Imaging of Scaphoid Fractures According to the New S3 Guidelines

Bildgebende Diagnostik der Skaphoidfrakturen nach den aktuellen S3-Leitlinien

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Abstract

Up to 30 % of acute scaphoid fractures are missed in conventional radiography. CT and MRI should be early performed in the diagnostic workflow, when radiograms (dorsopalmar, lateral and Stecher's views) are negative or inconclusive in fracture detection. Significance of CT is different from that of MRI: Sensitivity of CT imaging (85 to 95 %) is superior to conventional radiography (about 70 %), but inferior to MRI (almost 100 %). However, CT (specificity 95 to 100 %) is able to provide more detailed anatomic information of the fracture pattern when compared to MRI (specificity 80 to 90 %). Particularly, differentiation of bone contusion ("bone bruise") and non-displaced fracture can be difficult in MRI. Thus, CT indication is not only given for fracture detection, but also for assessing the morphology in scaphoid fractures (localization, fragment dislocation, comminuted zones) and the fragment instability, too. MRI should be limited to equivocal trauma cases presenting pain in the snuff box, but with inconclusive CT findings. In CT and MRI of scaphoid fractures, image display must be aligned along the longitudinal extension of the scaphoid, either by acquiring or reformatting oblique-sagittal and oblique-coronal planes.

Key points
- Radiography can be limited to the dorsopalmar, lateral and Stecher's views in scaphoid fractures.
- In CT and MR imaging, the dedicated anatomy of the scaphoid has to be covered with oblique-sagittal and oblique-coronal images.
- CT provides most detailed information of scaphoid fractures (localization, fragment dislocation and instability pattern). However, its capability in detecting non-displaced fractures is inferior to MRI.
- All scaphoid fractures are seen in MRI. But differentiation of bone contusion (bone bruise) and a non-displaced fracture can be crucial.
- This order is recommended in the diagnostic algorithm of scaphoid fractures: 1. radiography, 2. CT, and 3. MRI.

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Zusammenfassung

In der Projektionsradiografie werden bis zu 30 % der Skaphoidfrakturen übersehen. Deshalb sollten die Schnittbildverfahren der CT und MRT großzügig eingesetzt werden, wenn die Projektionsradiogramme (dorsopalmare, seitliche, Stecheraufnahmen) keinen oder einen unsicheren Frakturnachweis ergeben. Die Aussagemöglichkeiten der Schnittbildverfahren müssen differenziert betrachtet werden: Die CT weist mit einer Sensitivität zwischen 85 % und 95 % mehr Frakturen als das konventionelle Röntgen nach, jedoch weniger als die MRT (Sensitivität annähernd 100 %). Demgegenüber liefert die CT (Spezifität 95 – 100 %) bessere anatomische Informationen zum Frakturmuster und zur Fragmentdislokation im Vergleich zur MRT (Spezifität 80 – 90 %), bei der die Differenzierung einer Knochenkontusion („bone bruise") gegenüber einer nicht dislozierten Fraktur schwierig sein kann. Neben dem Frakturnachweis ist die CT daher bei jeder Skaphoidfraktur zur Beurteilung der Morphologie (Frakturlokalisation, Fragmentdislokation, Trümmerzone) und der Stabilität indiziert. In unsicherer Situation sollte die MRT eingesetzt werden, wenn am symptomatischen Kahnbein mit der CT

der Frakturnachweis nicht gelingt. Die Schnittführung muss sowohl am CT als auch am MRT parallel zur Längsachse des Kahnbeins mit schräg-sagittalen und schräg-koronalen Schichten ausgerichtet werden.

Epidemiology and Problems

Scaphoid fractures are the most common injuries to the wrist, accounting for approximately 70 % of hand injuries. Even today they are overlooked or diagnosed only after development of scaphoid pseudarthrosis. The reasons for this can vary. The patient can minimalize the hand injury and not bother to get medical advice, or therapy is inadequate despite a proper diagnosis. A scaphoid fracture can only be properly detected based on symptoms and clinical examination ("snuff box" tenderness, compression pain at the base of the thumb). However, diagnosis has only 85 % sensitivity and a 40 % specificity [1]. The finding of the physical examination should be largely indicative of the need for radiological diagnosis which should be carried out as early as possible.
Based on experience, a scaphoid fracture is frequently not detected during the first medical consultation because initial imaging was limited to a projection radiograph, and a definitive diagnosis was not forthcoming. But subsequent diagnosis using CT and MRI examination may obscure the proper diagnosis if the clinical indication is insufficiently focused or cross-sectional diagnosis was performed using acquisition parameters that did not take into account the particular anatomy of the scaphoid.
The following overview is essentially based on the diagnostic section of the currently approved AMWF-S3 Guideline "Scaphoid Fracture" [2] and provides commentary on its contents.

Scaphoid Anatomy

Orientation

The scaphoid extends in two directions, and is oriented radially approx. 45 degrees in the coronal plane and approx. 45 degrees in the palmar direction in the sagittal plane. Due to its oblique orientation in the region, the radiological length of the scaphoid is attenuated accordingly in the dorsopalmar and lateral projection planes (**Fig. 1**).

Surface

Since the scaphoid articulates with five partners (radius, capitate, lunate, trapezoid and trapezium), it is covered 90 % by cartilage, with only the tubercle and a dorsal bony ridge being exposed. Due to the wide cartilage covering and resulting absent open periosteum there is no appreciable formation of periosteal callus when the fracture heals.

Vascularization

The scaphoid is supplied by vessels of the radial artery entering distally via a dorsal bony ridge into the scaphoid bone, then distributed to the waist and distal bone segments. Thus the waist and distal scaphoid bone segments have a sufficient blood supply, whereas the proximal portion as a final route is supplied via an intraosseous collateral network, thus representing a vascular terminal zone. The retrograde blood flow has an important influence on the healing of scaphoid fractures. In the case of proximal fractures, the intraosseous vascular network can be critically interrupted, and the proximal pole can develop nutritive deficiency with hypoxia. In proximal scaphoid fractures, the thus disturbed vitality can frequently lead to pseudarthosis and osteonecrosis of the proximal fragment.

Scaphoid Fracture Biomechanics

Force vectors

The following pathoanatomical mechanisms can underlie scaphoid fracture.

- Generally there has been a fall onto the outstretched hand, and the extended scaphoid bone is caught between the ground surface and the dorsal edge of the radius (proximal scaphoid section in a fixed position between the radius and the radioscaphocapitate ligament, unprotected distal scaphoid). Anatomy of the joint and the force vector in the combined extension radialduction result in a distal scaphoid fracture, whereas a combined flexion ulnarduction causes a proximal fracture.
- The less frequent fall upon the flexed hand generally results in a shear fracture of the tubercle of the scaphoid bone.
- A high-velocity injury to the wrist can result in a complex luxation fracture including scaphoid fracture, e. g. transscaphoid perilunate dislocation.

In rare cases scaphoid fracture is associated with a distal fracture of the radius.

Fracture localization

For purposes of localization, the scaphoid bone is divided topographically into three parts [3]. Scaphoid fractures occur more frequently in the waist (60 %), whereas the proximal and distal thirds account for about 15 % each. The remaining 10 % concern fractures of the extra-articular tubercle of the scaphoid bone.

Fragment dislocation

Two forms of dislocation are characteristic of scaphoid fractures.

- The first is the so-called "humpback" deformity due to the curved shape and palmar alignment of the scaphoid, whereby the distal scaphoid fragment tends toward further palmar tilting and the proximal fragment is pulled into extension. The buckled angular deformity leads to increased pressure load on the palmar fracture segment. The consequence is increased bone resorption with further development of the existing humpback deformation [4].
- The second form is adlatus dislocation frequently occurring with fractures of the proximal scaphoid pole. In this case, the fracture line runs parallel to the longitudinal axis of the forearm, thereby subjecting the proximal fragment to increased rotational load.

The humpback dislocation is in the waist of the scaphoid bone, the lateral dislocation in the proximal third.

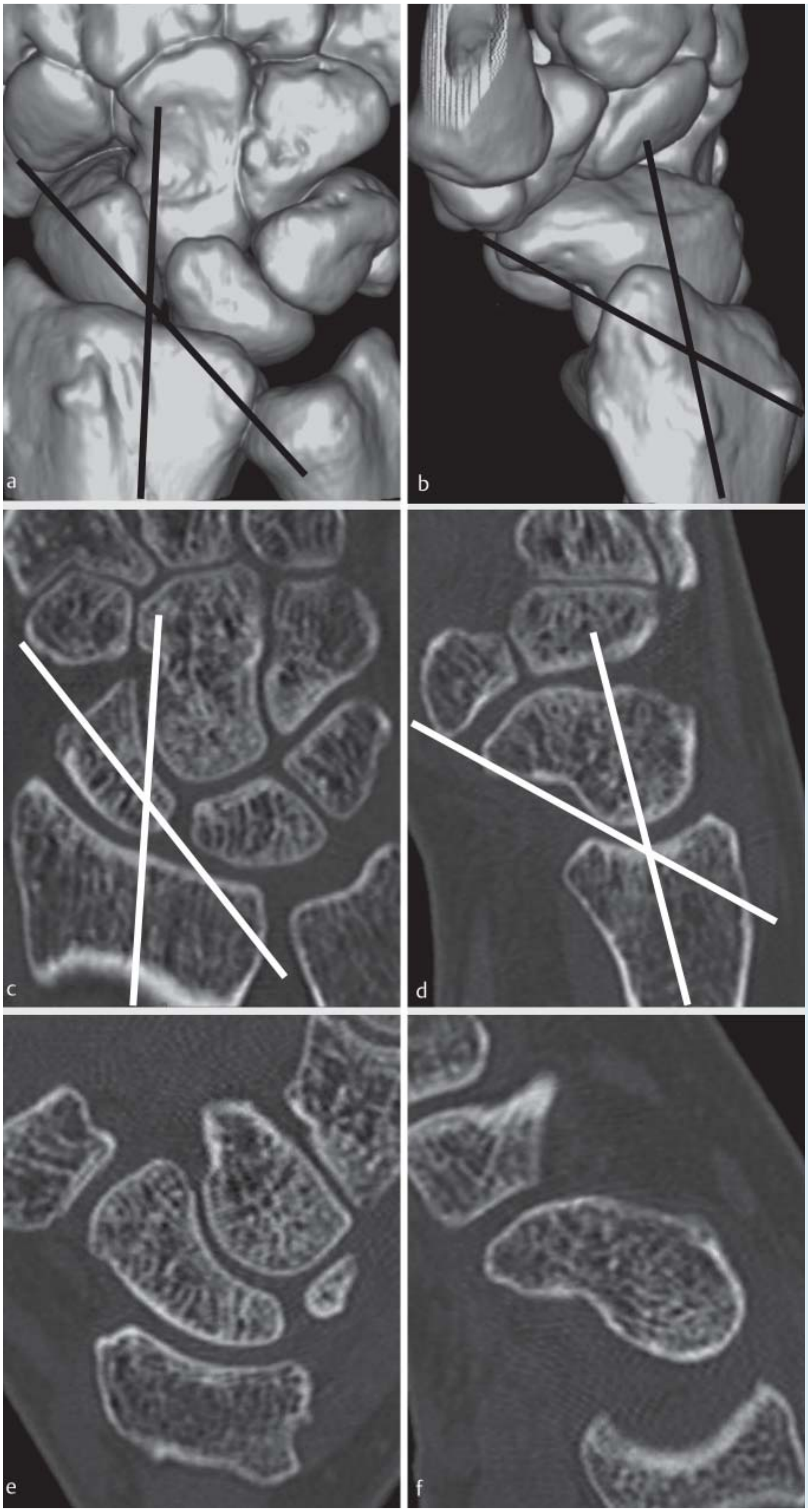

Fig. 1 **a** Scaphoid topography within the carpus as seen in CT images. 3 D VRT image with dorsal view of the carpus. The longitudinal axes are delineated by the radius and scaphoid. **b** 3 D VRT image with radial view of the carpus The longitudinal axes are delineated by the radius and scaphoid. **c** Coronal MPR image through the carpus. The scaphoid appears shortened. Longitudinal axes are delineated by the radius and scaphoid. **d** Sagittal MPR image at scaphoid height. This appears shortened. Longitudinal axes are delineated by the radius and scaphoid. **e** Oblique coronal MPR image parallel to longitudinal axis of the scaphoid. Compare the full extension of the scaphoid with Fig. 1c. **f** Oblique sagittal MPR image parallel to longitudinal axis of the scaphoid. Compare the full extension of the scaphoid with Fig. **1 d**.

Classification and Stability

The descriptive classification according to Russe [3] distinguishes between horizontally-oblique fractures and those that are transverse or vertically oblique. In the AO classification, scaphoid fractures are distinguished as type C1 (ligament avulsion), potentially unstable type C2 (horizontal, transverse and oblique fractures) and unstable type C3 (vertical or multiple fragment fractures).

From the therapeutic viewpoint, the fracture classification according to Herbert and Fischer [5], based on conventional projection radiography, and its modification by Krimmer, Schmitt and Herbert [6] have achieved prominence (Table 1, Fig. 2), the latter being based on image analysis of anatomically-oriented CT thin slices. A distinction is made between stable (types A1 and A2) and unstable (types B1 through B4) scaphoid fractures. Classification of a scaphoid fracture should preferably be based on computed tomography, since all its fracture-related parameters (localization, course, dislocation, instability) can be assessed with greater certainty.

Types A1 and A2 stable scaphoid fractures undergoing conservative therapy have a high chance of healing regardless whether the course of the fracture is complete or partial.

Unstable scaphoid fractures have reduced healing potential, and thus an increased risk of developing pseudarthrosis. Types B1 and B2 fractures generally exhibit fragment dislocation greater than 1 mm or fragmentation zones, whereby healing depends on the degree of dislocation. The likelihood of healing significantly decreases when the fracture gap is 2 mm or wider [7]. In principle, all fractures in the proximal third (type B3) are considered unstable, independent of the degree of dislocation, due to their critical perfusion situation and increased rotational load. This likewise applies to scaphoid fractures with accompanying perilunate luxation fracture (type B4). In the case of unstable scaphoid fractures (location in proximal third, fracture dislocation, fragmentation zone), surgical therapy (closed or open screw fixation, palmar or dorsal access path) can be precisely planned.

If immobilization or minimal osteosynthesis does not consolidate a scaphoid fracture within 8 weeks, the situations should not be considered delayed union. It should instead be assessed as scaphoid pseudarthrosis and treated as such.

Radiological Diagnosis

Projection radiography

When a fracture is suspected, projection radiography is first performed as a basic diagnosis of the wrist.

Technique

The standard procedure is to obtain three defined projections on the wrist without either a cast or splint.

- Maintaining a neutral position is important for the dorsopalmar and lateral image. The dorsopalmar image must be obtained at shoulder height with abduction of the upper arm and elbow flexion each at 90°. For the lateral image, the upper arm is moved toward the trunk and the elbow is bent 90°.
- The so-called Stecher's view is obtained in a dorsopalmar projection with closed fist and ulnar deviation. The purpose of this projection is film-parallel alignment of the palmar-facing scaphoid in its entire longitudinal extension [8].

Free exposure employs an image voltage of 48 to 55 kV and tube current of 4 to 5 mA. If CT or MRI diagnosis can be ensured, the earlier scaphoid quartet series (images with closed fist and ulnar deviation, 45° semi-pronated, extended and in hyperpronation) can be omitted.

Findings

The projection radiographs of a scaphoid fracture can contain the following indications.

- In a pseudo-normal finding the X-ray image appears unremarkable if the fragments have readapted exactly to

type	stability	fracture localization and morphology	therapy
A1	stable	fracture of the tubercle of the scaphoid bone	immobilization
A2	stable	non-dislocated transverse fracture in waist and distal third	immobilization or surgery[1]
B1	unstable	extended oblique fractures	surgery
B2	unstable	all dislocated or gaping transverse fractures	surgery
B3	unstable	all fractures of the proximal third	surgery
B4	unstable	transscaphoidal perilunate luxation fractures	surgery

[1] A2 fractures can also be surgically treated in order to shorten immobilization.

Table 1 Scaphoid fracture classification according to Herbert and Fischer (1984) as well as Krimmer, Schmitt und Herbert (2000).

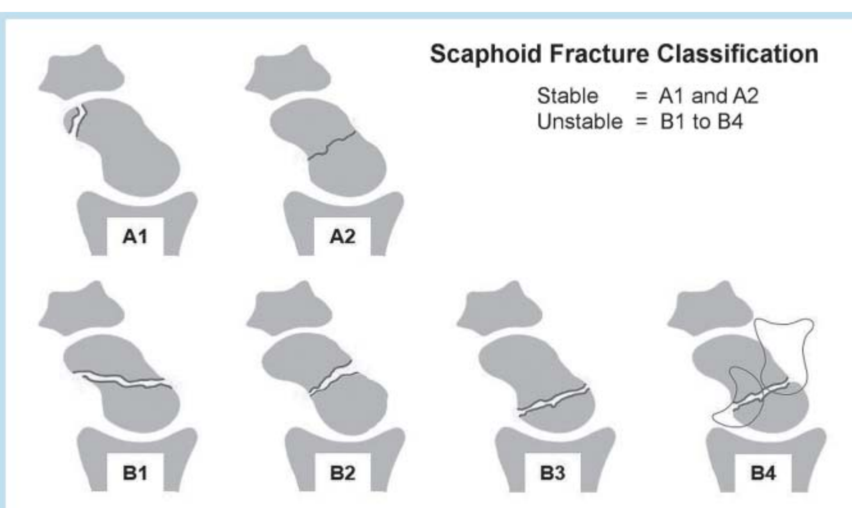

Fig. 2 Scaphoid fracture classification according to Herbert and Fischer (1984) as well as Krimmer, Schmitt and Herbert (2000). A distinction is made between stable (types A1 and A2) and unstable (types B1 through B4) fractures. The details are explained in the test and in Table 1.

their original position due to restoring forces or if a discrete fragment offset is not recognizable in the projections. Despite the fracture, the cortex appears attached on all sides and the trabecular network seems to be intact. False-negative findings account for 15 – 30 % of projection radiographs [9].

- The scaphoid fat stripe sign is an indirect and unreliable fracture criterion. Physiologically a 1 mm wide transparent fat stripe runs between radial collateral ligament and the tendon of the extensor pollicis brevis muscle. In scaphoid fractures, hemarthrosis can result in a shift or obliteration of the fat stripe.
- A certain fracture exists if a fracture line with interruption of the cortex and trabecula is visible (**Fig. 3**) or if the scaphoid exhibits a change in shape as a result of fragment dislocation. A scaphoid fracture is characterized both by a humpback deformation in which the proximal fragment rotates during extension and the distal fragment turns during flexion, as well as misalignment of a fragment in the case of proximal fractures.
- In a perilunate injury pattern a scaphoid fracture can be combined with other wrist fractures and luxations, frequently along the greater arc running through the radial styloid process, the scaphoid, the capitate, the hamatum or triquetum, as well as the ulnar styloid process.

Evaluation

In almost a third of scaphoid fractures, projection radiography provides uncertain or false-negative findings when confirming fracture, i. e. the fracture is not apparent in the X-ray image. Furthermore, diagnostic radiology allows only insufficient determination of fragment dislocation. Finally, a secondary cross-sectional image should be undertaken for the purpose of

- confirmation of fracture if conventional X-ray projections are suspicious, and
- fracture staging if a fracture has been ascertained.

Early utilization of cross-sectional imaging shortens the time to diagnosis and eliminates the previous repeated X-ray after 2 weeks as well as bone scintigraphy.

Computed Tomography

CT is the imaging method of choice for demonstrating the bone structure of the scaphoid.

Technique

Due to the size range of the scaphoid, from 24 mm to 28 mm, the following parameters are used for CT of the bone: field of view (FOV) 50 mm to 60 mm, acquired (or calculated slice thickness 0.5 mm or 0.6 mm (always smaller than 1 mm), high-resolution ossification center in image calculation and overlapping image reconstruction (increment less than 70 %).

Representation of the scaphoid in its entire length in oblique-coronal and oblique-sagittal slices are important for the topographic diagnosis of the fracture and operation planning. Two procedures are possible, depending of the equipment [10, 11].

- Using the latest generation of high-end CT scanners, a volume data set of the entire carpus can be acquired by means of isotropic voxel sizes (slice thickness 0.4 to 0.6 mm, image matrix 1024x1024, voxel edge length of 0.5 mm or less). During subsequent postprocessing, oblique-coronal and oblique-sagittal thin slices through the scaphoid are calculated with the same slice thickness using multiplane reconstruction (MPR).
- When using older CT scanners with poorer imaging geometry allowing only anisotropic voxel sizes, the best detail of the scaphoid is represented via primary acquisition of oblique-sagittal slices parallel to the longitudinal axis. Perpendicular to this, multiplane reconstruction is subsequently used to calculate oblique-coronal images. The patient is placed on the examination table in prone position with the arm above the head ("Superman" position)

Fig. 3 **a** Projection radiograph of a scaphoid fracture. Initial presentation of a 26-year-old football player 10 days after a fall. **a** Dorsopalmar projection with suspicion of fracture in the scaphoid waist. **b** Lateral projection unremarkable. Normal joint arrangement of scaphoid with central carpal pillar. **c** Stecher projection with distinct oblique fracture in scaphoid waist (fracture type B2).

so that the lower arm is positioned 45° to the longitudinal direction of the table and the hand is placed in pronation. The thumb is abducted, thus parallel to the gantry laser. After a coronal planning image, oblique-sagittal primary slices are acquired parallel to the longitudinal axis of the scaphoid (voltage 100 kV or 120 kV, current strength 100 mA to 150 mA).

Findings

Unlike conventional radiography which projects the entire carpal volume into the imaging plane as a summation method, thin slices are generated in CT which substantially facilitate diagnosis of scaphoid fractures due to detailed representation of the scaphoid in sub-millimeter slices. CT offers the following advantages:

- by means of CT the fracture is detected with high sensitivity (85 to 95 %) and specificity (95 to 100 %) and is thus greater than in projection radiography (sensitivity by 70 %, specificity 70 % to 85 %) [9, 12, 13]. Cortical and trabecular disruptions are sensitively demonstrated in CT (▶ **Fig. 4**). A fracture gap or trabecular impaction has to be visible in several adjoining slices [7, 14, 15]. If, however, there is no dislocation of the compact and spongy bone, the fracture cannot be detected, even using CT [16]. In the rare case that MRI is used to detect or exclude fracture, its sensitivity is 100 % ("no fracture missed"), but its specificity – 80 to 90 % – is lower than CT [17].
- Fragment dislocation can be precisely ascertained with CT, in particular with respect to small cortical fragments and multiple-fragment fractures [11, 18]. The extent of axis buckling of humpback dislocation can only be determined exactly using oblique-sagittal CT (▶ **Fig. 4 d**). Likewise, CT better displays adlatus dislocation of fractures on the proximal scaphoid pole.
- Utilization of CT is decisive in assessing fracture stability. Instability criteria include: a) fracture dislocation in the proximal third, b) adlatus displacement of a fragment larger than 1 mm c) humpback dislocations as well as d) scaphoid fracture in conjunction with perilunate luxation damage.
- Concomitant carpal fractures, even in the form of perilunate damage patterns, are more frequently revealed in CT compared to projection radiography if the entire carpus lies in the CT examination volume.
- Fracture consolidation: A periosteal callus does not form when a scaphoid fracture heals. CT allows an exact view of the sub-millimeter anatomy of the fracture gap where endosteal bone regeneration exclusively occurs [7, 15, 19]. In the first 4 weeks there is physiological descaling on the fragment margins, making the gap appear widened. Afterward remineralization sets in, followed by fine bony bridges in the fracture gap. Starting with the 6th week the bridges are visible in CT; they largely cover the gap by the 9th week. Bony regeneration of the frac-

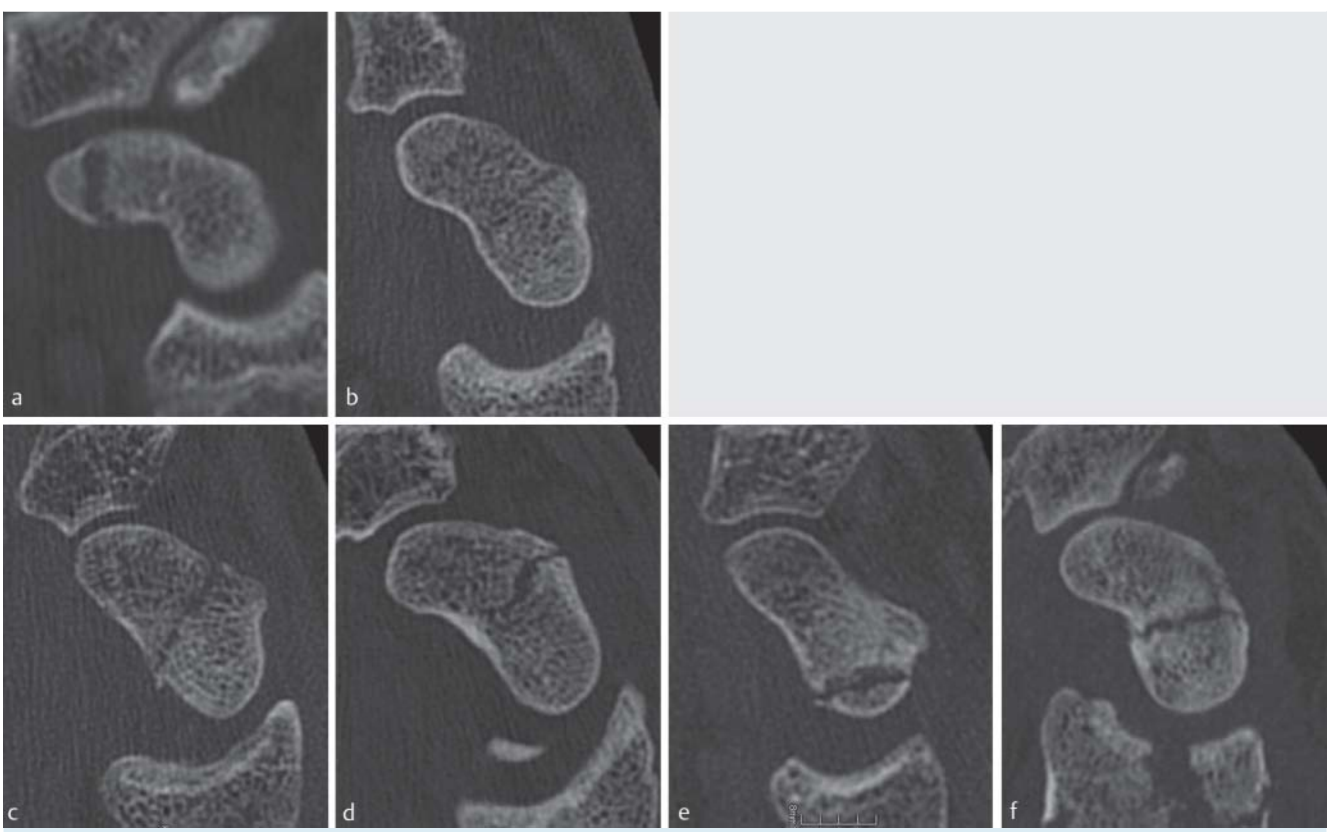

Fig. 4 **a** Compilation of scaphoid fractures according to the classification of Herbert and Fischer (1984) as well as Krimmer, Schmitt and Herbert (2000). Oblique-sagittal CT images of 6 different patients are shown. **a** Scaphoid fracture in distal third, 3 weeks old (fracture type A1). **b** Non-dislocated transverse fracture in waist (fracture type A2). **c** Non-dislocated oblique fracture in waist (fracture type B1). Small palmar cortical fragment. **d** Slightly dislocated transverse fracture in waist (fracture type B2). The fracture gap gapes dorsally with minimum humpback deformity. **e** Non-dislocated transverse fracture in proximal third (fracture type B3). 3 mm-long fragment already with margin resorption of 2-week-old fracture. **f** Non-dislocated transverse fracture in waist in combination with distal fracture of the radius with intra-articular course (fracture type B4).

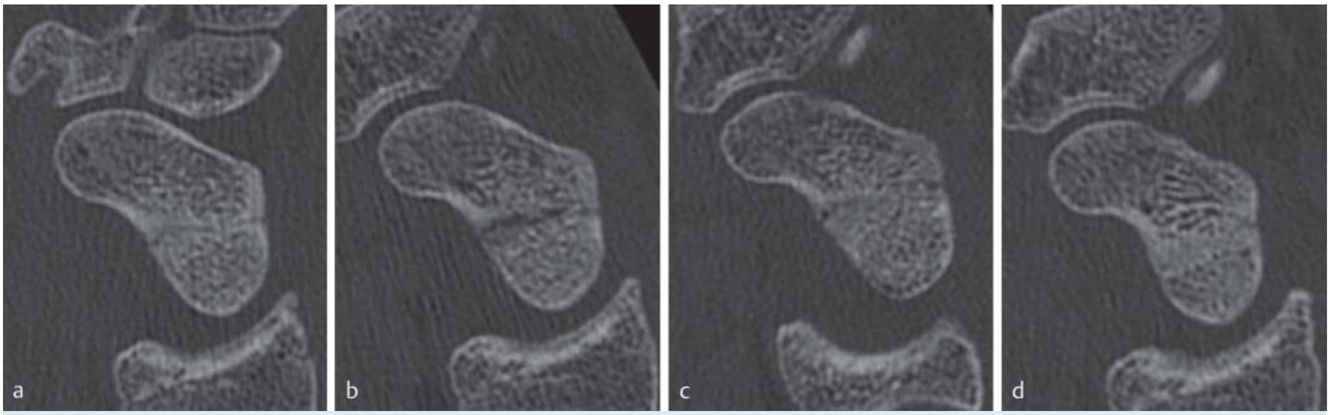

Fig. 5 **a** Healing of conservatively treated scaphoid fracture (type A2). With oblique-sagittal CT images. **a** Finding 1 week post-trauma. **b** Finding after 5 weeks with margin resorption. **c** Finding after 10 weeks with initial bony bridges. **d** Finding after 20 weeks with complete union. From: Schmitt R, Krimmer H. Skaphoidfrakturen. In: Schmitt R, Lanz U. Bildgebende Diagnostik der Hand. 3 rd edition. Thieme. Stuttgart 2004: 283 – 296.

ture is underway if bridging bones are evident in at least 8 adjacent slices with 0.5 mm thickness (corresponding to 5 layers that are 0.75 mm thick) (**Fig. 5**). Even after complete union. trough-shaped depressions remain on the periphery. CT can demonstrate normal or absent union with certainty.

- Postoperative status can be well documented using CT, since the HBS® or Accutrac® screws create few artifacts [20], as they result in a narrow hardening zone at the edge of the screw, whereas large sections of the fracture zone can be evaluated without restriction. Improperly positioned screws are more easily identified using CT compared to projection radiography.

Evaluation

In cases of clinical suspicion and unremarkable X-ray findings, CT is well-suited to detect fractures. CT has a lower sensitivity compared to MRI when detecting fracture, but it has a higher specificity, particularly with respect to cortical fractures. For scaphoid fractures, CT is the imaging method of choice in pre-therapeutic fracture staging (extent, stability and classification of the fracture). Therefore CT should be employed for detection and well as staging of acute scaphoid fractures. In case of questions regarding healing, CT significantly contributes to definitive clarification.

Magnetic Resonance Imaging

Flux densities of 1.5 Tesla or 3.0 Tesla and a gradient field strength greater than 15mT/m are required for diagnosis of the hand. The strength of MRI lies in detection of bone marrow edema which is detectable in fractures on the scaphoid with a sensitivity of about 100 % [12, 13].

Technique

In order to perform an MRI of the scaphoid, the hand is positioned either using the "in-center" technique in which the hand is placed above the patient in the prone position ("Superman" position) or using the "off-center" technique with the patient in supine position, with the hand placed sagittal next to the hip. Dedicated phased-array multichannel coils (8-, 16- or 32-channel coils) are recommended to take advantage of parallel imaging. Alternatives are wrap-around coils and sandwich coils. Data acquisition employs a high-resolution coil to provide a field of view of 80 mm to 100 mm and a slice thickness of 2.0 mm or 1.5 mm without slice gaps (interleaved technique). In addition to the orthogonal standard planes, the scaphoid should be imaged in at least one sequence parallel to its length, i. e. in oblique-sagittal and or oblique-coronal orientation [11].

Two types of sequences with fat tissue suppression can be used to show marrow edema:

- frequency-selective (spectrally) saturated TSE sequences with medium repetition time (PD weighting) or longer repetition time (T2 weighting), and
- the STIR (Short Tau Inversion Recovery) sequence which physically represents T1 weighting, but in the diagnosis based on the image impression appears as "T2-like".

In both sequence types, the edema appears hyperintense compared to the fat-suppressed and therefore hypointense bone marrow.

A contrast-enhanced, T1-weighted sequence without fat saturation can be used to try to display the hypointense fracture as highly-contrasted compared to the marrow with slightly-raised signal intensity. In addition, intravenous administration of contrast medium facilitates detection of collateral damage to the adjoining scapholunate ligament using focal enhancement.

Findings

The hyperintense bone marrow edema is a sensitive but unspecific sign of fracture to the scaphoid bone [12, 13]. A distinction must be made among three post-injury situations with similar edema patterns, but with different therapeutic consequences.

- Post-traumatic diffuse edema without indication of a fine, generally hypointense fracture line or a gaping fracture represents a bone bruise to the scaphoid [16, 18]. A bone bruise is a microtrabecular infraction without destabilizing discontinuity.
- A demonstrative guiding symptom of scaphoid fracture is a combination of bone marrow edema and a long fracture line running through the scaphoid [18, 21]. In a non-dislocated fracture, the fracture line is hypointense in T1 and T2 weighting; on the other hand, a fracture gap with articular effusion is hyperintense in T2 weighting. Bone

marrow edema is found in both fragments (▶ **Fig. 6**). Scaphoid fracture may not be diagnosed in MRI without evidence of a fracture line or gap in several adjacent slices. The disadvantage of MRI compared to CT is its specificity of only 80 to 90 % in the correlation of a pathological bone marrow signal with a scaphoid fracture or bone bruise [16, 18].

- As a consequence of an osteoligamentous avulsion fracture the scaphoid develops a focal or diffuse bone marrow edema without evidence of a transverse fracture gap. Generally the dorsally-attached intercarpal dorsal ligament (DICL) is affected. The situation is biomechanically stable. Display of small avulsion fragments is poorer in MRI compared to CT [16, 18].

A supplementary CT is recommended to exclude or confirm a scaphoid fracture and to provide classification if needed if there is planar bone marrow edema and a questionable fracture gap.

Using a contrast-enhanced MRI, the vitality of a nutritionally vulnerable proximal scaphoid fragment can be estimated based on the intensity of the contrast enhancement. There is no therapeutic benefit to predicting the healing of fresh scaphoid fractures using MRI.

After a scaphoid fracture has consolidated the former fracture zone in the MRI is highly dependent on the local degree of sclerosis. The fracture region can appear hyperintense if fatty bone marrow has developed, or hypointense if a sclerotic zone has formed [19]. Because of this, MRI-based diagnosis cannot be used for assessing fracture union and progression, since signal interference can be associated with both consolidated and non-consolidated scaphoid fractures.

Evaluation

The possibilities for the use of MRI in the diagnosis of scaphoid fracture must be evaluated differentially. With a sensitivity of 100 %, MRI provides good evidence of a scaphoid fracture. However its specificity is only 80 to 90 % in differentiating a fracture from a bone bruise and cortical avulsion injury. Therefore MRI should be employed to rule out a fracture, if despite clinical suspicion of a fracture, the projection radiographic findings and CT are negative or uncertain, thus MRI serves as a "referee" in such cases. Irrespective of MRI findings, CT is the imaging method of choice for the determination of bone-related morphology, classification and stability of scaphoid fractures. MRI has only limited applicability in planning therapy and assessing bone healing.

Bone Scintigraphy

Using hotspots, ^{99m}technetium MDP three-phase scintigraphy can confirm scaphoid fractures. The utilization of three-phase scintigraphy is supported by the high negative predictive value after the third day post-injury, the high positive predictive value in the case of patients with an initial negative X-ray finding and simultaneous evidence of injury to the remaining bones of the hand [13, 17, 22]. Due to its poor spatial resolution and low specificity, positive findings in scintigraphy must always be supplemented by a subsequent CT and/or MRI diagnosis. Bone scintigraphy is no longer recommended for diagnosing fresh scaphoid fractures, as its application is very limited due to methodological redundancy and an average radiation exposure of 3 mSv.

Sonography

Sonographic examination of the scaphoid employs a high-frequency transducer (sound frequency > 10 MHz) applied to the radial side of the wrist that has been placed in ulnar deviation. Sonography can detect dislocated fractures of the scaphoid waist based on cortical disruption and/or parossal hematoma [23]. Limitations of the method pertain to the proximal and distal thirds of the scaphoid, since these are difficult to scan. Non-dislocated fractures are likewise difficult to detect. Currently sonography is recommended only to be used for position monitoring of previously identified childhood fractures. Its use requires high expertise in musculoskeletal ultrasound.

Digital Volume Tomosynthesis (DVT)

In this recently-developed procedure, the tube/detector unit moves in a 180° direction around the wrist, creating a series of radiographs based on various projections. According to the literature, the detection rate of scaphoid fractures is better than projection radiography, but poorer compared to CT [24]. The related radiation exposure is in the range of conventional diagnostic radiology.

Therapeutic Methods

The goal of treatment is the restoration of hand function using conservative or surgical procedures. The selection of therapeutic method is essentially determined by the location, degree of dislocation and stability of the fracture.

- Stable scaphoid fractures as a rule are treated using immobilization for 4 weeks (type A1) or 6 to 8 weeks (type A2) using a plaster (plastic) cast on the lower arm. To shorten the immobilization time, stable scaphoid waist fractures (type A2) can also be treated using percutaneous screw fixation.
- Unstable scaphoid fractures are treated surgically with cannulated double-threaded (HBS®) screws or headless compressions screws (Accutrac®), frequently 22 mm in length. Both screw types achieve the same therapeutic result. Open reduction is necessary in cases of dislocated scaphoid fractures via dorsal access to proximal fractures (type B3) or via expanded palmar access in the case of types B1, B2 and B4 dislocated fractures. Four-week post-surgical immobilization is required for B1 and B2 fractures. B3 and B4 fractures require 6 weeks of immobilization followed by functional treatment for an additional 4 weeks.

Diagnostic Algorithm

The chronology of the treatment of scaphoid fractures includes the following diagnostic stages:

Primary Diagnosis

Detection and staging of a scaphoid fracture should be undertaken shortly after occurrence of the injury. To avoid re-examination, cross-sectional imaging should be performed as early as possible. CT evaluation of a perilunate luxation fracture is useful in an emergency situation; however further diagnosis should not cause a delay of required reposi-

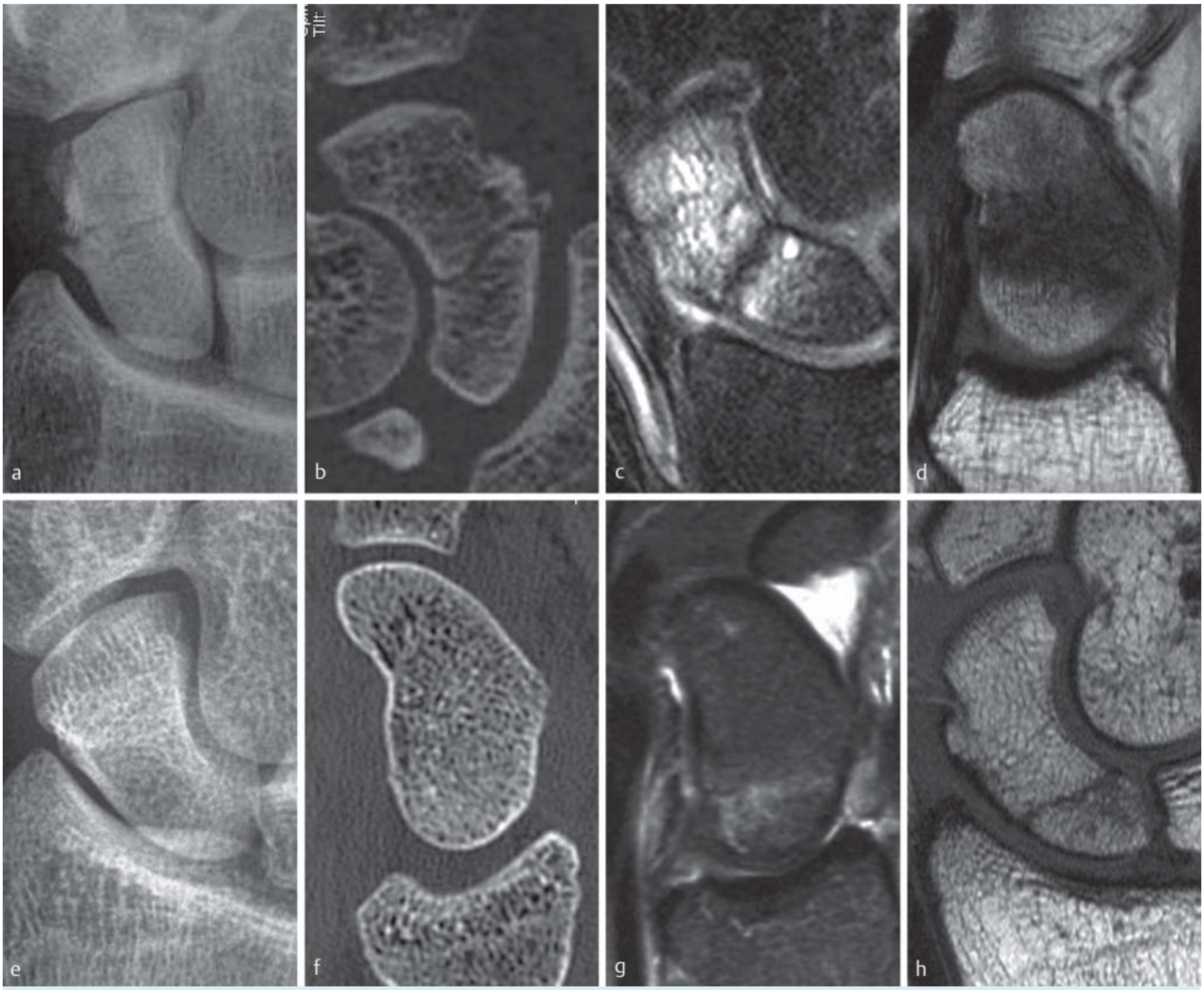

Fig. 6 **a** MRI diagnosis of two scaphoid fractures in conjunction with projection radiography and CT diagnosis. **a**–**d** Scaphoid fracture in the waist (type A2) visible in all imaging procedures. Stecher's projection **a** MPR CT image **b**, oblique-coronal image of a fat-saturated PD-FSE sequence **c** and oblique-sagittal T1 FSE image **d**. The fracture gap is recognizable in both MRI images, the associated bone marrow edema is hyperintense in T2-weighting **c** and hypointense in T1-weighting **d**. **b** MRI diagnosis of two scaphoid fractures in conjunction with projection radiography and CT diagnosis. **a**–**d** Scaphoid fracture in the waist (type A2) visible in all imaging procedures. Stecher's projection **a** MPR CT image **b**, oblique-coronal image of a fat-saturated PD-FSE sequence **c** and oblique-sagittal T1 FSE image **d**. The fracture gap is recognizable in both MRI images, the associated bone marrow edema is hyperintense in T2-weighting **c** and hypointense in T1-weighting **d**. **c** MRI diagnosis of two scaphoid fractures in conjunction with projection radiography and CT diagnosis. **a**–**d** Scaphoid fracture in the waist (type A2) visible in all imaging procedures. Stecher's projection **a** MPR CT image **b**, oblique-coronal image of a fat-saturated PD-FSE sequence **c** and oblique-sagittal T1 FSE image **d**. The fracture gap is recognizable in both MRI images, the associated bone marrow edema is hyperintense in T2-weighting **c** and hypointense in T1-weighting **d**. **d** MRI diagnosis of two scaphoid fractures in conjunction with projection radiography and CT diagnosis. **a**–**d** Scaphoid fracture in the waist (type A2) visible in all imaging procedures. Stecher's projection **a** MPR CT image **b**, oblique-coronal image of a fat-saturated PD-FSE sequence **c** and oblique-sagittal T1 FSE image **d**. The fracture gap is recognizable in both MRI images, the associated bone marrow edema is hyperintense in T2-weighting **c** and hypointense in T1-weighting **d**. **e** **e**–**h** Occult (hidden to X-ray and CT) scaphoid fracture in proximal third (type B3). Examinations on day of accident. Unremarkable dorsopalmar radiograph **e**. Likewise no fracture in oblique-sagittal CT. **f** **e**–**h** Occult (hidden to X-ray and CT) scaphoid fracture in proximal third (type B3). Examinations on day of accident. Unremarkable dorsopalmar radiograph **e**. Likewise no fracture in oblique-sagittal CT. **g** **e**–**h** Occult (hidden to X-ray and CT) scaphoid fracture in proximal third (type B3). Examinations on day of accident. Unremarkable dorsopalmar radiograph **e**. Likewise no fracture in oblique-sagittal CT. **h** **e**–**h** Occult (hidden to X-ray and CT) scaphoid fracture in proximal third (type B3). Examinations on day of accident. Unremarkable dorsopalmar radiograph **e**. Likewise no fracture in oblique-sagittal CT.

tioning of the fracture. Based on an exact clinical examination, the following radiological sequence of procedures is recommended (▶ **Fig. 7**).

- First-choice diagnostic method: Projection radiography, which can be limited to three standardized images (dorsopalmar, lateral and Stecher projections) allows an initial overview of the distal lower arm, the wrist and metacarpus.
- Second-choice diagnostic method: CT is used for primary diagnosis to detect a scaphoid fracture, support staging (fracture location, fragment dislocation, stability) and aid in fracture classification. The submillimeter oblique-

coronal and oblique-sagittal CT slices are ultimately needed for treatment planning of every scaphoid fracture. If an accompanying carpal fracture is suspected, the CT examination volume also includes the entire wrist.

- Third-choice diagnostic method: Since it is the most sensitive detection method, MRI should be utilized if projection radiography and CT fail to detect a fracture and cannot clarify the clinical symptoms of the radial wrist.

Intraoperative Diagnosis

Surgical fragment repositioning and screw fixation are guided with fluoroscopy using a C-arm system. It is recommended that the three standard projections be preferably employed for fragment position control and monitoring of the screw fixation procedure.

To document the surgical results, intraoperative fluoroscopic images can be acquired in the dorsopalmar, lateral and Stecher projection and subsequently stored in the clinic's PACS archive. Alternatively, documentation of the results can be obtained on the same or following day in the Radiology department using standardized projection radiographs without a cast. X-rays obtained immediately post-surgery are important because they represent the base documentation for the assessment of the continued healing process. An early CT control is indicated only in cases of uncertain fragment position and/or implant position.

Diagnosis of the Union

The evaluation of fracture union is based on both the general laws of the chronology and biology of fracture healing (stages of bone resorption, mesenchymal regeneration, formation of woven bone and transformation in lamellar bones), as well as on the fact that periosteal callus generally develops on the scaphoid after screw implantation.

After the cast is removed, evaluation of fracture healing should be based primarily on the three projection radiographs. The following are useful time points for diagnostic radiology:

- termination of immobilization (4 to 8 weeks depending on fracture type), and
- approval for full load bearing on the joint.

If fracture healing cannot be assessed with certainty, a supplemental CT should be performed after the 9th week after the injury or operation at the earliest [15]. If healing has not taken place, bone graft should be considered as in the case of scaphoid pseudarthrosis.

Diagnosing Complications

In the long term after treatment of the fracture, scaphoid pseudarthrosis can result in 4 to 11 % of fractures with or without proximal osteonecrosis as well as carpal arthrosis. Proximal, primary dislocated and unstable scaphoid fractures as well as fractures with additional concomitant carpal injuries have a poor prognosis. Following are primary diagnostic recommendations for post-treatment follow-up of an earlier scaphoid fracture as well as diagnosis of an older, non-primarily diagnosed fracture.

- Delayed or absent post-fracture union is best determined in CT based on bridging bony structures. These are insufficiently observed in MRI. Scaphoid pseudarthrosis is presumed without time restrictions if resorption cysts develop within the fragments in the vicinity of the pseudarthosis gap [19].
- The most serious complication of a scaphoid fracture is the formation of pseudarthosis [25], the consequence of which is regular periscaphoid osteoarthritis, followed by carpal structural breakdown with a loss of carpus height as well as radio- and mediocarpal osteoarthritis (so-called SNAC wrist – Scaphoid Nonunion Advanced Collapse). The cause of the phased development is loss of the stabilizing effect of the scaphoid, which after development of unstable pseudarthosis is no longer able to maintain the level between the proximal and carpal row. Carpal collapse (SNAC wrist) has three severity levels: SNAC 1 with focal arthrosis on the radial styloid process; SNAC 2 with arthrosis of the entire radioscaphoid com-

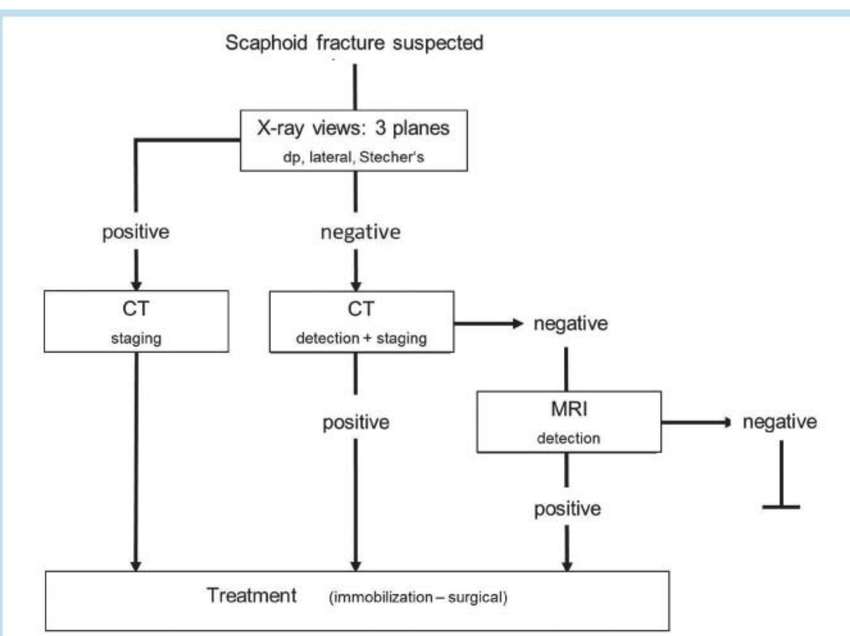

Fig. 7 Algorithm for imaging diagnosis of scaphoid fractures according to current S3 guidelines (AWMF 2015). The staged diagnosis with the sequence of projection radiography, CT and MRI is explained in detail in the text.

partment; and SNAC 3 after transition to mediocarpal arthritis [26]. In order to grade arthrosis in the case of carpal collapse, the entire wrist must be acquired in the projection radiographs and imaging procedures [11].

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