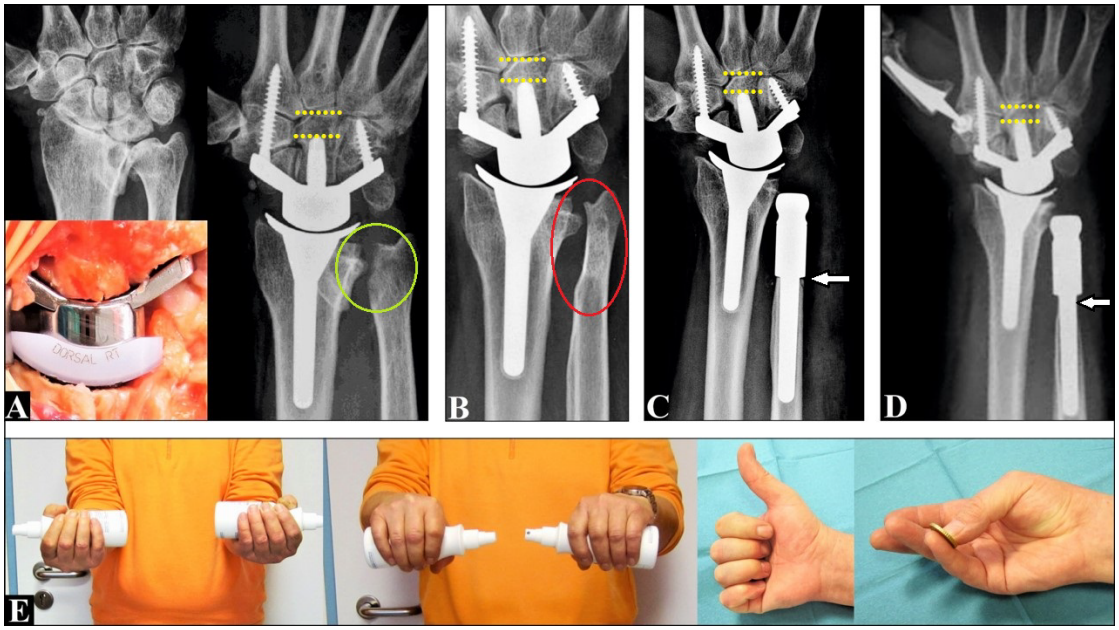

Figure 2. ***(55-year old male, right advanced stage of primary (or rheumatoid?) wrist and DRUJ arthritis [14], the further course is demonstrated in Figures 9A-E).:*** *(A) The primary cementless TWR utilizing the 1st Maestro type (non-locking screws for fixation the carpal component, a resection at the proximal pole of scaphoid was done and therefore, the carpal component has no scaphoid augment) combined with the ulnar head hemiresection (Bowers procedure, green circle) was performed. The two yellow pointed lines mark the distance between the tip of the capitate peg and the CMCJ III. (B/C) Three years after surgery, a painful convergence instability occured (red oval circle) that required a conversion to an UHR. The uHead prosthesis with a long revision stem was pressfit inserted on the top of the distal ulnar stump (white arrow). The carpal component of the Maestro implant was not subsided (two yellow pointed lines). (D) Five years after surgery, both implants were not loosened. Typically, asymptomatic PPO around the collar of the UHR was observed (steady state, white arrow), the carpal plate of the Maestro implant was unchanged not subsided (two yellow pointed lines), and an additional total TCMJ replacement with the Arpe prosthesis was performed six months after UHR. (E) At the 5-year follow-up, the patient was unchanged pain free and very satisfied with his functional outcome.*

wrist surgeries, therefore, surgeons might address the discussion about having one of both procedures earlier in the therapeutic management. Additionally, longstanding impaired wrist motion prior to TWA is associated with a better outcome after surgery than in patients with a short time of duration [26]. Furthermore, positive or negative thinking by the patients may have influence on their outcome after TWR or TWA, and this can be positively influenced by the surgeons giving accurate informations about the advantages and disadvantages of both procedures before surgery so that patients also feel like patients without medical knowledge and not like „colleagues of the surgeon“ [26]. Interestingly, in this study some patients undergoing TWA reported that the alternative of a TWR was never discussed before surgery suggesting that could be based on insufficiently available knowledge about recent evidence, personal experience and technical skills by the surgeons [26].

Outcomes and problems of TWR

Rheumatoid arthritis is the most common etiology of patients receiving TWR (71%), followed by post-traumatic conditions with 14% (scapholunate advanced collapse (SLAC) 6%, scapho-nonunion advanced collapse (SNAC) 4%, other 4%), other degenerative causes with 4%, Kienböck's disease with 2%, and 9% with not well specified causes [6]. Between 2001 and 2013 1,201 patients received a TWR in USA (National Inpatient Sample Database, ICD-9 code 81.73) with a female predominance (71%), 51.5% of them were aged 60+ years and followed by 25.0% in patients aged 50-59 years, and the majority of procedures (60.8%) were performed at urban teaching hospitals often regarded as academic centers of excellence, but the total numbers of procedures decreased by 26% annually [48]. The statistically significant decrease in frequency of arthroplasties (23%), arthrodeses (18%) as well as synovectomy procedures (39%) in particular in rheumatic patients was confirmed by a study from UK involving a total number of 1,109 wrist procedures (female to male ratio 4.9:1) between 1996 and 2009, and this is based on the effectiveness of the modern anti-rheumatic drugs, noted that only the total number of tendon surgery (21%) did not decrease significantly [49].

No reliable data exist on how a TWR can be exposed in vivo to maximum of load over a long time, therefore, in order to avoid PE wear and/or fracture, the mean age of patients who underwent a TWR with 58.3 years differs unchanged significantly to 52 years of patients who underwent a TWA ($p < 0.001$) [27]. Weiss and Akelman [50] advised their patients not to lift greater than 10 pounds in the hand which contains the total wrist implant from a safety perspective. However, there is a trend in the literature with encouraging results for detecting TWR in high-demand males with post-traumatic PPOA aged 52 years and younger if it exclusively wished by the patients and who are willing to accept the somewhat greater risk of revision surgery in the further course (Figure 7, Supplementary material: Videos 1-3) [51,52]. For this purpose, the use of dynamic or static orthotic devices imitating TWA during high-loaded occupational work can increase safety (Supplementary material: Video 4) [53,54].

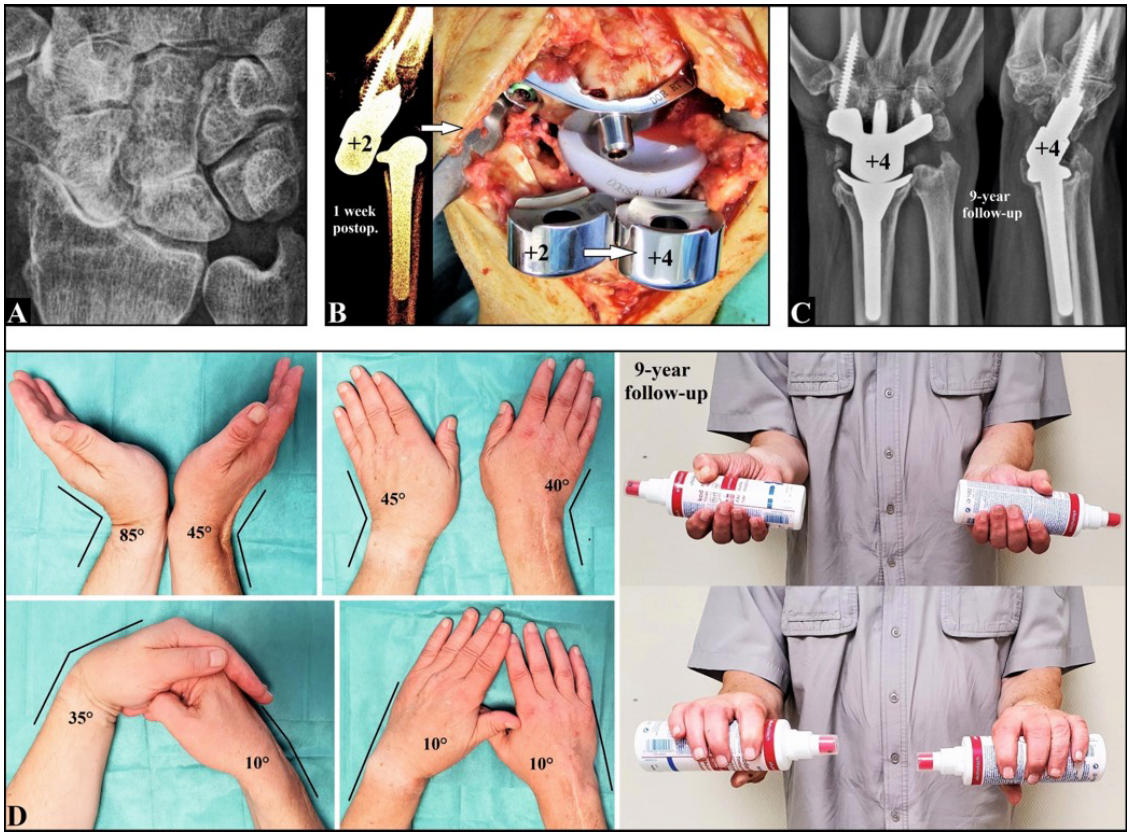

Figure 3 [14]: *(A) A 55-year old male presented with right advanced stage SLAC primarily treated by a cementless TWR utilizing the 2nd Maestro type. (B) One week after TWR, an atraumatic dislocation of the Maestro implant in volar direction occured despite immobilization of the forearm with a plaster splint. For improvement the resection-related loss of carpal height (longitudinal alignment), a revision with exchange of the primarily inserted carpal head size 2 to size 4 without the necessity of an exchange procedure of the entire carpal component was performed (white arrow, note that with the use of the 1st Maestro type the entire carpal component had to be replaced). (C) At the 9-year follow-up, the implant was unchanged stable and not loosened. (D) The patient is unchanged pain free and very satisfied with his functional outcome, but note the marked decreased flexion compared to his left unaffected wrist.*

Regarding the design there are some differences between the 3rd generation types. Both the Universal2/Freedom and the ReMotion work with an intercalated PE ball articulating in a metal cup of the radial components whereas the Maestro is (was) similiar to a small total hip replacement in which the distal metal head articulates in a proximal PE cup. However, the disadvantage of the Maestro is (was) that the PE insert is fixed to the radial body, and in case of PE problems the entire radial component had to be removed and/or exchanged requiring a large bony windowing although it is well osseointegrated with its porous titanium coated radial body (Figure 9B/C). An adjustment of the Maestro was made with the introduce of its 2nd type, for an exchange of the intercalated metal head the entire carpal plate no longer needed to be replaced (Figure 3).

Regarding survivorship (8 to 15 years) the Maestro is (was) with 95% superior over the ReMotion (90%) and the Universal2 (78%), and that can considered to be as result with the use of the 2nd Maestro type with locking screws for fixation of the carpal component in contrast to the ReMotion as well as the Universal2 (Figures 1,3-10) [29,44,55-58]. These results are absolutely comparable (or better) to those after total shoulder, elbow, and ankle replacements which are less debate in the literature. It remains to be seen whether recent reported encouraging short-term results with the Freedom (now with locking screws too) will be superior in mid- to long-term survivorship over the Universal2 [59]. Noted that the author of this article content has contacted the companies offering the ReMotion several times (stryker and Small Bone Innovations (USA) prior to stryker) to equip this implant with locking screws as well (and also with an additional 3rd larger intercalated PE ball for a better restoration of the resection-related loss of carpal height), but all requests remained unanswered.

The following outcomes are based on data extracted from three systematic review articles, and noted that for Patient-reported outcome measures (PROMs) the DASH and PRWE both have evidence of reliability, validity, and responsiveness for wrist pathologies [29,60-62]: Both TWR including all 3rd generation types and TWA are effective in reducing pain and improvement in DASH, and a poorer outcome in pain relief after TWR correlates with a poorer DASH. The DASH in patients with a TWR due to non-inflammatory disease is accompanied by a significantly better improvement than in patients with inflammatory disease ($p = 0.005$), but in QuickDASH no differences were found between rheumatic and non-rheumatic patients. The mean improvement in grip strength for TWR is 19% compared to preop., and no relevant differences were found compared to the unaffected contralateral wrist between TWR (58 – 72%) and TWA (50 – 79%). One study each revealed a return to work in 100% of patients with the Universal2 and 83% with the ReMotion, and no valid data exist about with the use of

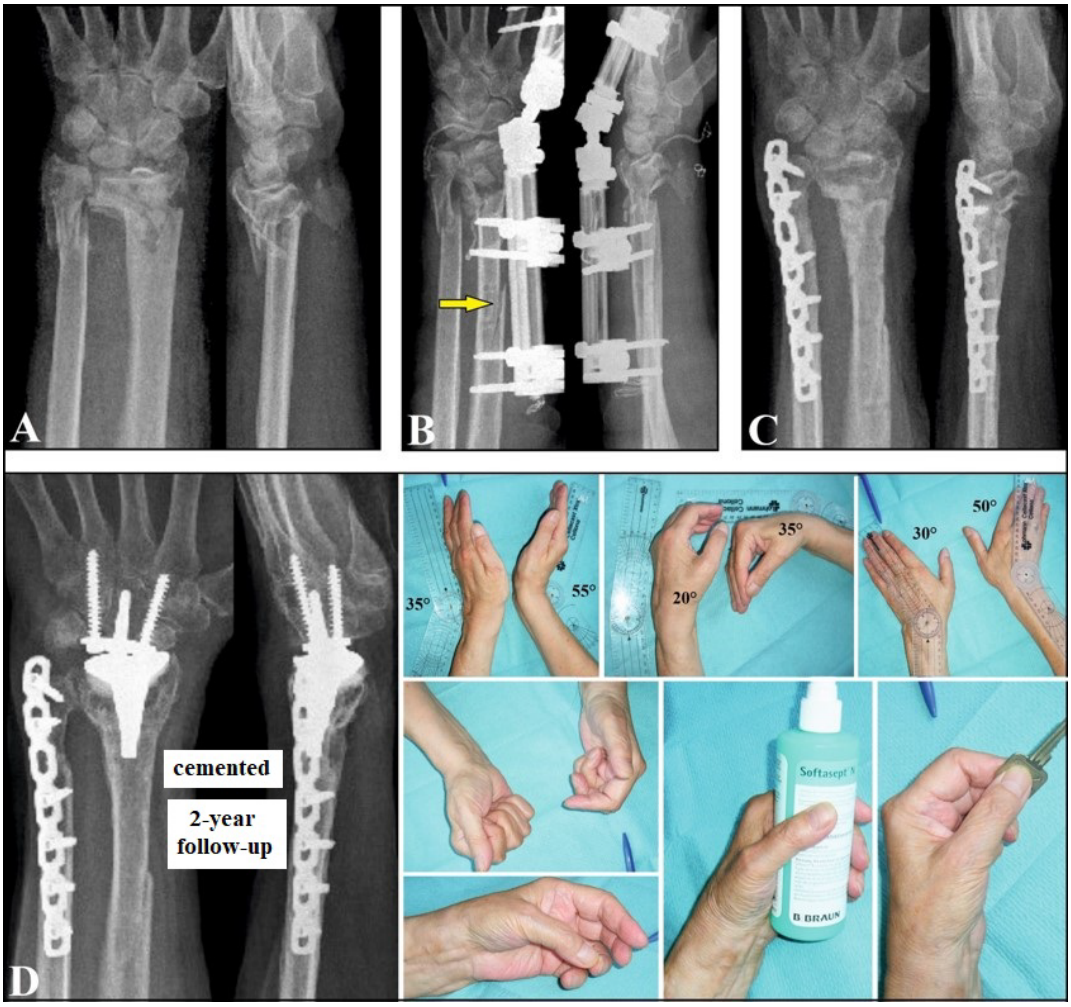

Figure 4. *(A) A 71-year-old female presented with a highy comminuted left distal forearm fracture associated with poor osteoporotic bone stock. (B) Primary external fixation was done. During the first attempt of external fixation an additional iatrogenic fracture at the radius shaft occured (yellow arrow) that required revision with re-placement of external fixation. (C) Six weeks thereafter, timely fracture healing was observed that makes the cemented TWR utilizing the ReMotion implant possible. (D) At the 2-year follow-up there was unchanged a correct positioning of the ReMotion implant without any signs of loosening, and the patient is unchanged pain free and very satisfied with her functional outcome.*

the Maestro but it was reported in a single case on a 31-year-old male with high claims in work and leisure [52]. Noted that a return to work in younger patients (average age 41 years, range 24-63) received a first-line TWA is achieved in 65% of cases only [17].

The functional outcome shows substantial differences between the implants with the Maestro being significantly superior to both the Universal2 and ReMotion in summation, and the following data were extracted from seven studies with a total number of 334 patients (mean differences pre- to postop.) [15]: (1) extension is improved for all implants (Universal2 +7.6°, ReMotion +5.8°, Maestro +16°), (2) flexion is equal with the Universal2 and detoriated for both the ReMotion (-4.1°) and the Maestro (-6°) (Figures 3,5B1/2 and 7), (3) ulnar deviation is improved for all implants (Universal2 +3.5°, ReMotion +4.1°, Maestro +11°), and (4) radial deviation is deteriorated for both the Universal2 (-4.1°) and ReMotion (-1.8°) whereas improved only with the Maestro (+5.5°). Both biological and design-related issues must be considered as reasons for the deterioration of flexion for all implants: (1) scarring around the large dorsal incision accompanied by loss of elasticity of the wrist capsule [3], and (2) the radial components of all implants with its straight offsets perpendicular to the longitudinal axis of the radius shaft do not obtain the anatomical volar tilt of the articular surface in the sagittal plane (Figure 5B1) [14,63]. The deterioration of wrist motion in opposite direction to the surgical incision due to scarring of the wrist capsule is a concern and also known from surgery of dorsal or volar wrist ganglions, and volar plating for treatment of DRF [64-66]. With regard to the known biomechanical findings about coupled wrist motion in TWR, the expected restriction of circumduction as well as the „dart-thrower's" motion is clinically often only of secondary relevance with our patients, and if slightly deteriorated, mostly not perceived as impaired by them (Supplementary material: Videos 1, 5-7, 9-11). But noted that an overall deteriorated flexion may have negative influence for "dart thrower's" motion towards to flexion-ulnar deviation alone (Supplementary material: Video 8). The rationale behind our clinical observation is that for performing the most important and frequent ADL only or less than 60% of the total wrist motion capacity is required, and, in contrast as prior assumed, the radiocarpal joint seems to be able to compensate the „dart thrower's" motion if the midcarpal joint is locked [21,67]. Additionally, the intercalated

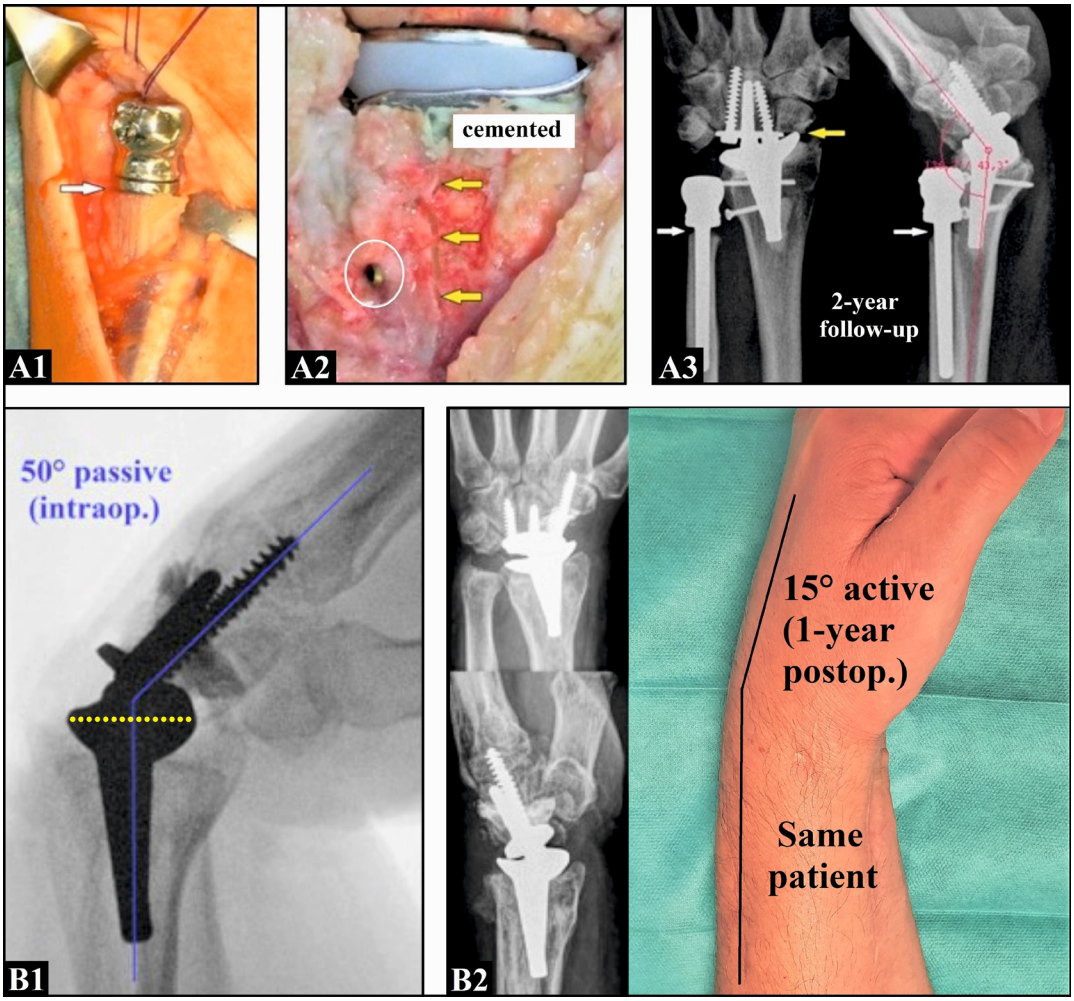

Figure 5. *(A1-3) A 62-year-old male presented with advanced stage of left SLAC and concomitant DRUJ arthritis, primarily treated by an UHR. The uHead prosthesis was pressfit inserted on the top of the distal ulnar stump (white arrow, A1). The UHR was followed by TWR six months later. During primarily cementless placement of the ReMotion implant with standard horizontal resection at the scaphoid, a large longitudinal periprosthetic fracture at the dorsal aspect of the distal radius metaphysis occured (yellow arrows) that required revision with a cemented replacement combined with a osteosynthesis using two 3.5 mm titanium compression screws (white arrow, A2). At the 1-year follow-up, an uneventful course was observed, but note the PPO around the collar of the uHead prosthesis (white arrows) and the impingement between the radial ReMotion component and the distal part of scaphoid after standard horizontal resection (yellow arrow, A3). (B1-2): Intraoperative dynamic fluoroscopy of a ReMotion implant (sagittal plane) demonstrating a possible passive flexion of 50° after all, note that the offset of the exactly aligned radial component is perpendicular to the longitudinal axis of radius shaft (i.e. no volar tilt like in a normal wrist) and the carpal component is exactly aligned to the 3rd metacarpal-capitate axis as well (yellow pointed and blue lines) (B1). Same patient at the 1-year follow-up, the active flexion is marked decreased to 15° only (B2)..*

carpal ball of the ReMotion can rotate 10° relative to the carpal component providing equivalent midcarpal joint motion as mentioned by the developer (Supplementary material: Video 12) [68].

The deteriorated radial deviation with the ReMotion manifests itself clinically with a painful radial impingement between the offset of the radial component and the scaphoid in both for the standard straight horizontal resection and an additional diagonal resection potentially leading to bony erosions into the distal part of scaphoid, and this can be avoided with removal of the entire scaphoid only (Figures, 5A3, 6A, 7D and 8C) [7,69]. Painful radial impingement is also observed after proximal row carpectomy, therefore, the ReMotion with it only available two intercalated PE balls is obviously not able to restore completely the resection-related loss of carpal height [15]. Noted that this impingement is often only detectable radiographically with the use of dynamic radiographs (terminal range of radial deviation) and not with a wrist held in static neutral position (Figure 6A). However, when the entire scaphoid is removed then the proximal part of the radial-sided fixation screw is not bony wrapped, and this must be considered as potential risk factor for mechanical failure. Froschauer et al. [70] reported about encouraging results with 21 patients (22 wrists) received a TWR with the ReMotion primarily combined with proximal row carpectomy and radial styloid resection, and at a mean time follow-up of 5.5 years radial deviation had improved from 10° to 15° (postop.) but there were still three special complications (13.7%, one case with subsidence of the carpal plate / two cases with screw breakages). With regard to this follow-up, it must be noted that the survivorship of all 3rd generation types is 90 - 100% at 5 years in most series, but it declines from 5 to 8 years [6]. Noted

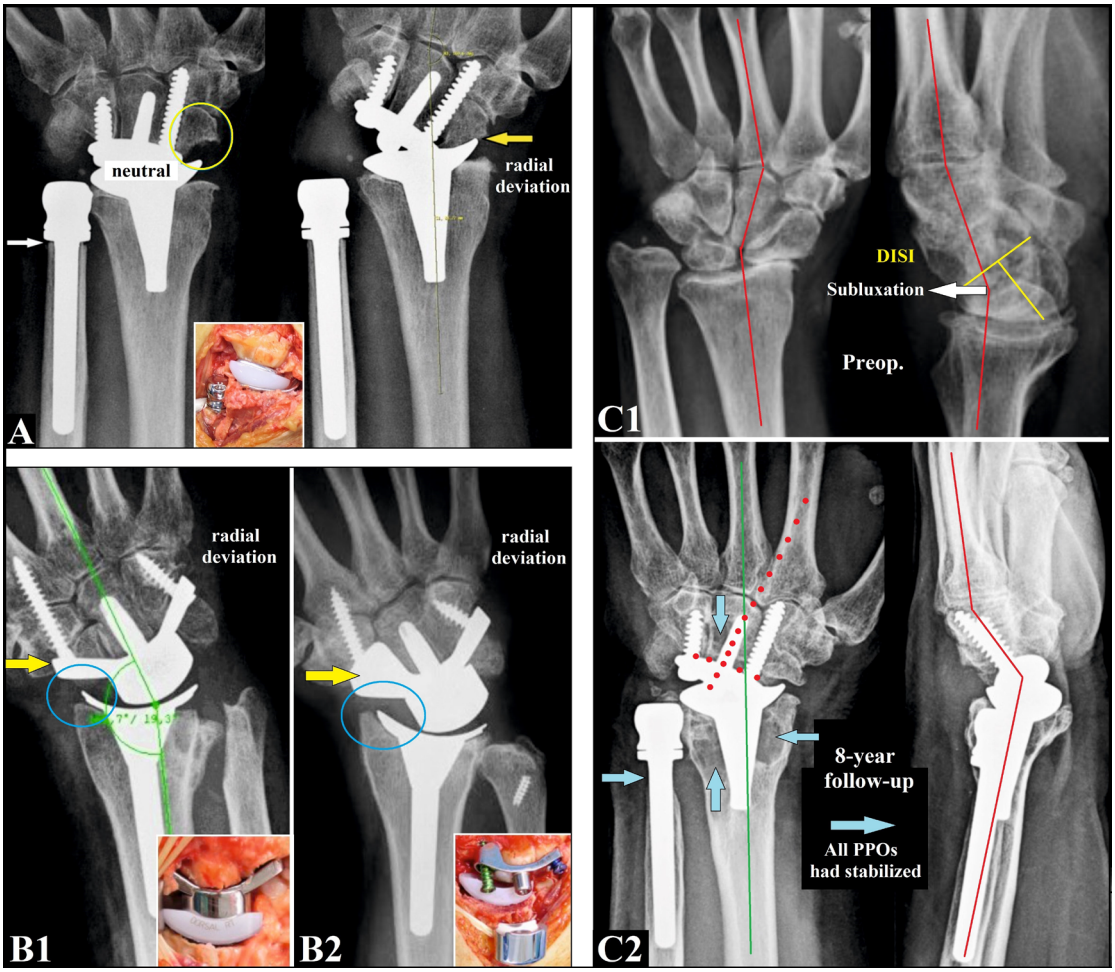

Figure 6 [14]: *(A) This 59-year-old female presented with left distal radius physeal arrest after a DRF with age of 11 years received primary combined replacements. The uHead prosthesis was pressfit inserted on the top of the distal ulnar stump (white arrow). Despite additional diagonal resection at the scaphoid a painful impingement between the radial ReMotion component (cementless) and the sacphoid with terminal range of radial deviation was observed (yellow arrow). Note the straight horizontal design of the carpal component. (B1-2) The radiograph of a 1st Maestro type (without a scaphoid augment, yellow arrow) showing no impingement with terminal range of radial deviation (yellow blue circle, B1), same situation with a 2nd Maestro type with scaphoid augment, note the concave to distally curved design of the carpal components for both types (B2). (C1-2) Same patient as in (A), the preoperative radiographs showing advanced stage of post-traumatic arthritis due to a pronounced carpal malalignment (Z-deformity, red lines) with marked dorsal intercalated segment instability (yellow lines) followed by fixed subluxation of the capitate against the lunate in dorsal direction (white arrow, C1). At the 8-year follow up, all PPOs had stabilized (steady state, yellow blue arrows). Note that the Z-deformity could be corrected in the frontal plane only by an incorrectly aligned carpal plate (green and red pointed lines, compromise solution) but not in the sagittal plane (red lines). The patient is unchanged pain free and very satisfied with her outcome, however, the persistent deformity must be considered as potential risc factor for mechanical failure of the carpal component (C2). This case was formerly published in 2014 at a 1-year follow-up [7].* ***Supplementary material: Videos 5 and 6 demonstrate well functioning circumduction and „dart thrower's" motion at the 9-year follow-up.***

as well that a radial styloid resection should be performed only distal to the origin of the radioscaphocapitate ligament (i.e. level A) to avoid instability of the wrist presented as radial wrist pain and/or ulnar carpal (prosthetic) dislocation tendency [52,71,72]. A novel approach in order to enhance the stability of the radial-sided screw could be cement augmentation of it. The background of this modified concept is the improvement of its pullout strength that has been prior well established for use at the spine, and for treatment of proximal humeral as well as intertrochanteric femoral fractures in the elderly [73-75]. For TWR only in a single case report at a short-term follow-up was reported about that in the literature ("off label" use), and further studies are needed to validate this concept (Figure 7) [76]. If the deteriorated radial deviation with the Universal2 / Freedom is also accompanied by a painful radial impingement is unknown to the author of this article content. The improvement of radial deviation with the Maestro is (was) considered to be as design-related advantage. In contrast to the ReMotion with it straight horizontal offset of the carpal component (also with the Univeral2 and Freedom), the offset of the Maestro is (was) concave to distally curved and the option for use of three intercalated metal heads allows a better restoration of the resection-related loss of carpal height (Figure 6).

Despite the superiority of the Maestro in terms of design with it high modularity, survivorship and functional outcome over the other types, this implant was surprisingly withdrawn from

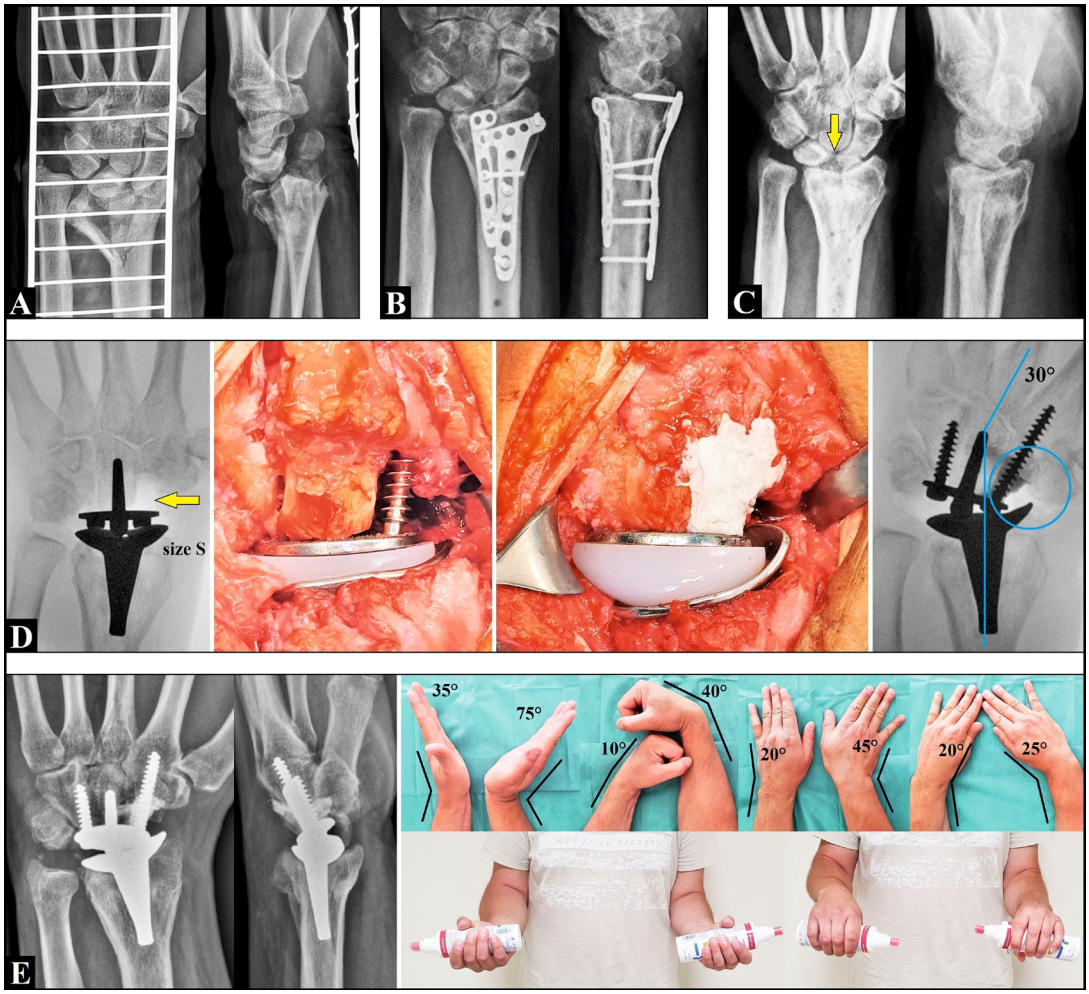

Figure 7. ***(primarily published in [76], Copyright Ingo Schmidt):*** *(A) A 39-year-old male presented with a left fracture-dislocation injury after a fall from height. (B) Primary treatment by open reduction and internal fixation (dorsal and volar plating). (C) One year after injury, a ponounced post-traumatic arthritis developed, both plates were removed, note the primarily overlooked scapholunate dissociation (yellow arrow). (D) Intraoperative fluoroscopy and clinical photographs showing the correctly inserted ReMotion implant after removal of the entire scaphoid (yellow arrow), cement augmentation of the not bony wrapped proximal part of the radial-sided fixation screw, and no impingement with terminal range of radial deviation (yellow blue circle and lines). (D) At the 1-year follow-up there was unchanged correct positioning of the ReMotion. Despite the marked decreased flexion compared to the right unaffected wrist the patient could be re-employed in his high-demand occupation as a mechanic.* ***Supplementary material: Videos 7 and 8 demonstrate well functioning circumduction at the 2-year follow-up whereas „dart thrower's" motion is deteriorated towards to flexion-ulnar deviation but not towards to extension-radial deviation that is based on the overal marked decreased flexion and ulnar deviation****.*

the marketplace by the company in February 2018 before the upcoming new CE certification worldwide. Zimmer Biomet stated officially that the Maestro was approved only for its cemented use by the US Food and Drug Administration and there were no publications in the literature about favorable results with it cemented use, and so, it cannot be guaranteed the surveillance of this implant if it inserted in a cementless manner (i.e. "off label" use). This statement is incomprehensible and contradicts any scientific knowledge. All 3rd generation types have porous titanium coated radial stems in order to induce a sufficient osseointegration (Figure 9B/C) which is absolutely comparable with all modern total hip replacements. There is a consensus in the literature that primary cementation is detected only in cases with poor osteoporotic or rheumatoid-related bone stock, periprosthetic fractures, revision TWR, and for the use of custom-made implants for treatment of large tumors at the distal radial metaphysis such the giant cell tumor (Figures 1 A/B and 4) [1,2,5,6,10,13,44,77]. Moreover, a sufficient cementation of the carpal components with all 3rd generation TWR types is factually not possible. The cement placed into the small drilled holes would inevitably squeezed out when the capitate peg and the fixation screws are inserted. And now all surgeons have explanation miseries to their patients if a Maestro has been failed (a question to the author of this book chapter by a patient of him: „Doctor, why did I get a bad prosthesis implanted?"). For those cases the conversion to TWA is probably the only salvage option of choice [43]. Due to the required design-related deep metaphyseal insertion of the radial body with the Maestro, a motion-preserving revision TWR utilizing the ReMotion or Freedom with its shorter radial stems without the opportunity for a pressfit insertion into the diaphysis appears to be impossible or at least very questionable by a supporting filling off the deep cavity with cement. Interestingly, Zimmer Biomet offers unchanged the Taperloc hip prosthesis for use

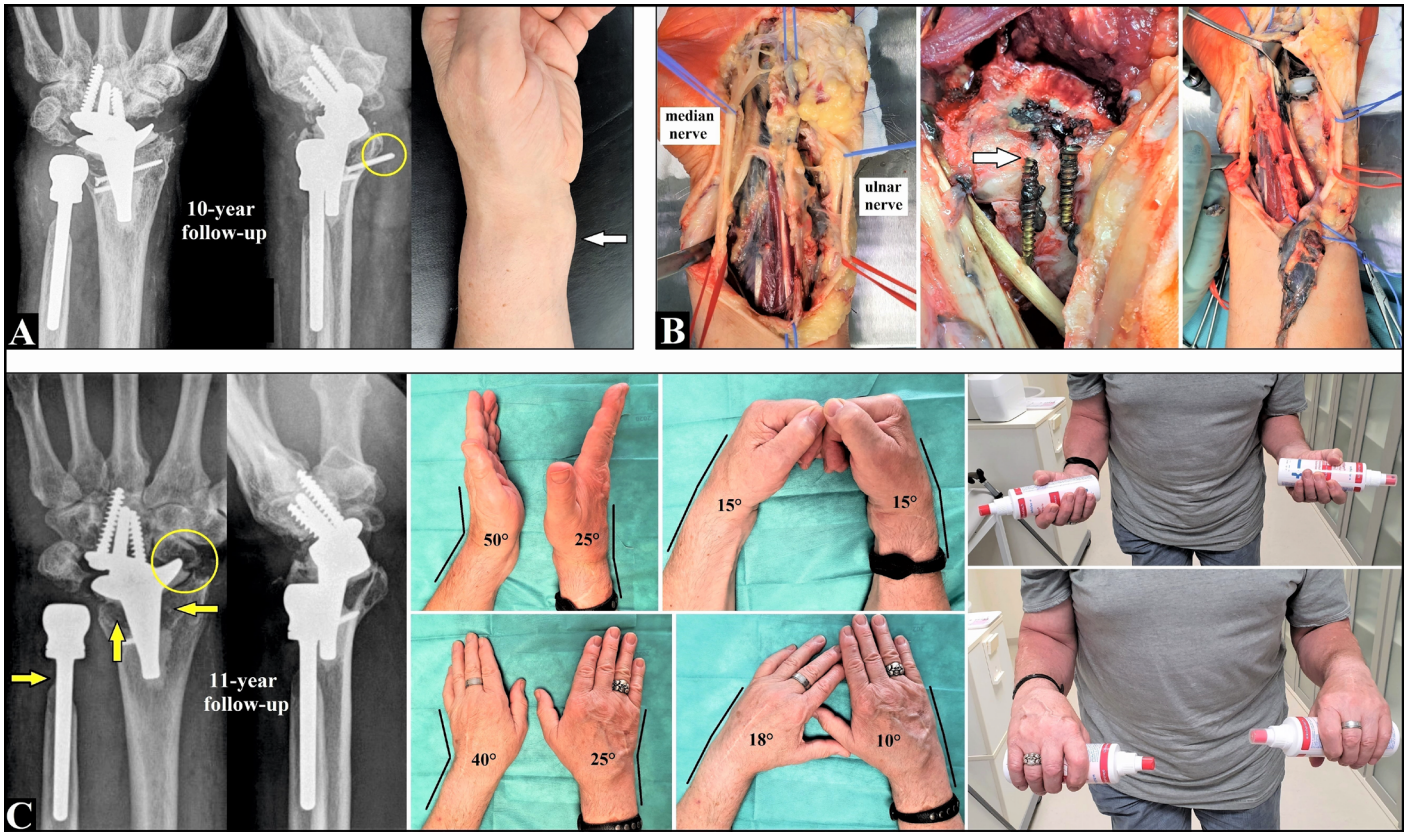

Figure 8. ***(Same patient as in Figures 5A1-3, now the 10-year follow-up, primarily published in [76], Copyright Ingo Schmidt):*** *(A) Migration of one screw to volar (yellow circle), painful swelling at the volar aspect of the wrist (white arrow), both ReMotion components are not loosened. (B) Massive metallosis originating from the holes of the non-locking fixation screws of the carpal component, the two 3.5 mm titanium compression screws were loosened within the PPO and one of them was broken (white arrow, this screw head could not be removed), a radical soft tissue debridement was done. (C) One year after revision there was no recurrence of metallosis. Both ReMotion components are unchanged not loosened, note the stabilized PPO around all implants (yellow arrows) and the marked radial impingement that led to a erosion into the scaphoid (yellow circle). The patient is unchanged pain free and very satisfied with his functional outcome.* ***Supplementary material: Video 9 demonstrates well functioning circumduction at the 11-year follow-up.***

only in a cementless manner, and this prosthesis with it porous titanium coated trochanteric part has an absolutely comparable stem design for osseintegration like the Maestro [78]. Therefore, it must be suggested that the Maestro was no longer profitable for the company [43,44,79].

Failure of TWR and salvage options

Historically, metallosis was found to be the most important cause for loosening with the metal-on-metal gliding implants [42]. However, it is also be observed in individual cases with the use of the 3rd generation types caused by micromotions at the interface between the (non-locking) fixation screws and the bone with or without loosening of the carpal components (Figures 8 and 9), impingement between the carpal plates and the surrounding carpal bones often presented primarily as carpal tunnel syndrome, or impingement between the radial TWR component and an additional UHR with a metal head [56-58,76, 80-83]. Recently, there is a consensus in the literature that the main cause for a failed 3rd generation type is mechanical imbalance of its carpal components, and secondarily followed by metallosis and PE wear (Figure 9) [32-34,58,63]. The predetermined mechanical imbalance can be amplified by an unstable inserted TWR potentially leading to screw loosening and/or breakage, and if the capitate peg cannot be correctly aligned along the straight longitudinal 3rd metacarpal-capitate line as the central axis for load transfer through the wrist observed in cases with chronic post-traumatic carpal malalignment (Figure 6C1/2) or progression of ulnar deviation in the CMCJs II-V due to the illness- or drug-related ligamentous insufficiency in rheumatic patients [7,43,84]. Furthermore, inexperienced surgeons who would like to start with TWR need assistance for their learning curves. Ocampos et al. [85] reported about the success rate of 14 surgeons in their first cases with the ReMotion, and in all cases the carpal components were failed inserted in all directions and most frequently as well as most clearly with 10.1° (mean, range 2 – 21°) outside the 3rd metacarpal-capitate axis of the capitate peg in the sagittal plane dorsally (Figures 5B1 and 6C1/2). Noted that it has been determined for the Biax that each degree with a failed dorsally angulated insertion of the capitate/3rd metacarpal peg was accompanied by a 17% increase in the risk of a required revision [36].

PE wear after loosening of the non-locking fixation screws observed with the 1st Maestro type revealed two different patterns (Figure 9) [58]: (1) considerable abrasions at the dorsal edge of the insert, and (2) more centrally located scratches in direction for abduction and adduction, pitches, and matt white subsurface regions probably due to oxidation. The abrasions at the dorsal edge of the insert appears to be typically for TWR,

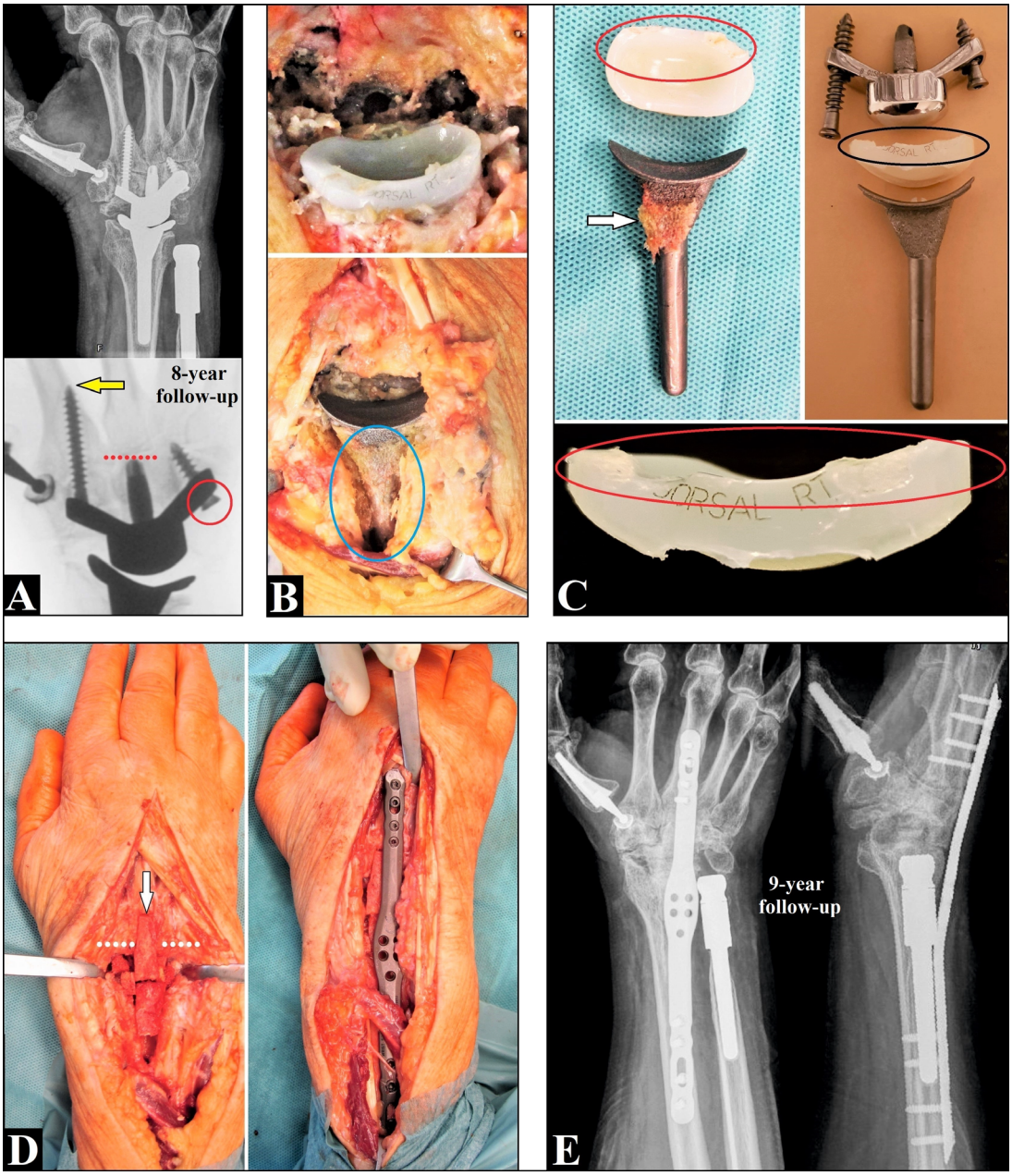

Figure 9. [14]: ***(Same patient as in Figure 2, now the 8-year follow-up [14]):*** *(A) Both non-locking screws were loosened and the ulnar-sided was dislocated into the articular space (red arrow). The carpal component was subsided (red pointed line, in comparison to the yellow pointed lines in Figure 2) accompanied by cortical migration of the radial-sided screw (yellow arrow). Therefore, the conversion to a TWA became necessary. (B) Intraoperatively, metallosis was present originating from the holes of both loosened screws and the capitate peg. For removal of the well osseointegrated radial component with it porous titanium coated radial body a large bony windowing at the dorsal aspect of the distal radius was required (blue oval circle). (C) Photographs of the explanted 1st Maestro type showing the well osseointgrated radial component (white arrow) and considerable PE abrasions at the dorsal edge of the insert (oval circles). The explant analysis revealed that the explant was found to operate under boundary lubrication associated with oxidation areas mainly in the centre of the insert [58]. (D) The TWA was done utilizing two corticocancellous iliac crest bone grafts (white arrow) crossing the CMCJ III (white pointed lines) into the 3rd metacarpal, and a 3.5/2.7 mm titanium wrist spanning plate. (E) One year after TWA there was a uneventful bony fusion, and the other two implants (Arpe, uHead) unchanged are well functioning.*

it was also observed with the Biax [37]. The rationale behind this finding is the biomechanically predetermined higher stress involvement of the insert at its dorsal and ulnar aspect which is magnituded in vivo because 21 of 24 (87.5%) functional tasks in ADL are performed with a wrist mostly in extension and 16 of 20 (80%) in ulnar extension [21,34,86,87]. The central damages were assessed by a biomechanical analysis of the explanted ArCom compression moulded ultra-high molecular weight PE insert of the patient demonstrated in Figure 9, and the lubrication analysis revealed that the explant was operating under boundary conditions that means theoretically that the majority of the surface asperities are in contact which will likely result in the wear of the softer material. These findings are comparable to those after total knee arthroplasy at the tibial

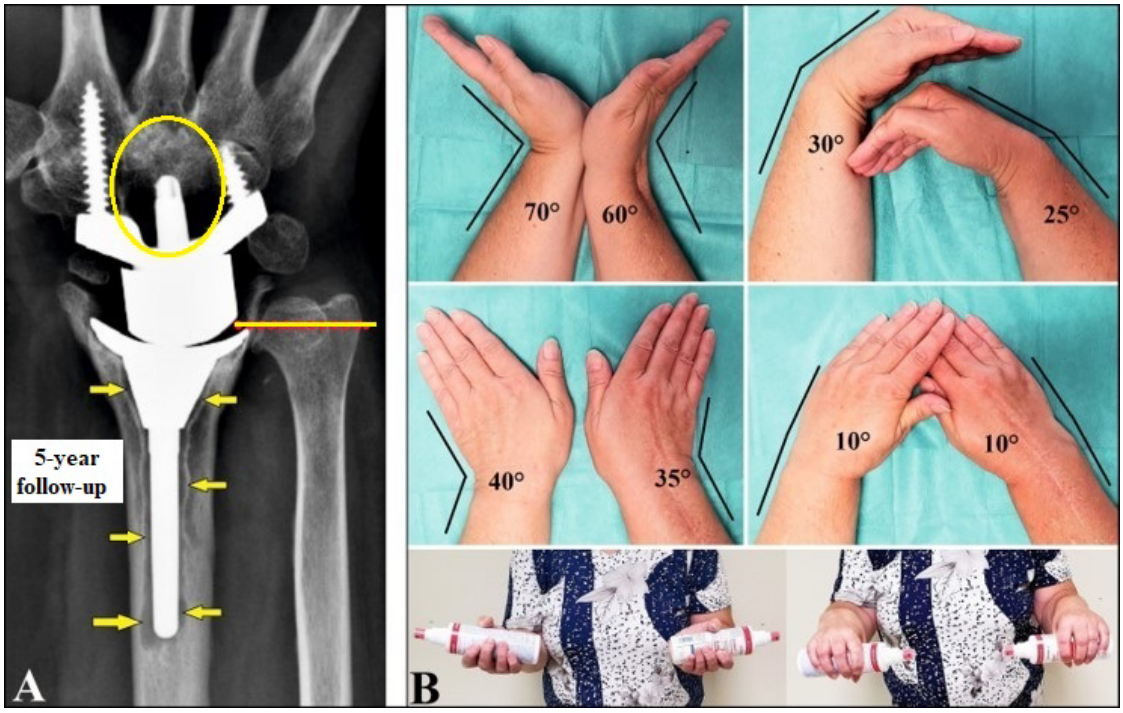

Figure 10. ***(51-year-old female, complicated course of a giant cell tumor at the right capitate, formerly published at a 1-year follow-up [9], now the 5-year follow-up [14])****: (A) Around the entire stem of radial component (2nd Maestro type, cementless) marked radiolucencies are present (yellow arrows) associated with asymptomatic subsidence (yellow line). There is a complete osteonecrosis around the entire capitate peg (yellow oval circle), but both locking screws are not loosened, and the carpal component is not subsided. (B) The patient is unchanged pain free and very satisfied with her functional outcome.* ***Supplementary material: Videos 10 and 11 demonstrate well functioning circumduction and „dart thrower's" motion at the 6-year follow-up.***

insert with it ellipsoidal configuration too and appears to be a general problem with joint replacements in human being.

Occurrence of periprosthetic osteolysis (PPO), mainly observed juxta-articularly, is a well-known phenomenon and remains unpredictable. With the ReMotion significant periprosthetic radiolucencies (more than two mm in width) were found in 36.4% under the offset of the radial and in 15.9% under the offset of the carpal components but clinical manifestation of loosening (defined as progressive angulation or subsidence) was present in 14% of all cases only, and it seem to be stabilized within three years after surgery (i.e. steady state) (Figures 6C2 and 8C) [88]. This discrepancy in survivorship between required revision at the final end point vs. a "theoretical" significantly lower implant survival if asymptomatic PPO had to be revised was confirmed in a large long-term follow-up study both for the Biax (86% vs. 50%), the Universal2 (83% vs. 70%), and the ReMotion (94% vs. 71%), and the results with the Maestro (93% vs. 90%) were significantly superior over the other types [79]. An in vivo investigation with the ReMotion revealed that neither PE or metal debris nor infectious or rheumatoid activity correlated with occurrence and the extend of PPO [89]. A newest study revealed that elevated serum titanium values are frequently found with the use of the Universal2 and Freedom being associated with often asymptomatic PPO in several patients, but the risk of loosening increased in implants older than 6 years, more than five PPOs, and serum titanium values between 26 to 31 µg/l [83]. PPO are commonly observed as well in 90% of cases one year after UHR around the collar of the uHead with it into the diaphysis pressfit inserted porous titanium coated stem (also found with all other UHR types), and PPO stabilized within three years postoperatively as well (Figures 2C/D, 5A3, 6A/C2 and 8C) [90-92]. Noted that the uHead including its option for total DRUJ replacement was withdrawn from the the marketplace by the company stryker (USA) in 2021 (prior offered by Small Bone Innovations / USA, financial interests?), despite well-known promising mid-term results [93]. The rationale behind this phenomenon seems to be an adjustment to the stress distribution away from the articular (sub)surface and towards to the shaft proximally which was also confirmed in a biomechanical investigation with the Maestro stem [94]. In this respect, these observations could also indicate more for a stable osseointegration than for loosening (i.e. stress shielding). Probably the most powerful proof to confirm this assumption revealed the results with the Zweymüller stem for total hip arthroplasty (comparable surface design like the Maestro and uHead, and pressfit inserted in a cementless manner too), the cumulative survival rate is reported to be 95.9% at a 25-year follow-up despite asymptomatic femoral osteolyses in 30% and proximal femoral osteopenia in 60% of cases were observed that was accompanied by cortical hypertrophy in 42% of cases more frequent around the distal part and tip of the stem (Gruen zones III/IV/V, "Wolff's law") [95]. Noted that locking screws for fixation of the carpal TWR components are obviously much able better to prevent loosening than non-locking screws if massive PPO around the capitate peg occur (Figure 10).

In summary, revision TWR or conversion to TWA should be born in mind only if PPO become clinically symptomatic and/or presented with safe radiographic signs of loosening such subsidence and/or progressive angulation in the sagittal or coronal plane of the carpal component (Pfanner classification

type A/B.1/B.2) with or without migration or breakage of the fixation screws (Figure 9A-C) [43,84,96,97]. For this circumstance, patients need to be educated that the results after revision TWR are significantly worse compared to first-line TWR, the cumulative 5-year survival rate is reported to be 83% only, and in 25 - 37% of cases repeat revision surgery is required within 6.6 - 10.3 years (mean) [98-100]. In contrast, recent evidence suggests that conversion of a failed TWR to second-line TWA (Figure 9) will produce comparable outcomes in PROMs and pain relief with those after first-line TWA, and the complication rates are also comparably high and differs not significantly with 47% for second-line TWA respectively 41% for first-line TWA [101,102].

In predicting the outcome of salvage procedures at the wrist the role concomitant psychological disorders and gender should not be underestimated. Swärd et al. [103] reported that preoperative pain catastrophizing, anxiety and depression with female predominance had a strong negative impact on postoperative DASH, PRWE, quality of life and grip strength. Moreover, patients with personal injury claims report about significantly more pain, worse hand function, and an extended time of return to their occupational work after major surgery at the wrist than those without such a claim [104].

Other designs and further developments

Another implant which is currently used is the Motec. The hemispherical ball-and-socket articulation either by a metal-on-metal or by a metal-on-polyetheretherketone (PEEK) gliding replicates both anatomical centers of rotation allocated at the proximal part of the capitate, and it can be considered a modified revival of older TWR types. First mid- to long-term results at a mean 8-year follow-up in high-demand patients with a mean age of 52 years (70.2% male) revealed promising results with a survival rate of 82% [51]. Both components with its conical straight stems are screwed deeply into the diaphyses that makes this implant also interesting for revision of a failed 3rd generation TWR with it shorter stems for both components. To minimize the risk of a dorsal breakthrough of the metacarpal stem as reported in one case, which was one of the major concern with the Biax as well, it is recommended to lift the capitate in dorsal direction exactly along the straight 3rd metacarpal-capitate line by performing a dorsal-wedged shaped resection combined with a fusion of the CMCJ III [36,37,105,106]. As further complications were reported about pseudotumor based on metallosis by using the metal-on-metal gliding, extensive synovitis based on adverse wear conditions in the cup by using the metal-on-PEEK gliding, and mechanical abrasions at the dorsal aspect of the hemispherical cup due to an impingement with the collar of the intercalated head component [107]. However, occurrence of dorsal impingement with the Motec can be avoided by inserting a longer intercalated head component which underlines the importance of restoration the resection-related loss of carpal height as already written in advance in this article content about the 3rd generation types [106]. In cases of a metal-induced synovitis if a metal-on-metal gliding was primarily inserted a conversion to a metal-on-PEEK gliding is reported to be one salvage option [108].

A new 3rd generation type was introduced in 2020 and revealed promising results at a minimum 5-year follow-up with a survival rate of 100% in 20 patients that includes asymptomatic radiographic signs of loosening of the carpal components in five patients (26%) without the need of surgical revision [97]. Interestingly again, PPO occurred in only one of these cases at the final follow-up, whereas the other four cases were observed within 1.5 years after surgery and it had been stabilized after that. This type has similarities with the Maestro in which a distal convex metal head articulates in a proximal concave PE cup, and it has three additional features: (1) the flexion-extension axis is aligned to the midcarpal joint line in an effort to limit stress on surrounding soft tissues as stated by the authors, (2) the carpal component is supported by a volar flange (i.e. similar to the Coonrad/Morrey prosthesis for total elbow replacement) in an effort to resist the posterior and rotational displacement forces as stated by the authors as well, and (3) this implant is detected only for patients with poor osteoporotic or rheumatoid bone stock because the radial component consists of a PE monobloc for exclusive use in a cemented manner [97,109]. The latter could prove problematic, if longstanding symptomatic surface PE wear or fracture occurs then the entire component must be revised even it may not be loosened, and noted that this was a worth considering disadvantage of the Biax as well as the Maestro and often possible only by a large bony windowing at the dorsal aspect of the distal radius meta-/diaphysis (Figure 9B) [37,58,110]. Therefore, removal of a cemented radial TWR component is certainly not entirely unproblematic, and in summary, any advantage of this specific radial PE monobloc component over the established porous titanium coated radial stems of the other 3rd generation types is not clearly discernible. Moreover, the problem of deteriorated flexion postoperatively observed in all other types is unchanged unsolved with this new type, and probably also based in its design with a likewise 90° bend of the offset of the radial component to its radial stem respectively radius shaft axis [97,109].

Hooke et al. [31] reported about first biomechanical investigations with a new 3rd generation type which has similarities with the Maestro too and which could be able to improve circumduction as well as the “dart thrower’s” motion, but clinical data are not available currently. Another approach could be the development of a new type which replicates the anatomical volar tilt of the radial component in the sagittal plane to improve flexion postoperatively [62].

The 4th (or 5th) generation types either by radial hemiarthroplasty with an unphysiological “metal-on-cartilage gliding” or by proximal interposition or carpal hemiarthroplasty with the pyrocarbon implants were introduced to avoid mechanical failure of the carpal components in TWR [111,112]. The feature of the KinematX with it implant-specific replacement of the proximal row is the anatomically allocated preservation of both centers of rotation in midcarpal joint theoretically resulting in decreased mechanical stress onto the component and simultaneously improved coupled wrist motion in comparison to TWR [113,114]. Various other implants with or without replacement of the distal radius metaphysis (Sophia, Cobra, Isoelastic Resurfacing Prosthesis) are currently used for treatment of highly comminuted DRF in the elderly with the aim of an early reintegration of the patients in their social environment [115-118]. However, the limitation of the high-friction “metal-on-cartilage gliding” could be erosion into opposing bones known from the monopolar hemiarthroplasty at the hip and observed at the wrist in 6% of cases in the approved carpal hemiarthroplasty with the Maestro that was additionally complicated by painful dislocation tendency in ulnar direction due to a mismatch in size between the carpal prosthetic head and the lunate facet [119-121]. The outcome with use of the Maestro as radial hemi wrist implant (i.e. “cartilage-on-PE gliding”, “off label” use) revealed inacceptable high complication rates based

on PE wear and resulting in pronounced tenosynovitis ("poly disease") as well as bony erosions in 50% of cases [110,120]. In summary, it remains to be seen whether or not the 4th generation types will actually be superior over the established 3rd generation types in future.

Another novel designs such the KinematX total wrist (Extremity, USA; Figure 11) and the Anika (USA) as total or hemi wrist are in use, but clinical outcome data are currently not available.

Conclusion

TWR is a viable salvage procedure in treatment of PPOA and not only detected in the elderly. Regardless of this, all surgeons who are willing to start with it need a learning curve. The knowledge about recent evidence and features in design of the available types, exact assessment of radiographic findings, presence of technical skills by the surgeons, and observance of the patient's expectations are the basic requirements for a successful TWR.

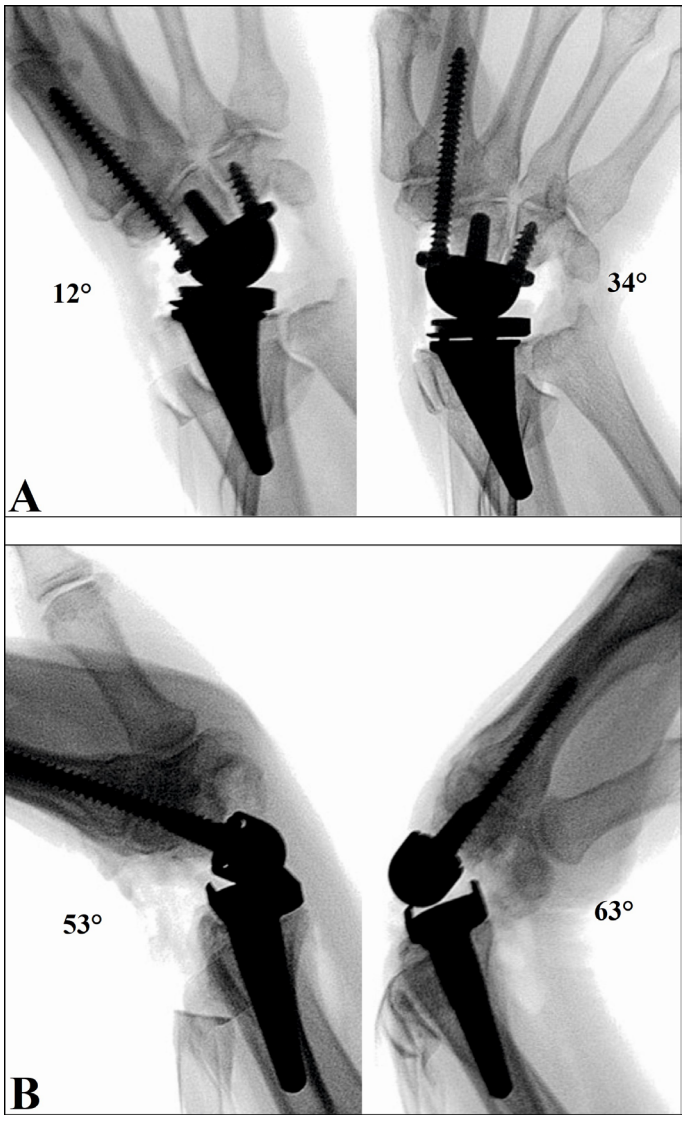

Figure 11. *(KinematX total wrist, Courtesy of Prof. Scott Wolfe, New York, USA, © 2022): (A) Intraoperative fluoroscopy with terminal range of radial and ulnar deviation showing no impingement. (B) Intraoperative fluoroscopy with terminal range of extension and flexion showing no impingement.*

Consent for publication

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Conflict of interest

The author declares no conflict of interest, financial or otherwise.

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Supplementary material (12 videos)

- **Video 1:** 31-year-old male, Maestro left wrist, 7-year follow-up, well functioning circumduction
- **Video 2:** Same patient as in video 1, high load in his occupational work
- **Video 3:** Same patient as in videos 1 and 2, high load in his leisure
- **Video 4:** Same patient as in videos 1-3, use of a orthotic device imitating TWA
- **Video 5:** 59-year-old female (Figure 6), ReMotion and uHead left wrist, 9-year follow-up, well functioning circumduction
- **Video 6:** Same patient as in video 5 (Figure 6), well functioning "dart thrower's" motion
- **Video 7:** 39-year-old male (Figure 7), ReMotion left wrist, 2-year follow-up, well functioning circumduction
- **Video 8:** Same patient as in video 7 (Figure 7), impaired "dart thrower's" motion
- **Video 9:** 62-year-old male (Figures 5 and 8), ReMotion and uHead left wrist, 11-year follow-up, well functioning circumduction
- **Video 10:** 51-year-old female (Figure 10), Maestro right wrist, 6-year follow-up, well functioning circumduction
- **Video 11:** Same patient as in video 10 (Figure 10), well functioning "dart thrower's" motion
- **Video 12:** 59-year-old female, ReMotion left wrist, 8-year follow-up, well functioning circumduction (feature of the ReMotion: 10° rotation of the intercalated PE ball against the carpal component)