Computed Tomography and Pathobiomechanical-Based Treatment of Volar Distal Radius Fractures

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Abstract

Today, there are various classifications for distal radius fractures (DRF). However, they are primarily based on plain radiographs and do not provide sufficient information on the best treatment option. There are newer classifications that simultaneously consider the pathobiomechanical basis of the fracture mechanism and analysis of computed tomography images. Main determinants of which type of DRFs occurs are the strength/direction of the applied forces on the carpus and radius, and the position of the wrist relative to the radius during the fall. Reconstruction of the mechanism of injury provides information about which anatomic structures are involved, such as torn ligaments, bone fragments, and the dislocated osteoligamentous units. This article attempts to combine and modify current pathobiomechanically oriented classifications with an improved understanding of the "key fragments" to subsequently offer a treatment approach to stabilize these critical fragments through specific types of internal fixation.

Keywords

- distal radius fracture
- volar locking plate
- complications
- outcome
- radiological

Distal radius fractures (DRFs) are one of the most common upper extremity fractures occurring in adults.[1–7] In the past, DRFs were treated conservatively by closed reduction and immobilization or K-wires. However, secondary dislocations occurred with these procedures, requiring corrective and even salvage procedures.[8–10] After the introduction of volar angular stable locking plates in the 2000s and the excellent reported clinical outcomes, the incidence of surgically treated DRF increased significantly. The first volar plates were not angle stable and have evolved from monoaxial to polyaxial angle stable screws. Thus, in the majority of cases, anatomic reconstruction can be achieved while simultaneously stabilizing a dorsally displaced DRF from volar without the increased risk of extensor tendon irritation.[11–15] Similarly, volar locking plate stabilization allows early active wrist rehabilitation without immobilization.[16–18] However, even the use of angle-stable plate fixation does not preclude secondary loss of reduction and possible resulting malunion, especially in cases with poor bone quality.[9,14,19]

For this reason, specific plate designs have been developed to increase stability and provide fixation options for each fracture type. Arthroscopically assisted techniques expanded the range of techniques, especially for the reduction of complex intra-articular fractures.[20–23]

With this progressive development, the optimal selection of the different treatment options became difficult, and an advanced biomechanical understanding of the different fracture types is necessary.[24]

The main objective of this work is to combine and modify current pathobiomechanical oriented classifications with an improved understanding of the "key fragments" to subsequently offer a treatment concept for stabilizing these critical fragments

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by specific types of internal fixation. In this context, fragment-specific fracture treatment includes analysis of radiographs (direction of dislocation), computed tomography (CT) scans (definition of the key fragment and fracture lines), and three-dimensional (3D) reconstructions/models (better fracture understanding and for teaching purposes).

This manuscript focuses specifically on volar fractures and key fragments of the distal radius and is only one part of the overall classification, which also describes other key fragments and nonkey fracture types. However, there are cases in which the other aspects must be considered. These remaining key fragments and nonkey type fragments are described in detail by Hintringer et al[24].

Classification of Distal Radius Fractures

Classifications of DRF have historically been based on plain radiographs only, tend to be descriptive with no conclusions for treatment. None of the existing classifications have proven to be usefully in helping the treating hand surgeon in decision-making for the best method of treatment. Equally, they failed due to a poor reproducibility and reliability, tend to be over-complex, and unable to classify the full spectrum of impairment and severity. As a result, they do not provide useful clinical insights. Furthermore, they do not take into account the mechanisms of injury and pathobiomechanics.[24,25]

The basic indications for surgery in DRF have also not been conclusively established to date. But particularly in young patients, most surgeons consider dorsal angulation >15 degrees, radial shortening >3 mm or intra-articular step-off >2 mm as indications for surgery.[26] In 1989, Lafontaine et al[27] identified five predictors of instability: dorsal angulation >20 degrees at presentation, dorsal comminution, intra-articular fracture, associated ulnar fracture, and age over 60 years. If three of these five predictors are present, the fracture is considered as potentially unstable and surgery is advised. However, recently Walenkamp et al[28] pooled the published data and found only a dorsal comminuted fracture, women and age over 60 years as significant risk factors for secondary loss of reduction. The matter is further complicated by the fact that there is strong evidence that patients over 60 years of age may not even benefit clinically from surgical treatment.[26,29,30]

Modern classifications include analyses of CT scans and 3D reconstructions, and they provide new insights, especially in intra-articular fractures.[31] Pechlaner[32] presented basic principles of fracture localization and formation on freshly frozen cadaveric-produced fractures. He showed that volar dislocated fractures can occur even in a dorsally extended wrist, depending on the point of impact. Similarly, the importance of ligament attachment points in dislocated fractures were classified as a function of the applied forces.

Mandziak et al[33] showed the correlation between fracture lines and insertion points of ligaments on the volar and dorsal aspect of the radius. Bain described the three fragments (volar ulnar corner, dorsal ulnar corner, and radial styloid) that make up the majority of the two-part intra-articular DRFs.[34] Each fragment has a ligament attached and coined the term "osteoligamentous unit," as each fragment includes its associated ligament. Brink used this concept, and added the distal ulnar, and referred to these as the four key fragments (volar, dorsal, radial, and ulnar key fragments).[35] In addition, we consider there to be a further key fragment, the central key fragment, which consists of only the central aspect of the articular surface.[24] It has no ligament attachments and therefore is not an osteoligamentous unit, but it is an important key fragment in the assessment and management of DRF.

Pathobiomechanics of Distal Radius Fractures

Basic requirements for regular motion of the carpus are (1) uninjured bonestock of the radius and ulna; (2) intact intrinsic ligaments connecting the bones of the proximal carpal row, forming a geometrically variable condyle relative to the immobile distal radius and distal carpal row; and (3) intact extrinsic ligaments coordinating the proximal row with radius and ulna against the distal carpal row, which acts like a rigid monolith (►**Fig. 1**).[36]

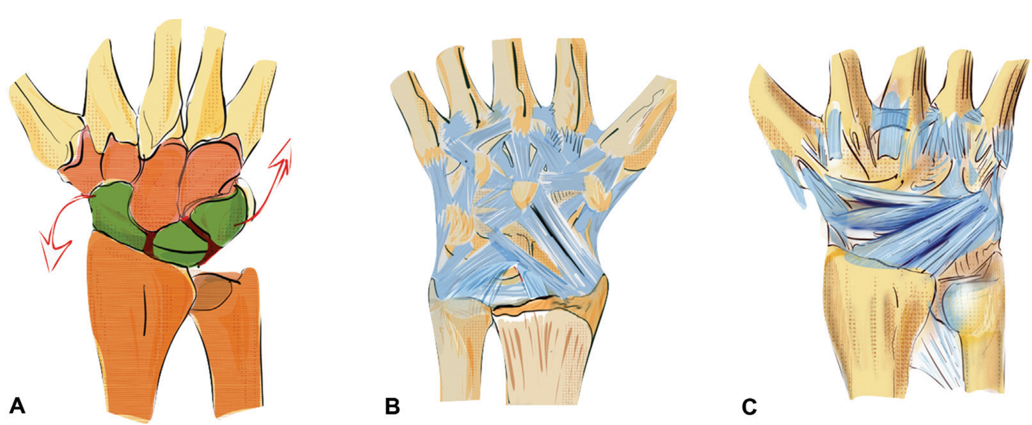

Fig. 1 Prerequisite for physiological biomechanics is an intact bone stock. (**A**) The first carpal row acts as an intermediate segment between the two other fixed partners (distal radius and distal carpal row) and is connected with short intrinsic ligaments. (**B**) Volar extrinsic ligaments: long extrinsic ligaments coordinate movement between the carpal rows and hold the lunate in position in the middle of the first row with a strong attachment. (**C**) Dorsal extrinsic ligaments coordinate movement on the dorsal side and help control the first carpal row. Image courtesy: Hintringer et al.[24]

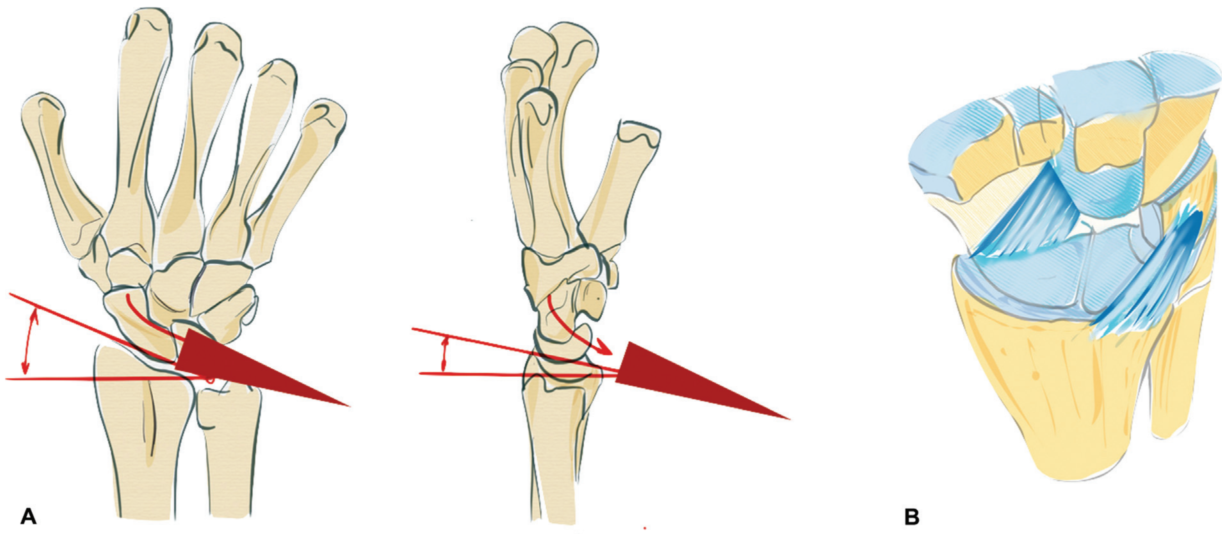

Fig. 2 Anatomical considerations. (**A**) The carpus tends to slide radially and ulnarly along the slope of the articular surface of the radius. (**B**) The extrinsic ligaments act dorsally and volarly and form together a sling against the displacing forces. Image courtesy: Hintringer et al.[24]

The dorsal and volar extrinsic ligaments counteract the physiological tendency of the carpus to slide ulnarly and volarly along the radial and volar inclination of the distal radius (►**Fig. 2A**). These extrinsic ligaments consist on the dorsal side of the wrist in the so-called dorsal "V-ligaments" and volarly in the proximal and distal "V-ligaments." Together they hold the carpus in position (►**Fig. 1A**) and form a sling around the wrist to provide resistance against the occurring forces (►**Fig. 2B**). The rather strong volar ligaments support the proximal row like a belly tie and act against forces to the volar and ulnar side like a traction band.[34]

In event of a fall on the extended wrist, either rupture of the ligaments, or if they remain intact, compression fracture of the dorsal or volar aspect of the distal radius can occur (►**Fig. 3A–C**).[35] In addition, both radial and ulnar fractures can occur depending on the direction of the acting forces (►**Fig. 4A**). Direction of the acting forces in relation to the position of the wrist determines the location of the resulting fractures (dorsal, volar radial, and ulnar) in the distal radius (►**Fig. 4B**). The interaction of these parameters results in specific fracture types.

The question arises whether the fracture lines have a distinct pattern or whether the fracture lines are random. Pathobiomechanical studies suggest that they typically occur between the attachments of the extrinsic ligaments on the distal radius (►**Fig. 5A, B**). Particularly, in two fragment fractures, the lines occur in the area between the ligamentous insertion zones.[33,37]

Intra-articular fractures show six different fracture patterns and at least one part of the articular surface remains in union with the shaft (►**Fig. 5A, B**). Biomechanically, these fragments form an osteoligamentous unit tending to dislocate in predefined directions depending on the region of the origin ligaments.

Volar Key Type Fractures

Volar Lunate Facet Fragment

Volar key fragments are induced by volar acting forces to the distal radius and result in fractures of the volar articular surface (►**Fig. 6A–E**). This may result in volar depression or volar cortex fractures. The occurring volar articular fractures

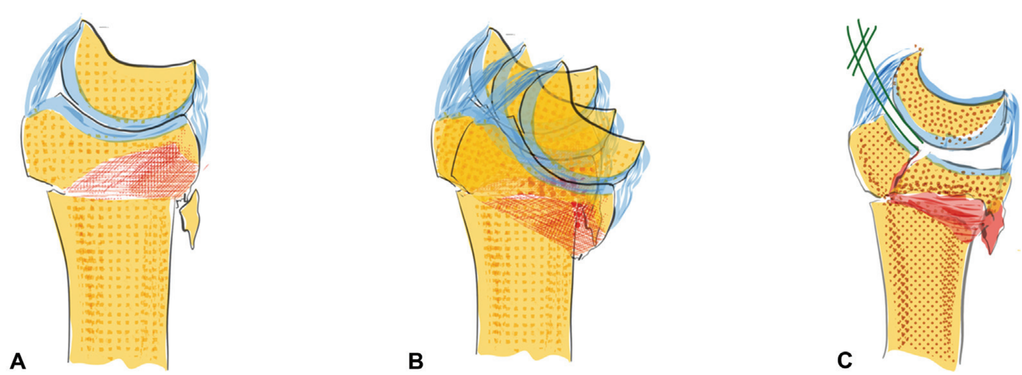

Fig. 3 Distal radius fracture origin. (**A, B**) Dorsal forces on the wrist produce dorsal compression fractures due to the leverage created by the volar extrinsic ligaments. The volar ligaments act as tension bands and produce additional volar avulsions. (**C**) If a compression component is added, intra-articular fractures with volar dorsal or radial key fragments occur. Image courtesy: Hintringer et al.[24]

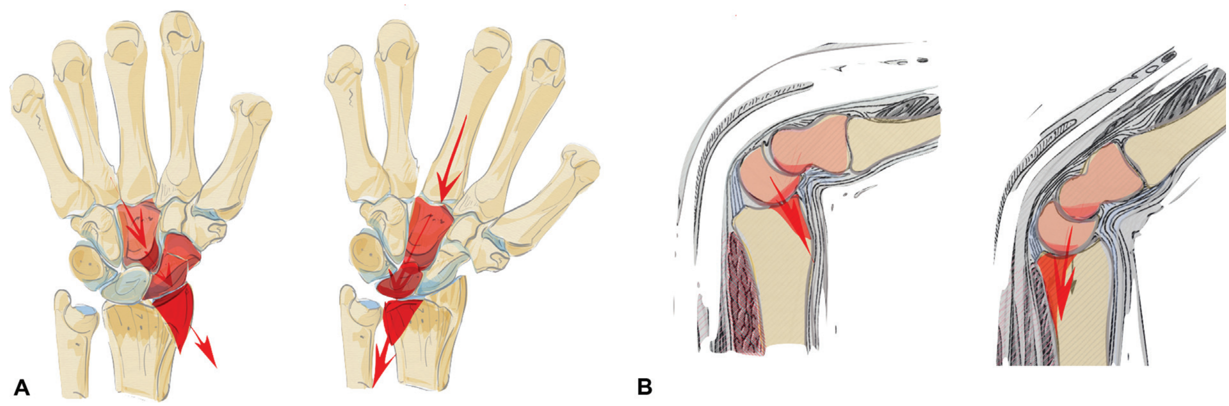

Fig. 4 Origin of the key fragments. (**A**) Depending on the force applied, radial-sided, or ulnar-sided fractures occur. In the first image, the applied force is transmitted via the capitate, scaphoid, and finally radial styloid, resulting in a radial-sided fracture. The second image shows a transmission of the applied force trough the capitate, lunate, and sigmoid notch, resulting in an ulnar-sided fracture. (**B**) A dorsally extended wrist does not necessarily result in a dorsally dislocated fracture. Depending on the direction of the applied force, dorsal or volar fractures may occur. Image courtesy: Hintringer et al.[24]

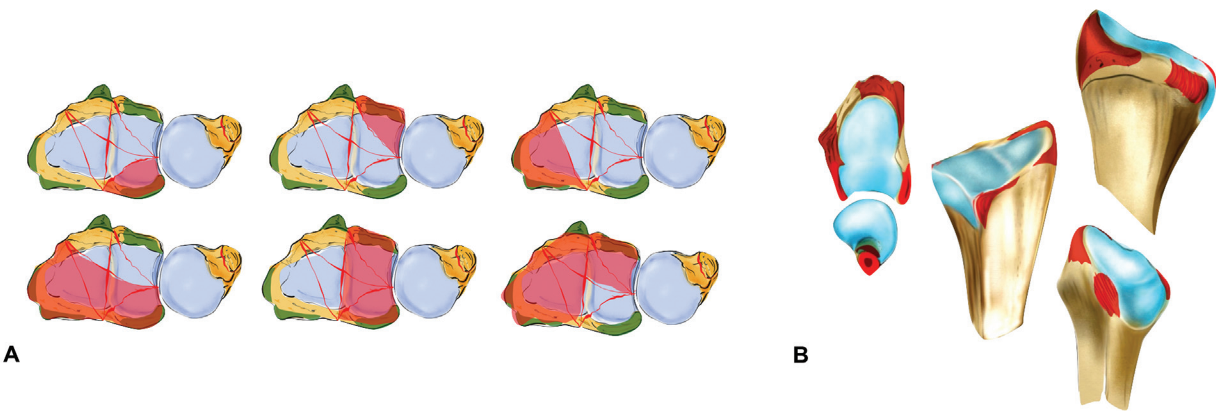

Fig. 5 Partial intra-articular fractures. (**A**) Six different patterns can be observed in partial intra-articular fractures. At least one corner remains intact and in continuity with the shaft. (**B**) The origins of the extrinsic ligaments are shown, which appear to reinforce the bone. Image courtesy: Hintringer et al.[24]

can be either small or large fragments (►**Fig. 6A**). Type of the developed fracture largely depends on the position of the dorsally extended wrist during the fall. They may be isolated fractures of the ulnar-volar rim as well as of the entire volar rim of the radius.[32]

The volar V-ligaments reinforce the proximal row against dislocation. If the fracture includes the ligamentous insertion, the entire carpus tends to dislocate to the volar side along with this as an osteoligamentous unit. As the ulnocarpal and volar radioulnar ligaments are the main stabilizers of the distal radioulnar and ulnocarpal joints, fractures of the volar ulnar rim (origin of these ligaments) result in destabilization of the radiocarpal, and sometimes of the radioulnar joint.

Volar Rim Fragment

Volar rim fractures with smaller fragments (called rim fragments) are often missed on plain X-rays and tend to show a higher degree of instability (►**Fig. 7A–G**).[4,19] In addition to these bony injuries, accessory ligament lesions are possible. Volar rim fragments have different sizes and shapes (►**Fig. 8A–C**). The formation of the fragments depends on the type of applied force (axial and/or volar) and volar edge blocks are formed, which can extend far into the socket.

The more tangentially the force is applied, the smaller become the fragments (shear fragments). They may be located exclusively volar ulnar (►**Fig. 7B**) or include the entire width of the volar radius rim (►**Fig. 7C, D**). Not only volar forces lead to volar edge fragments, but also dorsally dislocated fractures can cause ligamentous avulsion fragments (**7E–G**). These fragments are often dislocated dorsally, twisted during the subsequent reduction, and often come to lie 180 degrees inverted volar (►**Fig. 9**).

The position and shape of these fragments can be used to draw conclusions about the originating mechanism and the residual instability. It is also decisive whether the force is applied symmetrically from dorsal to volar or a certain rotational moment is present. In the former case, complete radioulnar edge fragments are formed. In the second case (rotational moment), purely ulnar edge fragments emerge. If the force is directed to the volar and rotational radially, purely radial shear fragments can also occur.

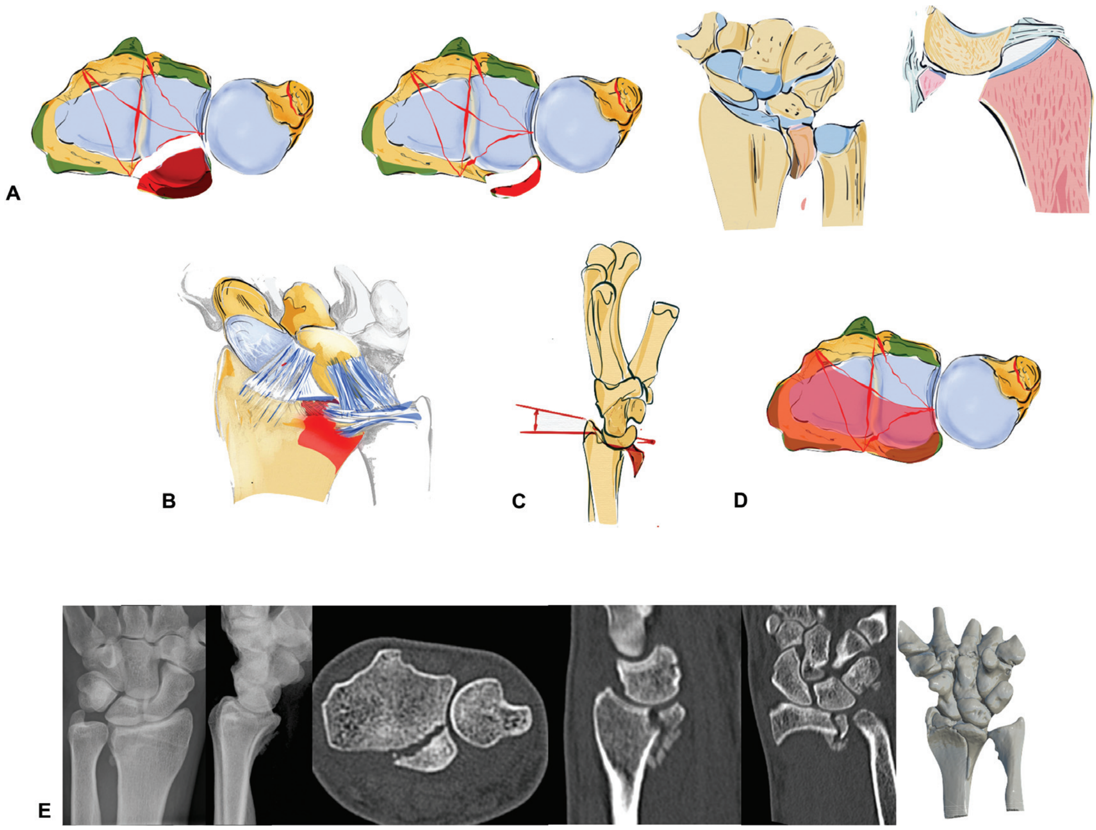

Fig. 6 Volar key fragment. (**A**) The volar-ulnar osteoligament unit can be either a large or a smaller rim fragment. It may be either ulnar or radial and also involve the entire volar radial rim. Dislocation is in volar direction, although the dorsal ligaments may remain intact. (**B**) Volar-ulnar fragment: origin of the important radioulnar and ulnocarpal ligaments. (**C**) The osteoligament unit dislocates volary. (**D**) In extreme cases, a complete radioulnar fragment is possible. (**E**) The small volar rim fragment is barely visible on the plain X-rays. It is best identified on the axial CT scans. The lateral images also show the degree of volar displacement of the entire carpus. Image courtesy: Hintringer et al.[24]

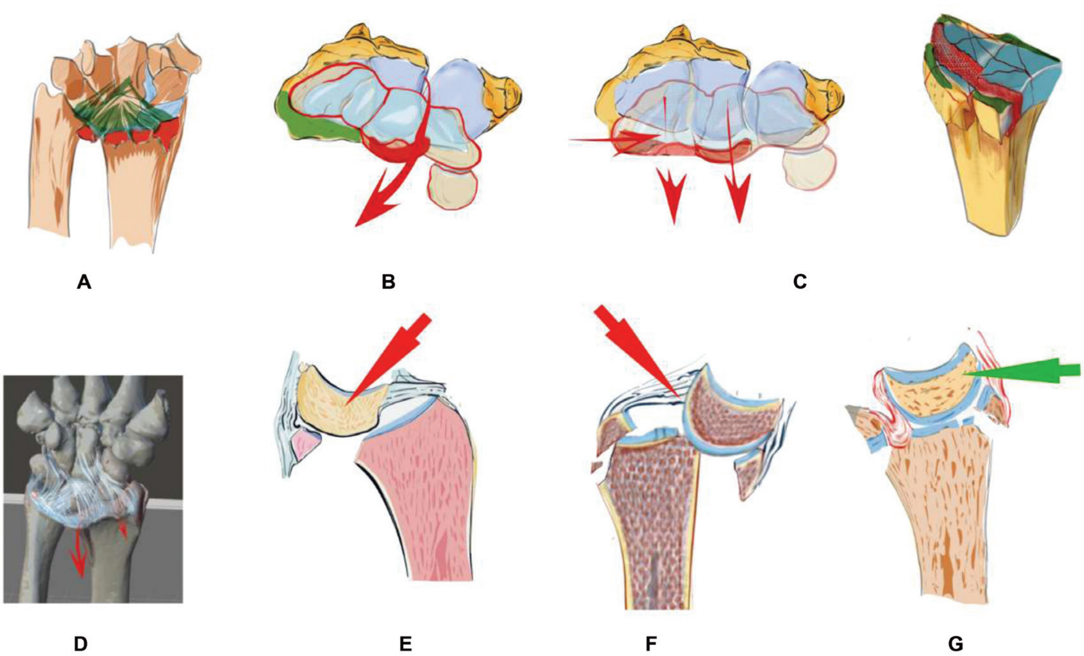

Fig. 7 Volar rim fractures. (**A**) Volar rim fragments over the entire width of the carpus with ligamentous attachments forming osteoligamentous units. (**B**) Rotatory dislocation of the carpus with isolated ulnar rim fragment. (**C–D**) Symmetrical volar dislocation of the carpus in a complete radio-ulnar shear fracture simulation of the volar ligamentous apparatus on the three-dimensional model. (**E**) Formation of the volar rim fragment during tangential acting force to the wrist joint. (**F**) Tear-out of the volar rim fragment with tangentially applied force to the extensor side and simultaneous shearing of a dorsal rim fragment. (**G**) Mechanism of inverting the volar rim fragment by 180 degrees during reduction.

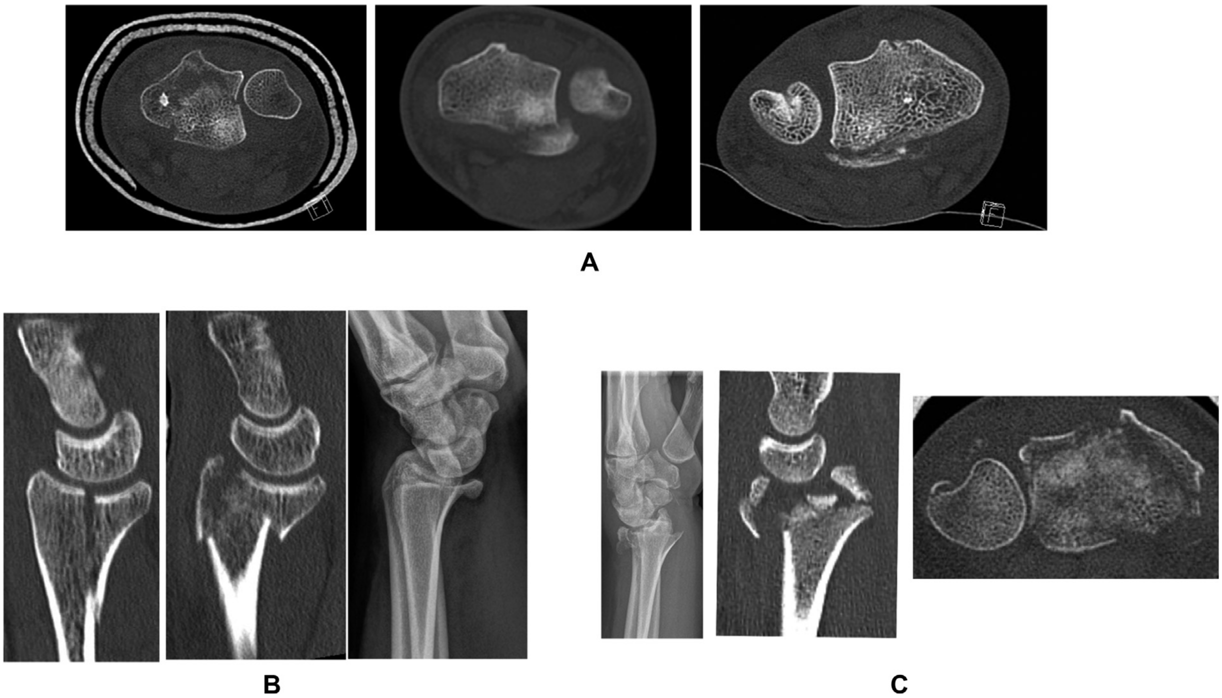

Fig. 8 Manifestations of volar key fragments. (A) Different sizes from volar key fragments, axial computed tomography scan. (B) Different sizes of volar fracture fragments cause volar luxation fractures because they have one thing in common: these fragments form osteoligamentous units with the carpus, which are displaced together in volar direction. (C) Dorsal and volar rim fragments 180 degrees rotated after dorsal dislocation of the carpus are indicators for multidirectional instability.

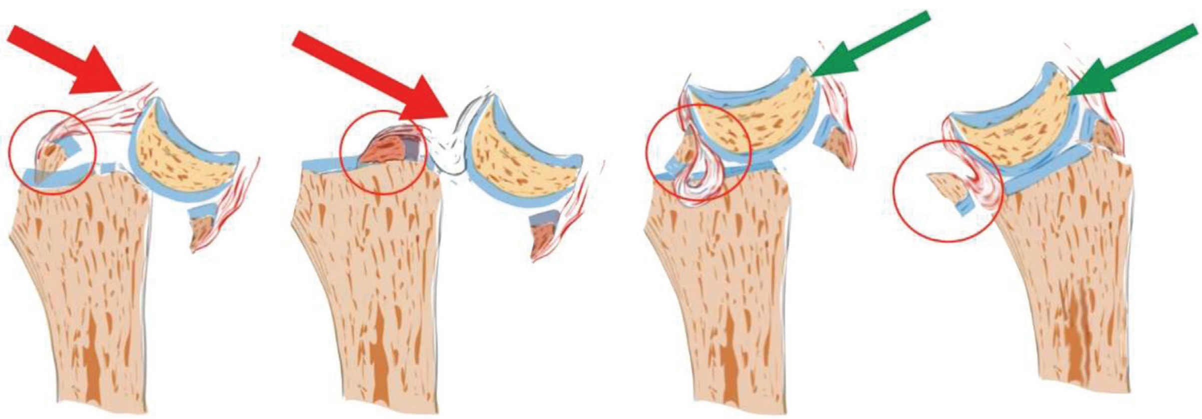

Fig. 9 Sequence of fragment displacement with dorsal dislocation. Subsequent reduction and inversion of the volar marginal fragment.

Radioulnar fragments dislocate symmetrically to the volar side, that is, scaphoid, lunate and triquetrum are displaced as a whole osteoligamentous block to the volar side, while in the case of a purely ulnar edge fragment the carpus is displaced rotationally on the ulnar-volar side. The scaphoid remains in the correct position on the radial side. Complete radioulnar edge fragments are more unstable than purely ulnar edge fragments.

The diagnosis of these volar edge fragments is best made on axial CT images, while they are often hidden on plain X-rays.

Process of Classification of Fractures of the Distal Radius

An absolute prerequisite for proper fracture classification is a plain radiograph in two planes and CT scan of the wrist. In addition, 3D reconstructions may be helpful in cases of intra-articular fractures. 3D printing of fractures appears to be a valuable teaching tool and may also add in plate fitting on a model. However, 3D reconstructions are mandatory for reconstructive osteotomies.

Plain radiographs provide an overview of the fracture, including the main direction of dislocation. CT scans allow a more detailed analysis of the articular surface of the fracture. However, in extra-articular fractures a CT scan is not mandatory in all cases. First, the axial image should be analyzed because only in this plane the location of the fragments in the sigmoid notch can be adequately assessed. Together with the other two planes, the entire 3D extent of the fracture can be recognized. The 3D imaging can be accompanied by 3D reconstructions.

Strategies for Selecting the Right Access and Implant Type

With the multitude of implants available on the market, it seems critical to consider which plate type is the best for stabilization, a particular fracture type from an economic standpoint. Not every fracture type necessarily requires the most expensive treatment.[14,38]

The first step is to determine the optimal approach and assess the necessary follow-up to prevent secondary dislocation of the carpus and fracture. This seems to be more important than perfect reduction.[26,39] Most modern plates are polyaxially angular stable and can stabilize the fracture with two rows of screws. Nevertheless, there are important aspects in the various forms of plates that are not commonly known.

The radially longer and more distal located plates, which have the advantage of grasping very radial and distal fragments, do not take into account the watershed concept. In contrast, the so-called watershed plates are ulnar longer and must be positioned proximal to the watershed line. They do not compromise the flexor tendons but offer limited ability to grasp and stabilize very distal fractures of the distal radius.[8,40,41] For volar-ulnar fragments, special plates are available that are designed to hold very distal ulnar fragments.[42] Cannulated self-tapping screws are becoming increasingly popular for the treatment of single fragments, especially in minimally invasive arthroscopically assisted methods.

Treatment Options for Different Volar Key Type Fractures

After classification of the fractures, recognition of the decisive key-type fragment represents the basic decision for optimal treatment. Volar plates should be used to treat volar key type fractures. Distinctions must be made between the various possible fragment locations and configurations: is it ulnar only, or is it a marginal fragment, or does it extend over the entire volar margin of the distal radius? (►**Fig. 10A**)

Volar Lunate Facet Fragment

The so-called watershed plates offer the best fixation method for ulnar volar fragments because they can be mounted very far ulnar distally (►**Fig. 11A, B**). At the same time, they do not compromise the flexor tendons on the radial side and are specially designed for stabilization of the lunate facet. These very narrow plates minimize contact with the flexor tendons but can only be used for limited indications.

Volar Rim Fragment

For very small volar marginal fragments that cannot be adequately stabilized with a single plate, alternatives such as small hook plates, screws, and special plates with attached

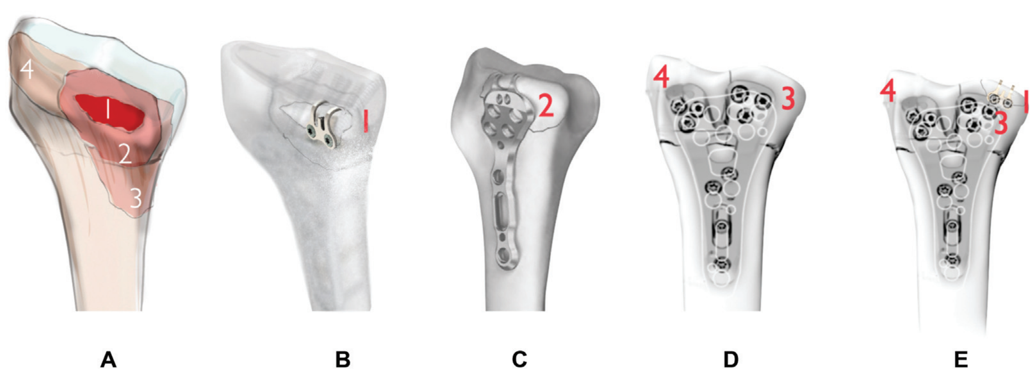

Fig. 10 Different ulnar orientated volar plates for the distal radius. (**A**) Various volar key fragments: (1) narrow rim fragment, (2) fragment extending just into the metaphysis, (3) ulnar volar block fragment, and (4) additional radial volar fragment. (**B**) Hooke plate grasps small volar rim fragment. (**C**) Special plate for ulnar volar larger rim fragments. (**D**) Watershed plates for radio-ulnar edge fragments, where the Y-shaped plate has a gap for the flexor pollicis longus tendon. Thus, the plate can be mounted more distally than other plates without compromising the Soong concept.[41,43] (**E**) If a small rim fragment is present in addition to a large volar metaphyseal fragment, hook plates can be used in combination with a watershed plate.

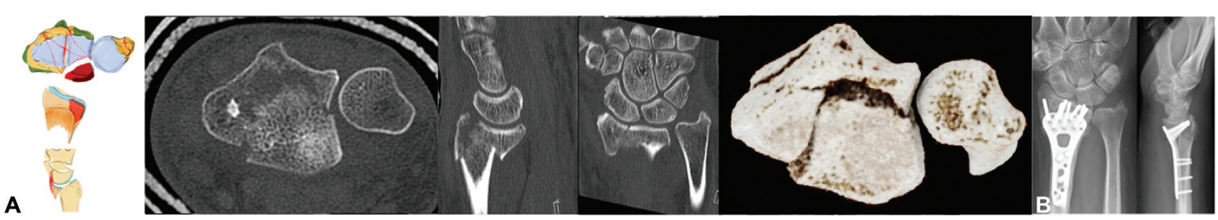

Fig. 11 Treatment options for volar lunate facet fragments. (**A**) Schematic illustration of a volar lunate facet fragment. Computed tomography scans show a volar dislocation of the carpus with a big fragment of the fossa lunata. (**B**) The watershed plates are ulnar longer and radial shorter and can therefore be mounted very far distally and ulnarly to fix these fragments. Image courtesy: Hintringer et al.[24]

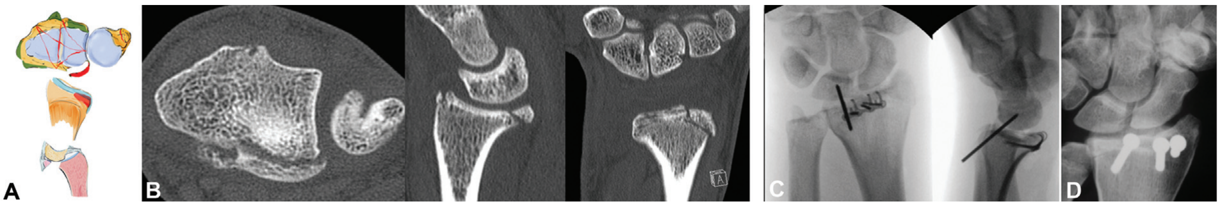

Fig. 12 Treatment options for volar rim fractures. (**A**) Schematic illustration of an ulnar volar rim fragment. (**B**) These small fragments can only be visualized on the computed tomography scan. (**C**) Small hook plates, (**D**) or screws can be used to fix these fragments. Image courtesy: Hintringer et al.[24]

hooks should be used for fixation (►**Fig. 12A–D**). This can increase stability and may prevent volar redislocation.

The size, location, and shape of these fragments determine the type of restoration (►**Fig. 10B–E**). While larger fragments can be addressed by plates extending ulnar distally, pure rim fractures must be stabilized by special claw plates (►**Figs. 11B and –12C**) or plates with attached claws (►**Fig. 10C**), because otherwise there is a risk that the complete first carpal row slips with the small rim fragment over the plate to the volar side. ►**Fig. 13** summarizes different possibilities to stabilize volar rim fractures.

After each stabilization, a translation test must be performed in a volar and dorsal direction (►**Fig. 14A**). If sufficient stability cannot be achieved despite stabilization of the small fragments, the carpus should be stabilized with a K-wire from the radius transarticularly into the lunate (►**Figs. 12C** and **14B**). In the case of symmetrical instability to the volar, a drill wire from the radius into the scaphoid can additionally increase stability.

Volar Radio-Ulnar Fractures

If the volar fragmentation runs over the entire aspect of the distal radius (►**Fig. 15A**) and this can be only the rim or also a bigger volar block, a wider plate can be used to embed these fragments (►**Fig. 15A–D**). Today, there are special plates with two separate arms that create a gap for the flexor pollicis longus tendon (►**Fig. 15D**). Theoretically, the tendon runs in this gap and the pressure on the tendon is reduced. The Soong classification for plate positioning in relation to the watershed line is not applicable for these plates.[41] As an alternative, special frame plates mounted far distally can be used. However, due to their position distally to the watershed line, early plate removal should be planned to avoid subsequent flexor tendon irritation or rupture.

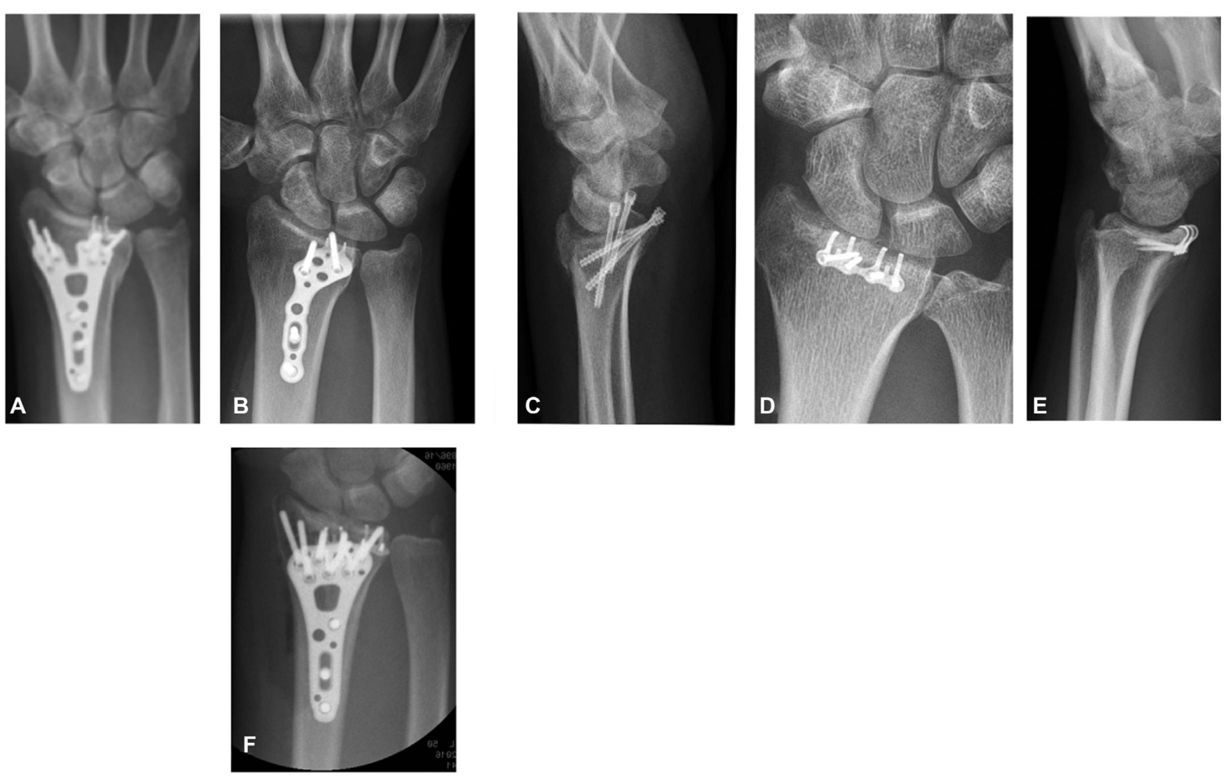

Fig. 13 Variety of volar plates for stabilizing volar ulnar key fragments. (**A**) FPL plate with a gap for the FPL tendon extends ulnar very far distally and can also reach a radial fracture due to the oblique arrangement of the screw holes. (**B**) Special hook plate for purely ulnar key fragments. (**C**) Double thread screws for boar rim fragments that must be large enough to catch them. (**D, E**) Hook plates bench for stabilizing narrow rim fragments. (**F**) Combination of a watershed plate with a hook plate for a combined fracture into the shaft. FPL, flexor pollicis longus.

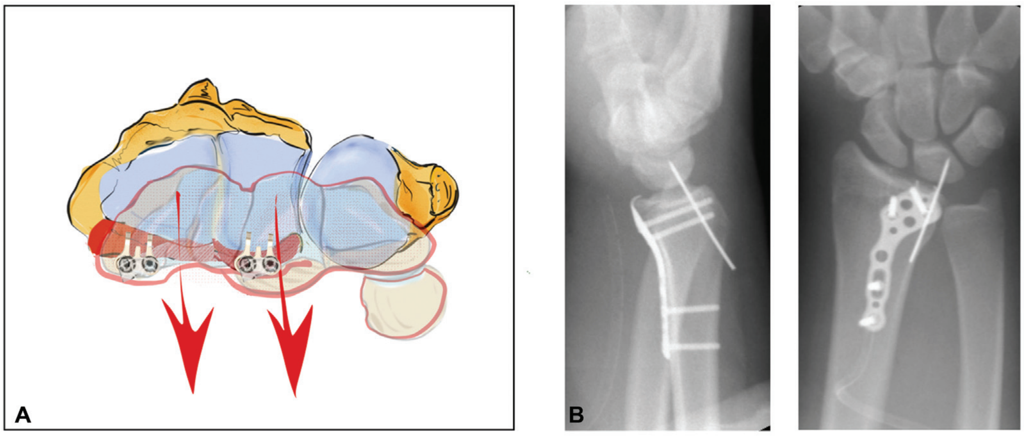

Fig. 14 Volar shift test and transfixation of the carpus. (**A**) After stabilization of volar rim fragments, a palmar shift test must always be performed, as additional ligamentous lesions may be present. If the carpus is unstable, it is recommended to drill a transfixing drill wire from the radius into the lunate in the correct position. (**B**) Transfixation of the carpus with the ulnar edge plate in place if the volar shift test is positive.

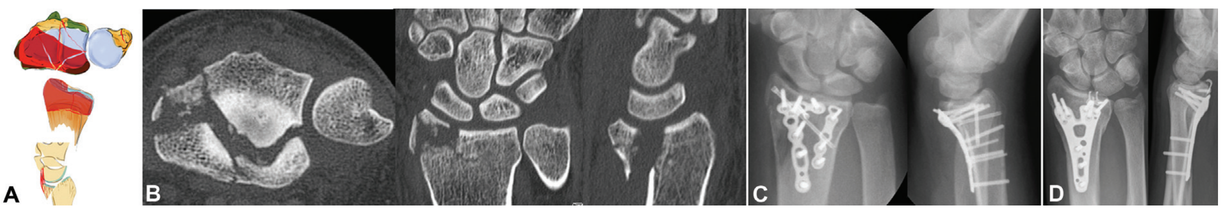

Fig. 15 Treatment options for volar radio-ulnar fractures. (**A**) Schematic illustration of a volar radioulnar key type fragment. (**B**) The fragment is easily identified in the axial computed tomography scan. (**C**) Long distal frame plates, fracture-specific plates or flexor pollicis longus plates (**D**) can be used in these cases. Image courtesy: Hintringer et al.[24]

Once the volar fragments are stabilized, testing for residual volar instability must be performed, as concomitant ligamentous lesions are often present. In these cases, the carpus must be temporarily transfixed to the radius in a neutral position of the lunate with one or two K-wires. The K-wires are removed after 6 weeks (►**Fig. 14A, B**).

Conclusion

Previous classifications of DRF were mainly based on plain radiographs and did not reflect the true severity and nature of the fractures. Furthermore, they are not clinically useful as they do not provide the treating hand surgeon with any guidance for the best method of treatment. Therefore, they are reserved for descriptive purposes or as research tools.[24–26]

More recent CT and pathobiomechanically based classifications include fracture mechanism and factors relevant to treatment and prognosis. Although the treatment of DRF has been revolutionized by the introduction of volar polyaxial angular stable plate systems, secondary dislocation may occur, leading to malunion or destruction of the articular surface with consequent osteoarthritis in the radiocarpal joint. In these cases, revision surgery and sometimes even rescue surgery such as radioscapholunate arthrodesis is often necessary.[7,8]

For preventing secondary loss of reduction many attempts were made to improve fracture fixation and different plate models emerged the market with the goal to increase stability. However, a basic understanding of the essential biomechanics in DRF is crucial to achieve sufficient stabilization and identify the so-called key fragments.[24]

The position of the wrist in relation to the distal radius during the fall plays a crucial role in the development of DRF. Similarly, the volar and dorsal radio- and ulnocarpal ligaments play an important role in stabilizing the carpus against its tendency to shift ulnar and volar along the radial and volar slopes of the distal radius. The fracture lines do not occur randomly but follow the insertion of the extrinsic ligaments and together form osteoligamentous units that act as key fragments in specific dislocations of the carpus. These key fragments should be given special consideration and stabilization in the treatment of DRF.

However, the present classification system of DRF with a focus on typical biomechanically important key fragments is based on previously published biomechanical studies and the experience/observations of the authors. It is intended to assist treating hand surgeons in selecting the best fixation method for these sometimes very difficult fractures. Likewise, there is still a lack of prospective studies confirming this key fragment-oriented treatment concept, apart from the authors' individual positive experiences.

Ethical Approval

Institutional review board approval was obtained for this study. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

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Conflict of Interest
None declared.

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