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REVIEW

K. Mader • D. Pennig

The treatment of severely comminuted intra-articular fractures of the distal radius

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Abstract Comminuted fractures of the distal end of the radius are caused by high-energy trauma and present as shear and impacted fractures of the articular surface of the distal radius with displacement of the fragments. The force of the impact and the position of the hand and carpal bone determine the pattern of articular fragmentation and their displacement and the amount and the extent of frequent concommitant ligament and carpal bone injury. The result of the osseous lesion in comminuted fractures was termed "pilon radiale", which emphasizes the amount of damage to the distal radius and the difficulties to be expected in restoring the articular congruity. Besides this the additional injury, either strain of disruption of the ligaments and the displacement of the carpus and/ or the triangular fibrocartilage complex will equally influence the functional outcome. This review will expand on the relevant anatomy, correct classification and diagnosis of the fracture, diagnostic tools and operative treatment options. Current treatment concepts are analysed with regard to actual literature using the tools of evidence based medicine criteria. A new classification of severely comminuted distal radius fractures is proposed using CT data of 250 complex intraarticular radius fractures. Finally a standardized treatment protocol using external fixation in combination with minimal invasive internal osteosynthesis is described.

Key words Distal radius fractures • External fixation • Plate osteosynthesis • Meta-analysis

K. Mader (✉) • D. Pennig
Department of Trauma and Orthopedic Surgery, Hand and Reconstructive Surgery
St. Vinzenz Hospital
Merheimer Straße 221–223
D-50733 Cologne, Germany
e-mail: k.mader@ndh.net

Introduction

More than 192 years have passed since Colles described a fracture of the distal end of the radius [1]. It is remarkable that this common fracture remains one of the most challenging of the fractures treated by orthopaedic or general surgeons. Comminuted fractures of the distal end of the radius are caused by high-energy trauma in young patients and by low-energy trauma in the elderly, and present as shear and impacted fractures of the articular surface of the distal radius with displacement of the fragments [2–10]. The force of the impact and the position of the hand and carpal bones determine the pattern and displacement of articular fragmentation and the amount and extent of the frequent concomitant ligament and carpal bone injury [11–13]. The result of the osseous lesion in comminuted fractures was termed "pilon radiale" [11], which emphasises the amount of damage to the distal radius and the difficulties to be expected in restoring the articular congruity. In addition, disruption of the ligaments and the displacement of the carpus and/or the triangular fibrocartilage complex (TFCC), will equally influence the functional outcome [14]. This review will expand on the relevant anatomy, correct classification and diagnosis of the fracture, diagnostic tools and operative treatment options.

Epidemiology

The distal radius fracture was clinically diagnosed in 1814 by Colles, who described this entity in a journal published in Edinburgh [1]. The treatment, however, even today, remains controversial. One of the reasons for this controversy is the heterogenic patient population in which the fracture occurs. In younger patients (those under 40 years of age) considerable forces are necessary to cause this fracture, which is defined as being localised within 3 cm of the distal end of the radius [2, 3]. There is a sharp increase in incidence above the age of 30 years, which apparently is associated with post-menopausal and age-related osteopenia. In the USA and Northern Europe this fracture is the most common one in women under 75 years old [15]. Studies looking at radial bone density failed to demonstrate significant reductions in bone density when radius fracture patients were compared with age-matched control subjects [16]. Sparado et al. could show that both the cortical and the trabecular bone contribute to the overall strength of the osteopenic distal radius. In effect, both the cortical comminution and the metaphyseal cancellous bone defect may contribute to the inherent instability of a distal radius fracture [17].

Looking at the epidemiology of distal radius fractures, the Reykjavik, Iceland, study showed that 249 fractures in patients over 15 years of age occurred within a total at-risk population of 100,154 [18]. The incidence pattern here is similar to those reported in other Nordic studies. The study analysed the distribution of distal radius fractures with regard to the social environment. With more than a half of the radius fracture patients being employed, the economic implications became evident [3, 19].

Evidence-based medicine and meta-analyses, randomised trials

Systematic analysis and the aim of introducing evidence-based medicine criteria in the diagnosis and treatment of distal radius fracture are connected to Helen Handoll and Raj Madhok at the Public Health Research Unit, University of Hull, UK. They have completed a portfolio of systematic reviews (published in The Cochrane Library) of the evidence from relevant randomised controlled trials (RCTs). Their five reviews, which examine conservative and surgical treatments, anaesthesia and rehabilitation, cover all of the key interventions for the management of these fractures [20–25]. The reviews include all published randomised or quasi-randomised clinical trials comparing various conservative and/or surgical interventions. Seventy-five trials, involving 6565 mainly female and older patients, were included. These were mainly single-centre trials performed in 20 countries with only one international trial. Overall, the 75 trials were only of poor to moderate quality as rated by the methodological checklist, using the three prime measures of internal validity, which are reported to affect the results of trials [26].

Even more so, their results on surgical interventions in radius fractures, a subgroup of their analysis, show the scientific standard in this medical field: 41 trials with 3193 patients studied surgical interventions. Twenty-one of these compared surgical intervention with conservative treatment, always plaster cast immobilisation for about 6 weeks. Three trials had more than 2 intervention groups and featured in 3 or 4 comparisons.

In summary, they found that a wide range of interventions had been used to treat distal radius fractures and there was insufficient robust evidence from randomised and quasi-randomised clinical trials for most of the interventions used.

There was evidence that some surgical methods showed better anatomical outcomes but there were insufficient data on other outcomes to determine whether surgical intervention in most fracture types would produce consistently better long-term outcomes.

Thus their findings reflect the limited scope, quantity and usually uncertain validity of the available evidence from the trials available. Heterogeneity and incomplete data either hindered or prohibited pooling of results from comparable trials and thus the potential of meta-analysis to enhance the precision of the results from small trials. There was considerable variation in trial design, such as patient characteristics, the type and application of interventions, the overall care programmes and so on. For example, there were 9 different external fixators as well as pins and plaster being compared with plaster cast immobilisation in the group of 13 trials that compared external fixation with conservative treatment. This sort of variation, with insufficient information on trial characteristics and incomplete and inadequate outcome assessment invalidated the interpretation of the results, and their clinical applicability [27]. Finally, information on resource use and costs was rarely available and, where provided, was minimal [28].

Having understood that the overall failure to produce a systematic evaluation of the treatment of distal radius fractures is mainly due to our own methodological incompetence as orthopaedic investigators, we should reconsider the evidence in the treatment of the subgroup of comminuted distal radius fractures. Here special attention should be paid to any evidence for superior outcome after plating of these fractures with new armamentarium on the orthopaedic market, especially for angle-stable implants.

In 2002, Handoll and Madhok found 44 randomised trials that did not provide robust evidence for most of the decisions necessary in the management of these fractures [28]. Although, in particular, there was some evidence to support the use of external fixation or percutaneous pinning, their precise role and methods are not established. It was also unclear whether surgical intervention in most fracture types would produce consistently better long-term outcomes [28].

In 2004, Paksima et al. published a meta-analysis of the literature on distal radius fractures, reviewing 615 articles [7]. Again, there was insufficient data to perform a scientific meta-analysis because of the poor quality of the studies and lack of a uniform method of outcome assessment. However, the data from the comparative trials showed that external fixation was favoured over closed reduction and casting. Additionally, comparing the results of the case series showed that external fixation was superior to internal fixation [8].

In 2005, Margaliot et al. performed a meta-analysis on outcome after plate fixation versus external fixation in unstable distal radius fractures [29]. The outcomes of internal and external fixation were compared using continuous measures of grip strength, wrist range of motion and radiographic alignment, and categoric measures of pain, physician-rated outcome scales and complication rates. Outcomes were pooled by random-effects; meta-analysis and meta-regression analysis were used to control for patient age, presence of intra-articular fracture, duration of follow-up period and date of publication. Sensitivity analyses were used to test the stability of the meta-analysis results under different assumptions. They could include 46 articles in the review with 28 (917 patients) external fixation studies and 18 (603 patients) internal fixation studies. Meta-analysis did not detect clinically or statistically significant differences in pooled grip strength, wrist range of motion, radiographic alignment, pain and physician-rated outcomes between the 2 treatment arms. There were higher rates of infection, hardware failure and neuritis with external fixation and higher rates of tendon complications and early hardware removal with internal fixation. Considerable heterogeneity was present in all studies and adversely affected the precision of the meta-analysis. They concluded that the current literature offers no evidence to support the use of internal fixation over external fixation for unstable distal radius fractures [29].

Looking at the systematic analysis of the "new" internal plating systems, we should draw an even more pessimistic view. Although there are publications of biomechanical testing of different plate systems [30–34] and non-randomised case series and so-called expert opinions of using these implants [4, 35–40], in September 2006 there are no scientific relevant studies available showing a superior outcome using the criteria of Handoll and Madhok [27].

In contrast, Kreder et al. in 2006 performed a randomised controlled trial in a total of 179 adult patients with displaced intra-articular fractures of the distal radius, that were randomised to receive indirect percutaneous reduction and external fixation (n=88) or open reduction and internal fixation (n=91) [41]. There was no statistically significant difference in the radiological restoration of anatomical features or the range of movement between the groups. During the period of two years, patients who underwent indirect reduction and percutaneous fixation had a more rapid return of function and a better functional outcome than those who underwent open reduction and internal fixation, provided that the intra-articular step and gap deformity were minimised. Grewal et al. in 2005 compared, in a randomised study, open reduction and internal fixation with dorsal plating (Pi Plate; Synthes, Paoli, PA) versus mini open reduction with percutaneous K-wire and external fixation [42]. At midterm analysis the dorsal plate group showed a significantly higher complication rate compared with the external fixator group; therefore enrolment in the study was terminated. The dorsal plate group also showed statistically significantly higher levels of pain, weaker grip strength, and longer surgical and tourniquet times. Based on these results they refused to recommend the use of dorsal plates in treating complex intra-articular fractures of the distal radius.

Classification systems

A number of authors have proposed systems for the classification of fractures of the distal radius, the most known and used being the AO [43], Fernandez [44], Frykman [45], Mayo [46] and Melone [6] classifications. Many of these systems combine intra-articular and extra-articular fractures; however recent studies have not revealed substantial interobserver agreement among fracture types determined by the use of the AO, Frykman, Mayo and Melone classifications [47]. Significant agreement ($p<0.05$) among surgeon classifications using the AO system was achieved only after the classification was reduced substantially, and freed from all subgroups, to the three major fracture types (A, extra-articular; B, intra-articular with part of metaphysis intact and C, intra-articular fractures with complete disruption of the metaphysis) [47].

AO classification

The AO classification system, which comprises 27 categories, is the most detailed. It also is the most inclusive, making it, in theory, useful for detailed anatomical categorisation for trauma registries [43]. Although it is widely used in the literature, it lacks any link between description of the fracture and any clinical decision-making for fracture treatment. Furthermore, Andersen et al. [47] and more recently Flikkila et al. [48], after inclusion of computed tomography (CT) scans in the diagnostic protocol, have shown that interobserver reliability was poor when detailed classification was used. By reducing the categories to five, interobserver reliability was slightly improved, but was still poor. When only two (!) AO types were used, the reliability was moderate using plain radiographs and good to excellent with the addition of CT.

They concluded that the use of CT combined with plain radiographs brings interobserver reliability to a good level in assessment of the presence or absence of articular involvement, but is otherwise of minor value in improving the interobserver reliability of the AO system of classification of fractures of the distal radius [48]. Therefore the AO classification system is not suitable for reliable classification of intra-articular fractures of the distal radius.

Frykman classification

This classification focuses on the intra-articular extension of the fracture and the involvement of the ulnar styloid process, implying that this involvement contributes to the seriousness of the fracture [48]. As one of the earliest systems for the classification of distal radius fractures, it drew attention to the distal radioulnar joint (DRUJ), which is important. The Frykman classification can be used to identify and separate extra- and intra-articular fractures, but, as there is no differentiation between displaced and non-displaced fractures, this system is also of minor use in the classification of intra-articular radius fractures.

Melone classification

This classification was the first to provide an accurate description of the way in which the fracture propagates through the articular surface of the radius and as early as 1993 showed the importance of the palmar and dorsal ulnar-sided key fragment [6]. The original paper by Melone was based on only 14 patients, but the analysis of the fracture pattern and fracture biomechanics is still extraordinary. We strongly recommend this paper for an understanding of the pathology of comminuted intra-articular distal radius fractures. The Melone classification has gained more reliability and precision with the inclusion of CT scanning in the diagnostic armamentarium and is therefore commended as the classification system of choice for intra-articular fractures.

Relevant anatomy

The articular surface of the distal aspect of the radius tilts 20° in the anteroposterior plane (radial angle) and 4°–10° in the lateral plane (palmar angle). The dorsal cortical surface of the radius thickens to form Lister's tubercle with further osseous prominences to support the extensors of the wrist. A central ridge divides the articular surface of the radius into the scaphoid and lunate facets. The so-called TFCC extends from the rim of the sigmoid notch of the radius to the ulnar styloid process. The only tendon that inserts onto the distal aspect the radius is that of the brachioradialis. All other tendons of the wrist pass across the distal aspect of the radius to insert onto the carpal bones or the bases of the metacarpals, or form the extensors or flexors of the fingers. Delicate extrinsic and intrinsic ligaments maintain the carpal bones in a smooth articular unit. Because of the different areas of bone thickness and density, the fracture pattern tends to propagate between the scaphoid and lunate facets. The degree, direction and extent of the applied load in addition to the actual position of the wrist and hand causes additional coronal or sagittal splits within the lunate and/or scaphoid facet. The palmar thickening of the distal radius with its capsular attachment forms the palmar lip, and more proximally the pronator quadratus muscle ensheaths the palmar aspect of the distal radius.

While implants for internal fixation can be applied safely on the palmar aspect of the distal radius, both the radial and dorsal aspect are densely covered with tendons adjacent to the joint capsule, which leaves these areas more vulnerable to tendon adhesions or tendon injury when implants are used in these areas.

Diagnostic tools

Conventional X-ray

Standard posterior-anterior, lateral and oblique radiographs of the wrist show the extent and direction of the initial displacement. They should be followed by repeat radiographs after reduction and cast application in order to identify residual deformity and the degree of intra-articular comminution. Special attention is paid to the capitate-lunate axis relative to the radius, identifying dorsal or palmar carpal dislocation. Incongruencies in the proximal carpal bones, can reveal intracarpal fracture dislocations or intercarpal dissociation, most commonly scapholunate [49]. Of utmost importance is the evaluation of the DRUJ. Incongruency disruption or subluxation of the DRUJ can be readily seen on conventional X-rays and will influence both treatment protocol and final outcome. Because fractures of the distal radius and ulna and related ligamentous or bone injuries to the wrist can be occult, precise evaluation of the soft tissues of the distal forearm and wrist can be key for correct diagnosis, and a systematic approach to the soft tissues is useful. Two fat planes on the lateral view and five fat planes on the posterior anterior view are useful for analysis, the most important being the deep fat pad of the pronator quadratus muscle [50].

CT scan

In all cases with fracture comminution, displacement or complex intra-articular extension of the fracture, conventional radiography is insufficient and CT is warranted. In our unit, a standard CT examination is performed on all intra-articular fractures of the distal radius. After marking the region of interest (usually extending from the radial metaphysis to the distal carpal row) the CT scan is performed with 1-mm sections and a table propagation of 1 mm, giving the highest possible resolution. These sections are strictly transverse and will allow for two-dimensional reconstruction in the frontal and sagittal planes. The images are displayed in the bone-sensitive window. The transverse plane reconstruction is used to evaluate the distal radioulnar joint and carpal bones and the pattern of articular fragmentation. The coronal or frontal plane provides an image similar to the standard PA radiograph and will provide better bone detail and intra-articular step-off or gap. The sagittal plane will give a clear view of dorsal or palmar dislocation of the carpus and any separation of the dorsal or palmar articular rim of the radius. An additional oblique sagittal plane in the long axis of the scaphoid is performed to better assess the scaphoid. In subtle cases of radioulnar subluxation a comparison of transverse CT images of both wrists in neutral, pro- and supination is an excellent way of evaluating distal radioulnar joint incongruency. With this diagnostic tool, an accurate Melone classification is possible and secondly a definite operative approach can be planned. In addition, a CT-based classification and treatment plan can be developed.

The benefit of using CT scans in addition to plain radiography for the evaluation of small (<5 mm) intra-articular displacements of distal radius fracture fragments was shown first by Cole et al. in 1997 [51]. They concluded from their study that CT scanning data, using the arc method of measurement, were more reliable for quantifying articular surface incongruities of the distal radius than plain radiography measurements were.

Katz et al. showed that the addition of CT results in changes in the evaluation and treatment of intra-articular distal radius fractures [52]. CT scans improved the sensitivity of measurement of articular surface separation and the accuracy of detection of comminution and DRUJ involvement, and altered the proposed treatment plans in observers. A very recent study by Harness et al. evaluated the hypothesis that three-dimensional CT images would further increase the reliability and accuracy of radiographic characterisation of distal radial fractures [53]. They showed that three-dimensional CT improved the intraobserver agreement, but not the interobserver agreement, regarding the presence of coronal plane fracture lines and central articular fragment depression. Three-dimensional CT improved both the intraobserver and the interobserver agreement regarding the presence of articular comminution. Interobserver agreement increased when three-dimensional CT was used to determine the exact number of articular fracture fragments. Although they stated that three-dimensional CT improves both the reliability and the accuracy of radiographic characterisation of articular fractures of the distal radius and influences treatment decisions, we find that we obtained sufficient information from transverse section and the addition of sagittal and frontal reconstruction allows us to make a CT-based classification of intra-articular fractures of the distal radius and to form our treatment plan.

Classification based on CT data and operative strategy

In a prospective evaluation 250 severely comminuted distal radius fractures were treated according to a prospective protocol. In all cases a CT scan was performed with the parameters outlined in the previous paragraph. Analysis of the CT scans led to five distinct fracture types, which can be used for a CT-based classification of comminuted intra-articular fractures of the distal radius.
The following fracture types were identified:

(1) Intra-articular fracture with displaced dorsal fragment (Fig. 1)

In addition to intra-articular fragmentation there is a displaced and rotated dorso-ulnar fragment, which causes incongruency of the dorsal part of the DRUJ. This fragment should be reduced via a limited dorsal approach and fixation should be performed either with a single screw or a small dorsal straight plate.

(2) Dorsal split with dorsal dislocation (Fig. 2)

This fracture type is defined by a transverse dorsal split with dorsal dislocation of the fragment(s) and the carpus. These fractures are actually fractures of the dorsal articular margin with dorsal radiocarpal subluxation and are therefore unstable [4]. Most of the bony ridges are very small and therefore difficult to refix with implants such as screws or plates and indirect techniques of reduction of the fragment and the carpus (by ligamentotaxis with an external fixator) will reduce the fracture. After reduction those fragments will be fixed indirectly with the means of screws through palmar plates.

(3) Palmar split with palmar dislocation (Fig. 3)

These fractures are caused by an opposite (palmar) displacement of the carpus disrupting a small palmar margin of the articular surface and are equally unstable. Here

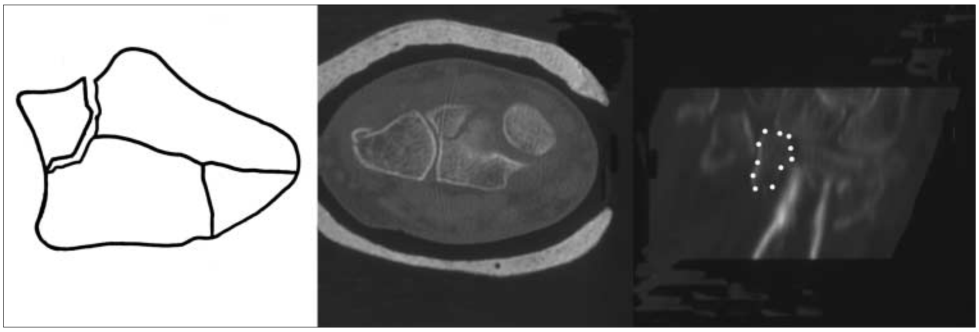

Fig. 1 CT-based classification of comminuted intra-articular fractures of the distal radius. Type I: intra-articular fracture with displaced dorso-ulnar fragment

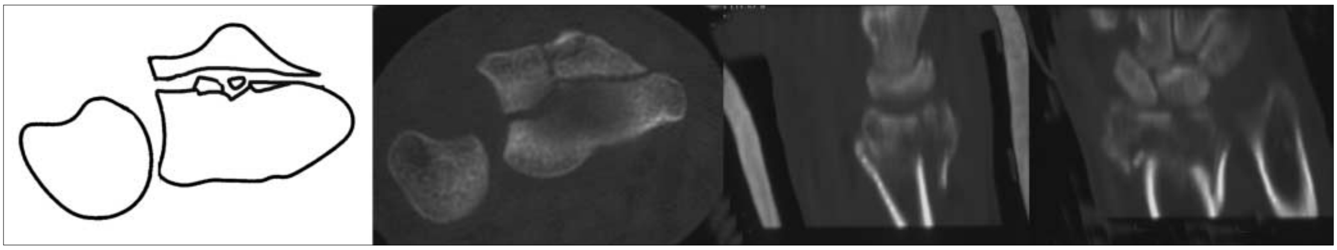

Fig. 2 Type II: dorsal split with dorsal dislocation

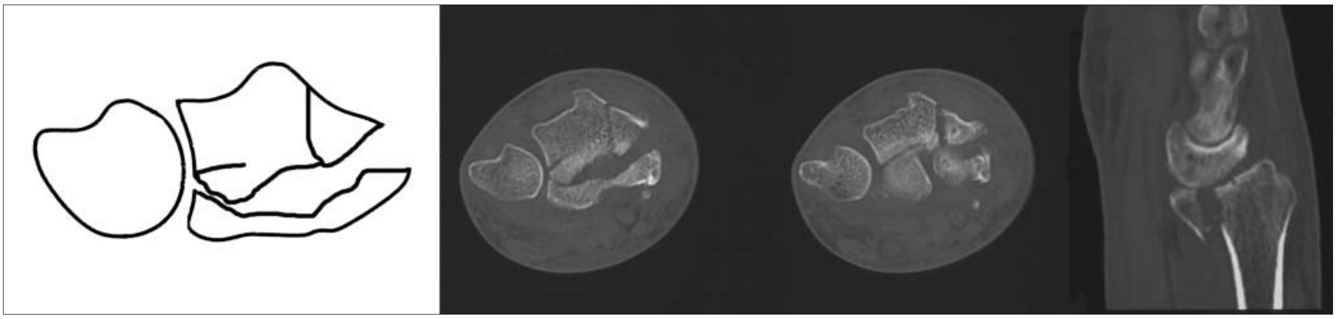

Fig. 3 Type III: palmar split with palmar dislocation

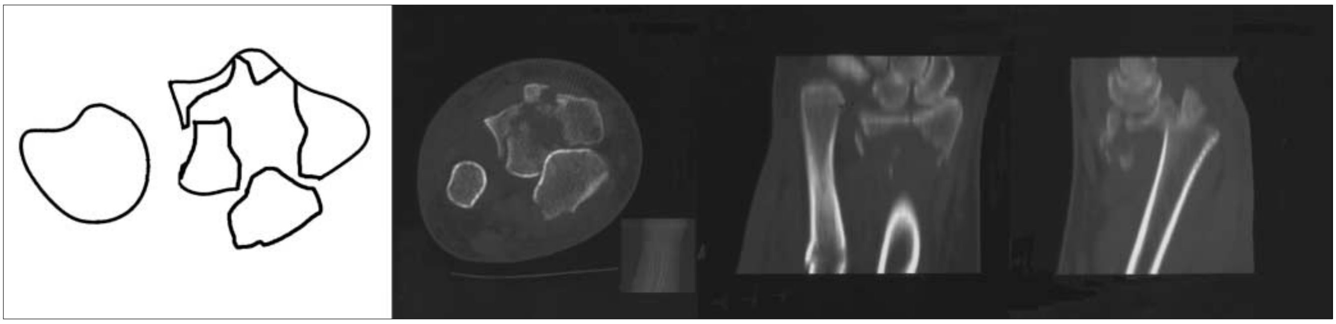

Fig. 4 Type IV: complex distal radius fractures with metaphyseal separation

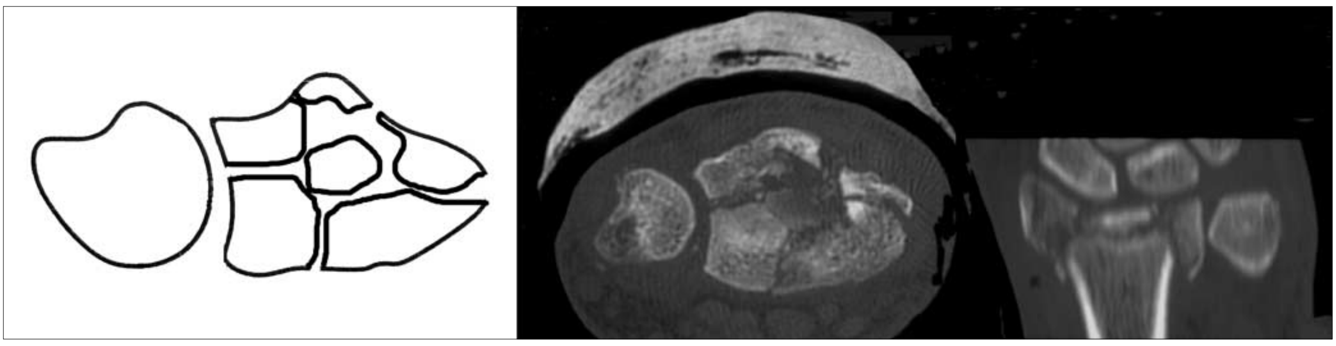

Fig. 5 Type V: destruction of the articular surface

reduction of the palmar is achieved via a palmar approach and small buttress plating. Again the deforming forces and palmar (sub)luxation of the carpus are counteracted by a neutralising external fixator.

(4) Complex distal radius fractures with metaphyseal separation (Fig. 4)

These fractures are defined by complete additional dorsal or palmar disruption of the metaphysis with severe comminution. They often show a total disruption of the DRUJ and gross displacement.

(5) Destruction of the articular surface (Fig. 5)

On this CT evaluation there is destruction of the very distal aspect of the distal radius, with involvement of the greater part of the articular surface. These fractures are the most difficult ones to treat, because major parts of the articular surface are destroyed and displaced. A combination of reconstruction of the articular surface and minimal distraction of the carpus is necessary to unload the articular cartilage during bone healing.

The analysis of 250 complex distal radius fractures reveals the pattern of location and distribution of the fragments relative to the joint line. It was interesting to note that most of the fracture lines were distal to the so-called "watershed line" (a line at the metaphyseal articular junction bordered by the bulky palmar lip), which is the line that should not be crossed with the use of modern palmar implants. More than 60% of the fracture lines originated distal to this watershed line. Therefore to treat the majority of these fractures implants must be placed distal to this watershed line and therefore have a very low profile design in order not to impede the palmar tendons.

Concomitant injury to the distal radioulnar joint

Lindau and Aspenberg performed a detailed analysis of the literature in 2002 and showed, that evidenced-based information on injury to the DRUJ combined with a distal radius fracture is actually absent [54]. They searched The Cochrane Library and Medline regarding the radioulnar joint in distal radial fractures and found no randomised or controlled studies. Their excellent review presents the descriptive literature by summarising accepted views and controversies. There is only weak (evidence-based) support for the commonly accepted treatments.

The major stabilisers of the DRUJ are the ulnoradial ligaments, which represent the transverse, peripheral part of the TFCC. The ligaments pass from the fovea of the ulnar head and the base of the ulnar styloid to the dorsal and palmar edges of the distal radius. The TFCC includes a central articular disc and the ulnocarpal ligament. The articular disc bears a compressive load and acts like an ulnocarpal cushion, but gives no stability to the DRUJ [54]. It is cartilaginous and avascular. The ulnocarpal ligament arises from the fovea of the ulnar head and inserts on the palmar surface of the triquetrum. It may partly contribute to the stability of the DRUJ [55, 56]. It is generally accepted that, in addition to the TFCC, stability is achieved by various degrees of contribution from the extensor carpi ulnaris tendon, the pronator quadratus muscle and the radioulnar interosseous membrane [55–61].

It has been increasingly accepted that fractures of the distal radius in patients below the usual age for osteoporosis are associated with tears of the TFCC [12, 54]. These ligament tears have been found on wrist arthroscopy and occur with or without fractures of the ulnar styloid. This implies that distal radial fractures in younger patients are frequently complicated by injuries that cannot be seen on radiographs. Some authors advocate including supplementary arthroscopy into the operative regimen [10, 12, 54].

Cole et al., in a recent biomechanical cadaveric study, examined the effects of the volar and dorsal lips of the sigmoid notch and the volar and dorsal aspects of the TFCC on DRUJ stability [62]. Sequential fractures of the distal radius and sectioning of the TFCC were performed followed by measurements of ulnar translation with the forearm in pronation, neutral and supination. A dorsal lunate facet fracture created instability in pronation. Lunate facet fractures alone did not create instability in other forearm positions. Sectioning of the volar TFCC after loss of the dorsal TFCC by a dorsal lunate facet fracture caused DRUJ instability with the forearm in neutral position. Sectioning of the dorsal TFCC after loss of the volar TFCC due to a volar lunate facet fracture created instability in neutral and pronated positions [62]. These findings show clearly the importance of identifying the dorsal or palmar ligament-bearing fragments during surgery and reattaching them with fragment-specific internal fixation.

In 2002 May et al. showed that distal radius fractures complicated by DRUJ instability were accompanied by an ulnar styloid fracture [63]. A fracture at the ulnar styloid's base and significant displacement of an ulnar styloid fracture were found to increase the risk of DRUJ instability. At the end of the surgical procedure the position and stability of the ulnar styloid fracture should be visualised and documented. While a perfectly reduced and stable ulnar styloid fragment can be left for fibrous healing, an unstable and or dislocated ulnar styloid fragment is reduced and fixed via a limited ulnar-sided approach. The supplementary use of an ulnar outrigger to prevent rotation of the forearm during healing is associated with a better outcome, especially forearm rotation [64].

Hirahara et al. showed, in a biomechanical study in 9 fresh cadaver limbs, in a malunion model of the distal radius, that torque across the DRUJ was affected by the degree of a simulated malunion of the distal radius. They concluded that reduction of distal radius fractures to within 10° of dorsal angulation is needed to allow patients to maintain full forearm and wrist rotation [58].

The main unsolved problem resulting from concomitant injury to the DRUJ is posttraumatic DRUJ laxity, which shows no correlation to radiographic changes at the time of fracture or at follow-up [54].

As Lindau stated correctly in 2005, the current problem of the concomitant injury to the DRUJ is that neither the initial ligament injury nor the posttraumatic laxity is detectable with radiographic methods, which creates future challenges regarding diagnosis and treatment [65]. We therefore have to critically analyse each fracture in each patient and be aware of the complexity of the entire injury to the wrist.

Associated injury to carpal ligaments and carpal bones

In 2002 Pechlaner et al. performed an extensive cadaver experiment, in which his group attempted to simulate the pathomechanism of distal radius fractures and evaluated the bony and soft tissue lesions [14]. With the help of a materials testing machine, 63 prepared cadaver arms were hyperextended in the wrist joint until a radius fracture occurred. The concomitant lesions were registered radiologically and by dissection. Additional cadaver arms were deep-frozen and examined by means of computer tomography and cryosection techniques. Through experimental hyperextension it was possible to generate dorsal, central and palmar types of fractures. The subsequent dissection showed in 40 cases (63%) mostly multiple concomitant lesions and in 23 cases (37%) none of these. Most frequently (27 cases, i.e., 43%), they found a destabilisation of the articular disk with or without a bony avulsion fragment (fracture of the ulnar styloid). They also commonly found ruptures of the interosseous ligaments between scaphoid and lunate (20 cases, i.e., 32%) and lunate and triquetrum (11 cases, i.e., 18%).

As early as 1997 Lindau et al. investigated intra-articular lesions in distal fractures of the radius in young adults in the clinical setting [66]. They examined the frequency of associated chondral and ligament lesions in distal fractures of the radius in young adults (men 20–60 years, women 20–50 years). By supplementary arthroscopy they found chondral lesions in 16 patients (32%). All patients but one were found to have a ligamentous injury in the wrist. The most frequent ligament tear was the TFCC in 39 cases (78%), with a statistical correlation to ulnar styloid fractures. The scapholunate ligament was partially or totally torn in 27 cases (54%). No correlation was found between specific fracture types and the pattern of ligament injury. They concluded that chondral and ligamentous lesions were frequent and may explain poor outcomes after seemingly well healed distal fractures of the radius.

This high frequency of associated intracarpal lesions was clinically confirmed by Schadel-Hopfner et al in an arthroscopic study and by Laulan and Bismuth in a radiographic analysis [67, 68]. Lutz et al. showed, in a well documented clinical series, that sagittal wrist motion of carpal bones following intra-articular fractures of the distal radius was reduced due to an increased intra-articular depth after operative treatment of intra-articular fractures of the distal radius as a result of chondral lesions and persisting pressure on the articular surface [13]. The benefits of the use of external fixation in the treatment of complex carpal lesions were shown by Fernandez and Mader [69].

External fixation

Comminuted fractures of the distal radius are, as previously discussed, not a bony lesion, but a complex injury to the carpal ligaments and the DRUJ. After anatomical reconstruction of the articular surface, it is important to neutralise the deforming palmar or dorsal forces on the carpus [9, 70]. The external fixator is ideal for postoperative wound access, moderate unloading of the carpus and stabilisation of the carpal ligaments by means of ligamentotaxis, and can be used for mobilisation of the wrist if an appropriate device is employed [13, 71–74] (Fig. 6). In contrast to statements of other authors, we believe that the external fixator is not suit-

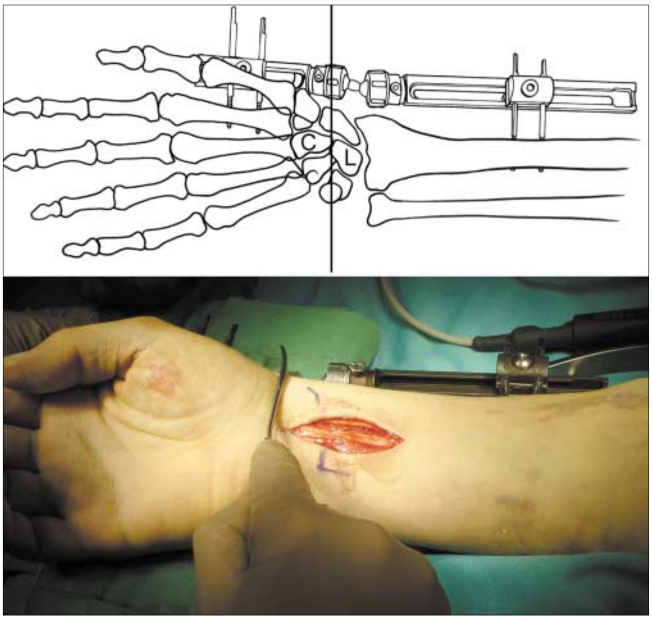

Fig. 6 Schematic drawing of a monolateral external fixator with double ball joints after application to the radial aspect of the second metacarpal and diaphysis of the radius: the distal ball joint is centred between the capitate (*C*) and lunate bone (*L*) (intraoperatively by identification with a bone elevator under image intensification, lower part of the image) to allow for mobilisation of the fixator

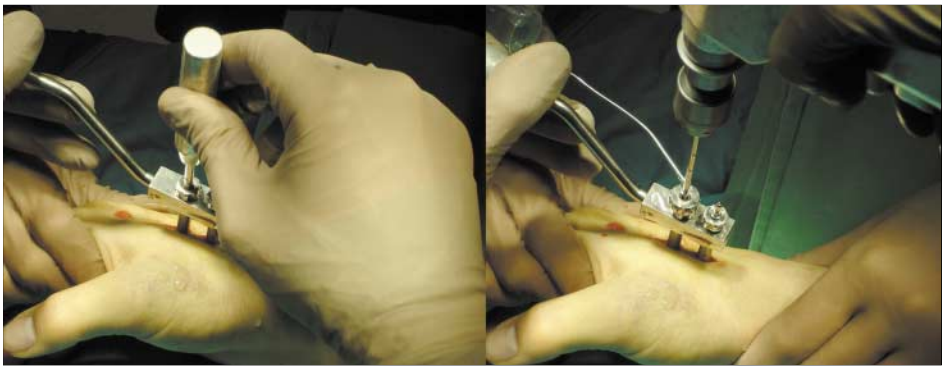

Fig. 7 Intraoperative images during application of fixator pins into the base of the second metacarpal. On the *left side* the appropriate use of a screw guide and a trocar is shown, and on the *right side* predrilling with cooling of the drill bit is demonstrated

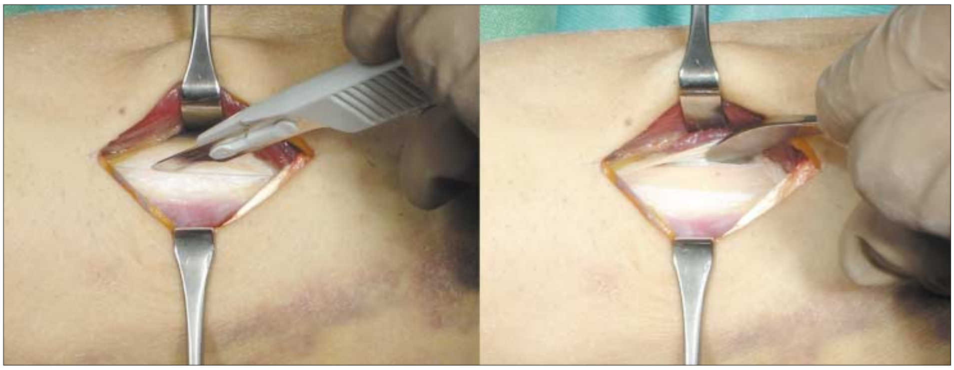

Fig. 8 Intraoperative images during application of fixator pins into the diaphysis of the radius: the soft tissues are retracted, the periosteal sleeve is incised (*left*) and detached from the underlying bone (*right*)

able for the reduction of the fragments in severely comminuted distal radius fractures, because the ligament-bearing fragments are individually rotated and displaced in different directions, and will not derotate during simple distraction of the external frame [6, 13, 75–77]. Although a variety of external fixators are available, only a few have the versatility to align the carpus correctly with the wrist in a neutral and functional position, allowing for the placement of an ulnar outrigger and can be mobilised after proper application [78–83]. The external fixator is placed strictly in the lateral plane from the radial side, with open insertion of threaded fixator pins into the proximal third of the second metacarpal and the radial aspect of the distal third of the radial diaphysis (Figs. 7 and 8). Care is taken to avoid injury to the dorsal cutaneous branch of the radial nerve with the use of open pin insertion and the proper use of screw guides and drill guides, and incision and detachment of the periosteum reduces the postoperative pain response [71–74, 84]. Predrilling was shown to reduce temperature during pin insertion, which is further lowered by using cooling during the drilling procedure [85]. After pin placement the internal fixation of the intra-articular fragments is performed by individual fixation and the external fixator is applied at the end of the operation in neutral ulnar/radial abduction and slight dorsal extension to allow for full power grip [79]. Special attention is paid to the position and alignment of the carpus and any intracarpal rotation, which can be corrected by ligamentotaxis. Overdistraction should be detected and released.

Reduction technique (ligamentotaxis)

Gupta outlined the principle of ligamentotaxis in the treatment of distal radius fractures in a prospective study in 204 consecutive patients using closed reduction and plaster immobilisation [86]. After comparing three different positions of the wrist in plaster (palmar flexion, neutral and dorsiflexion) he showed the lowest incidence of redisplacement, especially of dorsal tilt, and the best functional results with a dorsiflexed immobilisation of the wrist. He showed clearly that in palmar flexion the dorsal carpal ligament is taut, but cannot stabilise the fracture because of its lack of attachment to the distal carpal row. The deforming forces and the potential displacement of the fracture are parallel and in the same direction. In dorsiflexion, the volar ligaments are taut and tend to pull the fracture anteriorly, thereby placing the deforming forces at an angle, which tends to reduce the displacement of the fracture. This tightening manoeuvre of the volar ligament complex is termed “Gupta’s manoeuvre” or multiplanar ligamentotaxis.

In 2000 Dee et al. showed that by using an external fixation with two ball joints, this manoeuvre can be integrated into the reduction technique for comminuted distal radius fractures [79]. After preliminary restoration of radial length, the proximal ball joint is adjusted to the radiocarpal joint space and the distal ball joint is set to the so-called centre of rotation of the wrist joint (between capitate and lunate, Fig. 6). Palmar translation of the carpus in the unlocked proximal ball joint provides restoration of the physiological palmar tilt, while traction via the radiodorsal ligament complex adjusts the distal fragment with no need for flexing of the wrist. The distal part of the fixator is extended dorsally in the midcarpal level and the distal ball joint then locked. As discussed before, flexion in midcarpus does not control the dorsally tilted distal fragment because of the mainly proximal insertion of the dorsal wrist ligaments on the proximal carpal row [86], but translation and dorsiflexion tethers the stronger palmar ligaments, thus stabilising the reduction result while the added longitudinal traction protects against redisplacement.

Overdistraction led, in their clinical series, to loss of reduction and dorsal tilt of the fragment and a pressure rise in the carpal tunnel. This reduction technique allowed for anatomical positioning of the distal radius in neutral or even dorsiflexion and avoids overdistraction and the so-called "extrinsic-extensor-plus" position (Cotton-Loder or Schede position), which may lead to finger stiffness and increased carpal tunnel pressure. Free MP joint motion is the major clinical indicator of the correct use of the Gupta multiplanar technique. Ligamentotaxis can only be transmitted to the fragment with intact capsular attachments and therefore can only be executed after refixation of the ligament-bearing fractures of the distal radius.

Mobilisation of the external fixator

The benefit of unlocking a transarticular fixator at the wrist joint level to allow for early mobilisation is a matter of debate. While the beneficial effect of limited motion on cartilage water content and proteoglycan synthesis was demonstrated by Behrens et al. in animal experiments in the dog knee [87] and on wrist function in a clinical setting [88, 89], the clinical benefit of mobilising a transarticular wrist fixator has not been demonstrated so far [83]. In a prospective, randomised study, Sommerkamp et al. compared the results of a dynamic external fixation (the Clyburn device) with those of static external fixation (the AO/ASIF device) [83]. Mobilisation of the wrist in the dynamic-fixator group provided little gain in the mean motion of the wrist at the time of the removal of the fixator and at follow-up. On the contrary, motion of the wrist in the dynamic-fixator group resulted in a statistically significant loss of radial length compared with that in the static-fixator group and complications were more frequent in the dynamic-fixator group.

In our opinion and experience, strict radial application of the fixator pins, with correct alignment of the mobilisation axis to the main centre of motion of the wrist and avoidance of overdistraction, may be the critical points to achieve the beneficial effect of mobilising the transarticular external fixator [13].

Different operative techniques and implants for internal fixation

Column model

Jakob et al. showed that the distal radius and the distal ulna form a three-column biomechanical construction [90]. The medial column is the distal ulna, the triangular fibrocartilage and the DRUJ. The intermediate column is the medial part of the distal radius, with the lunate fossa and the sigmoid notch, and the lateral column is the lateral radius with the scaphoid fossa and the styloid process. They were able to achieve stable internal fixation with two 2.0 AO titanium plates placed on each of the 'lateral' and the 'intermediate' columns of the wrist at an angle of 50°–70° [89].

Different implants and techniques

In recent years, it became clear that anatomic reduction and internal fixation with plates with minimising intra-articular incongruency led to an excellent or good functional outcome [8, 10, 91]. A variety of internal fixation plates have since been developed with emphasis on biomechanical testing and the clinical use of angle-stable implants [8, 30, 32, 35–37, 40, 92–95]. The clinical and functional benefit of these new implants has not so far been demonstrated (see section 'Evidence-based medicine and meta-analyses, randomised trials'). Several authors have recommended the supplementary use of arthroscopic techniques to improve anatomic reduction [2, 5, 96] and have shown the benefit of supplementary use of external fixation after articular joint reconstruction [9, 10, 97].

Lunate facet fragment

Axelrod et al. and Apergis et al. have shown clinically the importance of addressing the lunate facet fragments, either palmar or dorsal first, in order to reconstruct the DRUJ [98, 99]. In our opinion this is crucial for restoration of forearm rotation, and therefore reconstruction of the articular surface should start with the intermediate column [90].

Preferred operative technique: the minimal invasive osteosynthesis technique (MIOT)

The preferred operative technique of the authors is based on the experience with treating 250 comminuted distal radius fractures according to a prospective protocol. After application of a monolateral fixator with double ball joints for multiplanar ligamentotaxis, minimal internal osteosynthesis is performed.

After careful analysis of the trauma X-rays, a CT-scan is carried out in all AO type C fractures (Figs. 9, 10). The operation is performed under general or regional anaesthesia on a hand table; a tourniquet is advised. Based on the CT scans the surgical approach is chosen to allow a minimally invasive technique. Fractures involving the volar lip will require a volar approach, those involving the radial styloid alone may required a radio-dorsal or radio-volar approach, and those that are dorsal intra-articular will require a dorsal approach, through the appropriate tendon compartment.

The most common application is on the volar side. A 3–4-cm straight incision is made radial to the flexor carpi radialis tendon in order to protect the median nerve, staying close to the tendon in order to avoid an injury to the radial artery (Figs. 11 and 12). The tendon of the flexor pollicis muscle is identified and the pronator quadratus exposed. If the pronator quadratus is intact, an L-shaped elevation of the muscle with an incision based on the radial styloid and close to the volar lip is performed (Fig. 13). If there is an injury to pronator quadratus, the laceration may have to be included in the approach.

The fracture lines are exposed and most commonly two fragments will be visible. It is advisable to start with the ulnar-sided fragment, which will restore congruency to both the radio-carpal and the DRUJ (Fig. 14). Commonly a two- or three-hole T-shaped miniaturised implant is used in this position. Fine-wire screws (FFS) with a snap-off are used and the first to be inserted is the one proximal to the fracture line [100]. It is inserted through the slotted hole and should not be driven home completely to allow fine tuning of the implant position. The FFS snap-off screws are loaded directly in a Jacob's chuck. Commonly a 15-mm FFS snap-off screw with the washer is used in this position. Once the position of the implant is correct, the FFS snap-off screws close to the joint are inserted in the transverse position of the T. Here commonly 19- or 21-mm snap-off screws with washers are used. Once the two screws in the horizontal position have been inserted, a fourth screw is inserted into the long part of the T, usually 13 or 15 mm. An X-ray is taken to confirm the correct reduction of the volar ulnar fragment of the radius (Fig. 15). Reattachment of the radial styloid fragment can be performed with a straight implant of three or four holes, an L-shaped or a hockey stick shaped implant (Fig. 16). All these implants are anatomically precontoured and have the feature of a slotted hole to allow fine tuning of the position. Again, the first FFS snap-off screw to be inserted is the one just proximal to the fracture line through the slotted hole. This is not driven in completely and on average has a length of 15 mm. After correctly positioning the implant and maintaining the reduction of the fragment, the most distal screw hole is filled with an FFS snap-off screw

Fig. 9 Conventional X-ray of the right side in a 28-year-old male patient after a high-velocity injury (motorbike accident)

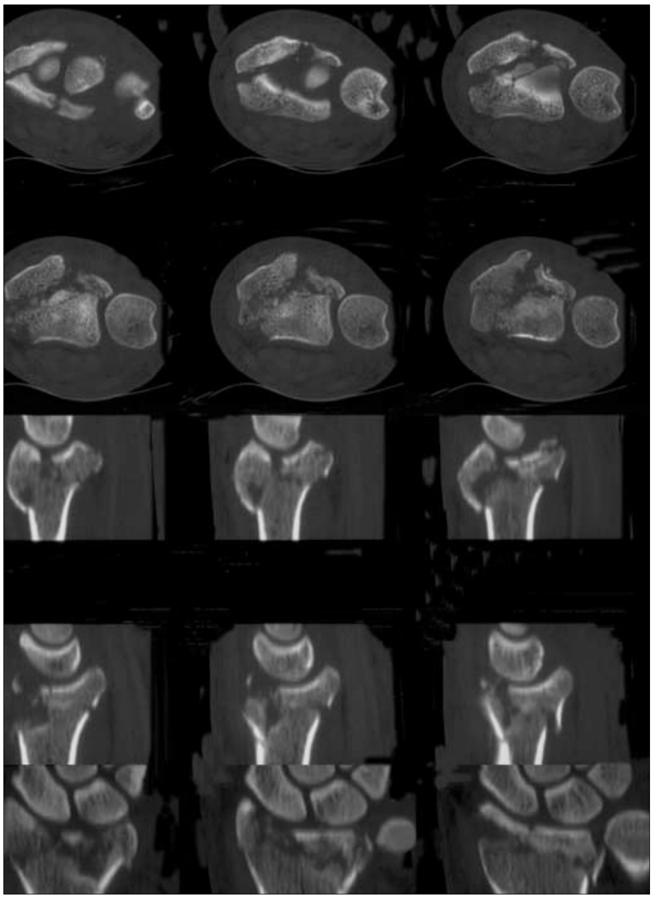

Fig. 10 CT scan of the right wrist after reduction in finger-trap traction and application of a dorsal and palmar cast allows for detailed analysis and classification of the fracture. According to the CT classification the fracture was classified as type II (dorsal split with dorsal dislocation of the carpus)

Fig. 11 Intraoperative images of the palmar approach: after marking the distal radioulnar joint and the palmar lip on the skin (using image intensification) a 3–4-cm straight incision is made radial to the flexor carpi radialis tendon (*left*); the pronator quadratus muscle is exposed, using Langenbeck retractors (*right*)

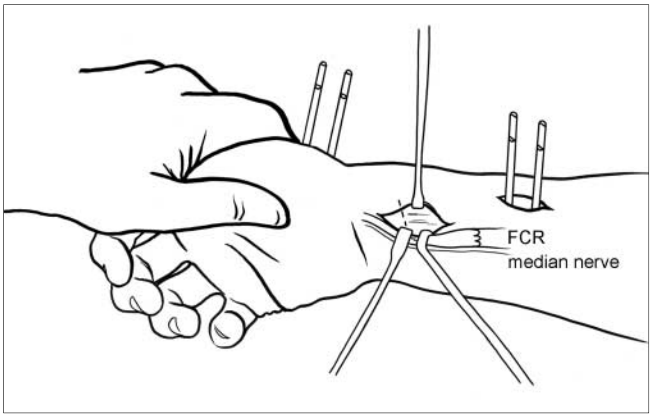

Fig. 12 Schematic drawing of the palmar approach: Langenbeck retractors are used on the ulnar side to protect the median nerve, which is ulnar to the flexor carpi radialis tendon (*FCR*)

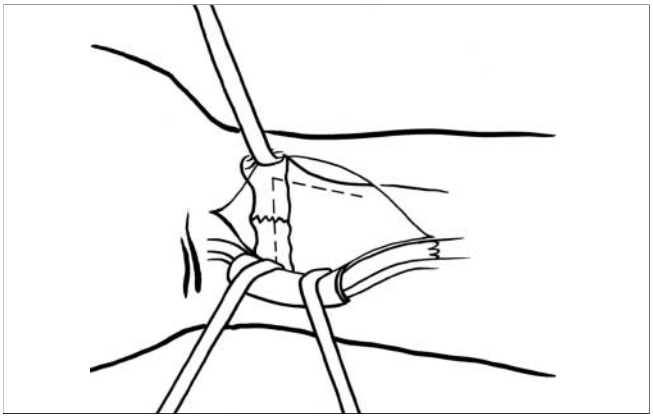

Fig. 13 Schematic drawing of the palmar approach after L-shaped incision of the pronator quadratus muscle; the muscle is placed under the Langenbeck retractor for protection of the ulnar-sided structures

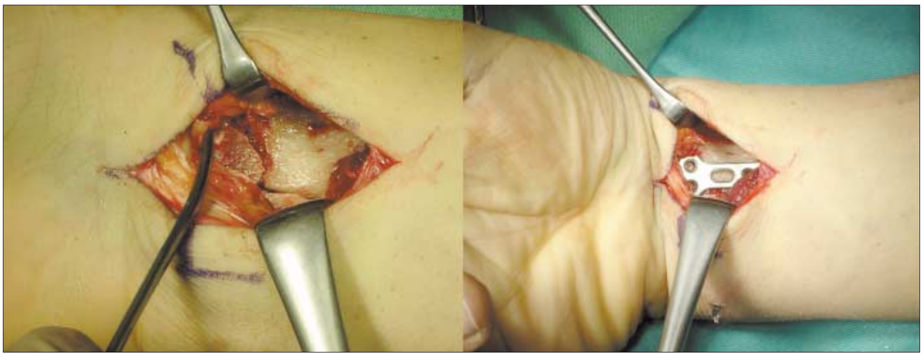

Fig. 14 On the left, disimpaction of the ulnar-sided palmar fragments is demonstrated, and on the right a T-shaped miniaturised implant is inserted to reconstruct the ulnar-sided palmar fragment

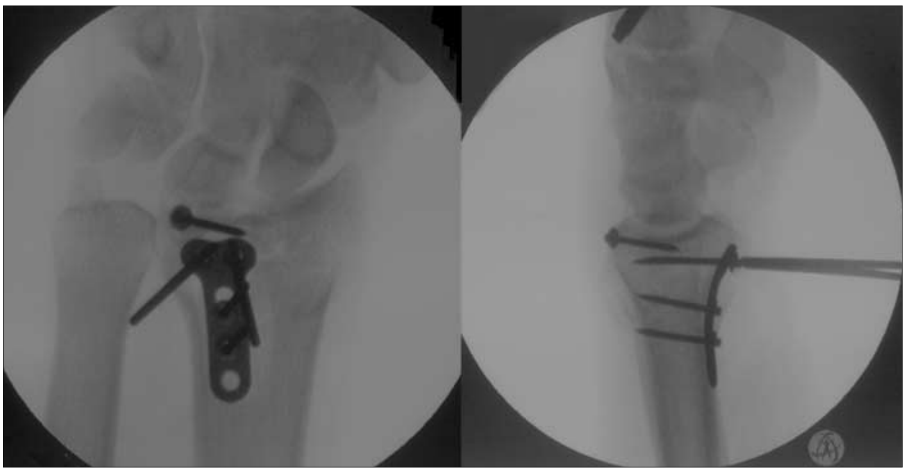

Fig. 15 Printouts of intraoperative image intensification demonstrating reconstruction of the ulnar die-punch fragments (intermediate column) with dorsal and palmar implants

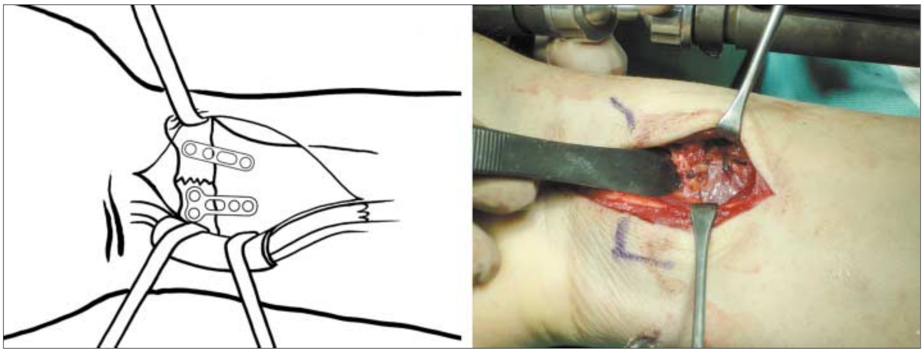

Fig. 16 Schematic drawing of the implants used for reconstruction of the palmar articular surface: a T-shaped implant is used for the ulnar die-punch fragment and a straight implant is used for the radial column (or styloid) fragment; the intraoperative image on the right shows the closure of the pronator quadratus muscle

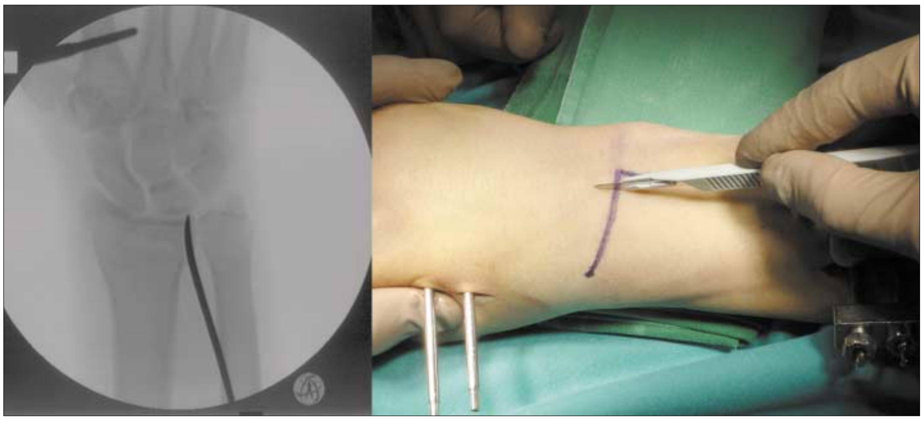

Fig. 17 Intraoperative images of the dorsal approach: after marking the distal radioulnar joint and the dorsal outline of the radius on the skin (using image intensification) a 1-cm straight incision is made radial to the distal radioulnar joint over the fourth extensor tendon compartment

Fig. 18 Intraoperative images of the dorsal approach: after identification and incision of the extensor retinaculum (*left*) the dorso-ulnar facet fragment is elevated, reduced and fixed with a fine-threaded screw with a washer

with a washer aiming at the tip of the radial styloid and X-rays are taken to confirm the position (Fig. 15).

Once the correct position has been confirmed radiographically, the remaining holes are filled with screws of appropriate length. The screw tips should not be protruding from the dorsal side and should sit inside the cancellous bone or just inside the cortical bone. Assessment of the dorsal pathology should now be performed. If the dorsal fragments can be reduced by ligamentosis, reduction can be maintained with transarticular external fixation.

Dorsal approaches in general require a CT scan in order to understand the position of the articular fragments (Fig. 10). An approach through the appropriate tendon compartment is performed after marking of the joint line and the dorsal aspect of the DRU joint under image intensification (Figs. 17 and 18). In general single screws or straight implants with three, four or five holes are used. In most cases it will be sufficient to use the implants as a buttress splint with a first FFS snap-off screw being inserted through the slotted hole. Division of the extensor retinaculum is generally advisable to distance the gliding tendons from the implant. Again a limited incision is sufficient (Fig. 17). A second screw is inserted in the proximal fragment and these screws measure in general 15 mm for the first and second screw. The remaining hole(s) do not necessarily have to be filled with screws if they act as a buttress splint. If the fragment is large enough or if the surgeon has to stabilise one solid fragment an FFS snap-off screw may be inserted through the distal holes. Again verification of the correct implant position and length is required by obtaining a radiograph (Fig. 19).

Bone grafting may be required if a corticocancellous bone defect cannot be reconstructed. Bone is best taken from the ileum with the use of a trephine and should con-

Fig. 19 Printout of intraoperative image intensification demonstrating reconstruction of the dorsal and palmar die-punch fragments and the styloid fragment

sist of cancellous and corticocancellous material. An alternative donor site is the olecranon. The void should be filled with the graft either prior to or after application of the MIOT distal radius system.

Closure of the volar wound is begun with reinsertion of the pronator quadratus muscle, which is best done with the arm in neutral rotation (Fig. 16). It has to be insured that the gliding of the flexor pollicis tendon is not impaired. The tourniquet is opened prior to closing of the wound to control bleeding and a drain may be inserted. On the dorsal side it should be confirmed that the gliding of the tendons is not impaired by the implant. If a fracture dictates the position of an implant close to a tendon then early hardware removal after 6–8 weeks is advisable. It should not be carried out later than three months.

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