

Instructional lecture

Scaphoid fractures and nonunions: diagnosis and treatment

SCOTT P. STEINMANN and JULIE E. ADAMS

Department of Orthopaedic Surgery, Mayo Clinic, 200 First Street SW, Rochester, MN 55905, USA

Abstract

Background. Scaphoid fractures are commonly seen in orthopedic practice. An organized and thoughtful approach to diagnosis and treatment can facilitate good outcomes. However, despite optimal treatment, complications may ensue. In the setting of nonunion or an avascular proximal pole, vascularized bone grafting may be needed.

Methods and results. In this article we review the literature regarding these injuries and describe an approach to diagnosis, treatment, and management of scaphoid fractures and nonunions.

Conclusion. Scaphoid fractures and nonunions may present as challenging problems in practice, but a systematic and deliberate approach can facilitate optimal results.

blood flow and appear from the distal palmar area of the scaphoid, arising either directly from the radial artery or from the superficial palmar branch.^{6,7} The proximal pole, therefore, is dependent entirely on intraosseous blood flow. This tenuous blood supply can result in a protracted healing process after fracture, with the average time to healing of an acute proximal pole fracture averaging 3–6 months.

Nonunion may occur (in 5%–10% of all cases, with an even higher incidence in displaced fractures), and numerous series document progression of nonunion to collapse and arthritis.^{5,8,9} It is for this reason that diagnosis and appropriate treatment of the acute fracture, and the possible sequelae of nonunion, is essential.

Introduction

Scaphoid fractures are commonly seen in young, healthy individuals and may occur as a result of a fall on the outstretched arm or a forced dorsiflexion injury of the wrist.^{1,2} Because fractures may disturb the scaphoid's tenuous blood supply, the healing process may be compromised. Osteonecrosis is said to occur in 13%–50% of cases of fracture of the scaphoid, and the incidence of osteonecrosis is even higher in those with involvement of the proximal one-fifth of the scaphoid.^{1,3–5}

The blood supply of the scaphoid is primarily from the radial artery via the artery to the dorsal ridge of the scaphoid, whose branches enter the scaphoid via foramina at the dorsal ridge at the level of the waist of the scaphoid.^{4,6} Subsequently, these vessels divide and run proximally and palmarly to supply the proximal pole of the scaphoid.⁴ Other branches provide 20%–30% of the

Classification

Classification of scaphoid fractures has been well described in the literature. Three common classifications used for scaphoid fracture include the Mayo classification, the Russe classification, and the Herbert classification.

Some series have demonstrated limited prognostic value and poor inter- and intraobserver reliability of scaphoid fracture classification schemes¹⁰; nevertheless, the Mayo, Russe, and Herbert classifications are in common use in clinical practice, and many authorities believe they are helpful for determining treatment options and providing prognostic information. The first two classifications are based on anatomical planes of the scaphoid, whereas the Herbert classification defines stable and unstable fractures.^{1,2,11} Thus, the Herbert classification may be particularly helpful when determining treatment options. The type A Herbert classification fracture is a stable acute fracture, and a type B is an unstable acute fracture. Stable fractures include fractures of the tubercle (A1) and an incomplete fracture of the waist (A2). These fractures can potentially be

treated nonoperatively. The other types of fracture in the Herbert classification usually require surgical treatment. Type B (acute unstable fractures) include subtypes B1 (oblique fractures of the distal third); B2 (displaced or mobile fractures of the waist); type B3 (proximal pole fractures); type B4 (fracture dislocations); and B5 (comminuted fractures). Type C fractures are those that demonstrate delayed union after >6 weeks of plaster immobilization, and type D fractures are established nonunions, either fibrous (D1) or sclerotic (D2).¹

Diagnosis and treatment of acute scaphoid fractures

The diagnosis of a scaphoid fracture can sometimes be difficult to establish, as patients may have normal radiographs early in their clinical course. Most patients demonstrate tenderness over the anatomic snuff box or over the distal scaphoid tubercle, pain with longitudinal compression of the thumb, and limited range of motion and pain at the end arc of motion, especially with flexion and radial deviation.^{11–13} Reduced grip strength may be noted.^{11–13} However, it is important to note that not all patients have pain over the scaphoid even with a well-defined fracture seen on radiographs.¹¹ Overall, sensitivity is quite high for the clinical examination, although specificity approaches only 74%–80%.^{12,13} Radiographic evaluation of the scaphoid is useful for determining if an acute fracture is present. A lateral radiograph is important in this regard, as it should demonstrate a co-linear capitate and radius, with the pisiform located between the distal pole of the scaphoid and the body of the capitate. This allows one to evaluate carpal alignment and distal radioulnar joint alignment. Classically, patients with clinical findings suspicious for scaphoid fracture but negative initial radiographs were treated with 2 weeks of cast immobilization followed by repeat examination and radiographic studies, with the idea that the time delay allows bony resorption adjacent to the fracture site to occur, making the fracture visible.^{11,14}

Although this remains an accepted treatment option, it may result in unnecessary immobilization, with adverse effects upon return to work and the need for repeat radiographs, clinical examinations, and splint or cast changes.^{15–17} Alternative imaging techniques may be useful for diagnosing a fracture, and magnetic resonance imaging (MRI) is superior to repeat radiographs for detecting an occult scaphoid fracture.¹⁸ Bone scans are sensitive but not specific for diagnosing a scaphoid fracture.¹⁹ Bone scintigraphy has demonstrated 100% sensitivity and 98% specificity for a scaphoid fracture compared with approximately 65%–70% sensitivity for plain radiography.^{7,20–24} MRI is considered by many to be the gold standard for detecting scaphoid fractures,

with sensitivity approaching 95%–100% and specificity approaching 100%.^{25–27} In addition, one may identify alternative pathology to explain the wrist pain. It is important to recognize that nonunion occurs in up to 12% of patients if an occult fracture is not defined and not immobilized. However, treatment (splinting and casting) can lead to loss of work and economic implications.^{16,17,19} The cost of time off from work, serial casting, and office visits easily outstrip the cost of an MRI or computed tomography (CT) scan for definitive diagnosis.¹⁶

Brooks et al.¹⁵ investigated the cost-effectiveness of MRI for diagnosing suspected scaphoid fractures in a randomized controlled trial involving 28 patients. Those who underwent MRI had a shorter duration of immobilization, decreased use of health care resources, but increased cost to treat when compared to patients who were randomized to the non-MRI group, in which patients were immobilized and evaluated by serial clinical and radiographic examination. Cost per day of unnecessary immobilization between the groups was \$44.37. However, these costs do not take into account absenteeism from work and leisure activities.¹⁵ Pillai and Jain¹⁷ reported a needless immobilization rate of >80% when all clinically suspected scaphoid fractures with negative radiographs were immobilized in the traditional treatment algorithm. They found that only 6.7% of the 90 initially radiographically negative wrists actually had a scaphoid fracture, and 10 additional patients had other injuries of the wrist not involving the scaphoid.¹⁷ The findings suggest that the cost of needless immobilization, with further clinical and radiographic studies, would have exceeded early alternative investigations, such as MRI or bone scan, which frequently were ultimately required anyway.¹⁷

Thorpe et al.²⁸ reported on a series of 59 patients with clinical symptoms suggestive of scaphoid fracture but in whom radiographs were negative. All underwent MRI, bone scintigraphy, and clinical follow-up. The clinical follow-up was deemed to be the gold standard for diagnosis. Clinically, 4 scaphoid fractures, 10 other fractures, and 3 significant ligamentous injuries were identified. All scaphoid fractures were identified by both MRI and bone scan; however, MRI was noted to have better interobserver agreement and fewer false positives. Likewise, other sources of pathology could be diagnosed on MRI, such as a ligamentous injury or carpal instability, whereas these findings were not diagnosable by bone scan. The authors further noted that the costs were similar.²⁸

In a study comparing the sensitivity and specificity of MRI and bone scintigraphy for diagnosis of occult scaphoid fractures, 43 patients with wrist trauma and normal radiographs underwent MRI and bone scans an average of 19 days after injury. Of these 43 patients, 6

(14%) ultimately were diagnosed with a scaphoid waist fracture. The patients were followed for >1 year after injury. MRI was noted to be more sensitive for detecting an occult scaphoid fracture, with fewer false positives than the bone scans.²⁹

Dorsay et al.¹⁶ investigated the cost-effectiveness of early MRI to detect occult scaphoid fractures. They noted that 75% of patients with clinical evidence of a scaphoid fracture would be immobilized unnecessarily if they were treated by the standard follow-up with repeat radiographs following immobilization. The cost differential between standard follow-up and MRI was small.¹⁶

The questions that often arise are when should you prescribe MRI and how early can you detect a fracture in the scaphoid? It is possible with modern MRI technology to detect a fracture within 4–6 h; however, owing to most hospitals' scheduling situations, obtaining an MRI examination at 36–48 h is a common goal. Again, MRI may demonstrate an occasional false-positive but rarely results in a false-negative examination. CT scanning is also a useful technology for diagnosing scaphoid fractures and can help determine nonunion or incomplete union, and it is helpful when planning for surgery to determine the intrascaphoid angle and elements of scaphoid collapse. It is not as accurate, however, as MRI for diagnosing an acute, occult fracture. It is helpful to remember that most patients with a suspected scaphoid fracture have not actually injured the scaphoid and that casting for no fracture just to present a conservative treatment modality results in overtreatment at the expense of office visits, radiographs, and lost work. MRI can give a relatively quick answer. A technetium bone scan is sensitive but false-positive findings can occur in patients with arthrosis or prior or concurrent injury. MRI tends to produce fewer false-positives, can pinpoint the location of the fracture more precisely, and can identify alternative diagnoses. Bone scans rarely miss a scaphoid fracture but require a delay in performing the test; they often do not adequately elucidate alternative diagnoses. MRI is at least as sensitive and more specific, involves less radiation exposure, and may allow one to diagnose alternative problems.¹⁵

A suggested algorithm, therefore, in a patient with wrist trauma is to obtain three radiographic views of the wrist, anteroposterior (AP), lateral, and oblique. If a scaphoid fracture is identified on the radiographs, a CT scan can be then obtained for surgical planning. If the radiographs are negative or equivocal, a limited MRI examination of the wrist is then obtained to determine the presence or absence of a scaphoid fracture. If needed, a CT scan can also be obtained after MRI to help plan for surgical treatment.

A question arises whether operative versus nonoperative treatment is indicated for scaphoid frac-

tures. The reason to consider operative treatment is that immobilizing the patient for 12 weeks is typical for scaphoid fractures, and in more proximally located fractures it may be much longer.^{3,11,30,31} Although few studies in the literature have documented the consequences of long-term cast immobilization, clearly it can result in significant stiffness that may require a significant rehabilitation period; moreover, some studies have suggested a poorer outcome following prolonged immobilization.^{30,22,32} In addition, union rates are higher with operative management, approaching 95% or more in most series of all types of scaphoid fracture.^{30,33–35} Multiple series have documented satisfactory outcomes and minimal complications with surgical management using percutaneous fixation of scaphoid fractures.^{1,30,35–43} Several studies have looked at surgery versus casting for acute fractures. Those who underwent surgical management with percutaneous screw placement demonstrated better range of motion at the wrist, earlier time to union (7 weeks vs. 12 weeks with casting), earlier return to work, and minimal differences in the two groups with respect to outcomes and satisfaction at the final follow-up. Importantly, no increased complication rate related to surgical treatment was observed.^{30,44,45} It appears, therefore, that percutaneous treatment of acute scaphoid fracture has a low morbidity rate and in the hands of an experienced surgeon does not result in a higher complication rate than nonsurgical treatment.¹

In a meta-analysis of scaphoid nonunion that reviewed 1121 articles, 36 of which met criteria for inclusion in this review, data were obtained for 1827 scaphoid nonunions.⁴⁶ When patients with avascular necrosis of the proximal pole were evaluated, union rates were 88% with vascularized bone grafting versus 47% with a standard graft.⁴⁶ In addition, those who had no postoperative immobilization were demonstrated to have the same union rate as those who were immobilized for >6 weeks postoperatively.⁴⁶ This study therefore lends support for immediate screw fixation and mobilization of the wrist versus prolonged cast treatment. Proximal pole fractures, however, remain a difficult treatment dilemma. Up to one-third of these fractures may result in nonunion even with appropriate immobilization. Several studies demonstrated good results with early surgical intervention, and it appears that a careful dorsal approach does not injure the blood supply.

Authors' preferred approach to acute scaphoid fractures

When considering overall treatment options, it is perhaps best for all proximal pole and displaced scaphoid fractures to be treated with surgery. The vascularity of the proximal pole can be determined preoperatively

with MRI. Acute fractures may demonstrate normal or decreased T1-weighted MRI intensity and increased T2 intensity.¹¹ Nonunion and impaired vascularity is often seen with low T1 and T2 marrow signal intensity, which may correlate with poor healing.^{11,47,48} Some series, however, have failed to find a correlation with preserved vascularity of the proximal pole and successful outcome of surgery.⁴⁹

Scaphoid nonunions

Despite optimal therapy, nonunion or malunion may ensue. Treatment of the established scaphoid nonunion requires consideration of patient and nonunion characteristics. Because the bony attachments of the dorsal intercarpal ligament and the dorsal scapholunate ligament are maintained when setting a fracture of the proximal one-third of the scaphoid, these fractures rarely demonstrate instability patterns such as dorsal intercalated segmental instability (DISI). Nonunion of a scaphoid fracture, however, can result in carpal malalignment and progressive radiocarpal arthrosis.^{5,8,9,11} The real effect of malunion, however, is less clearly defined. In a series of 160 scaphoid nonunions treated with internal fixation and bone grafting, of which 90% healed, failure to achieve union was related to a proximal fracture location, avascularity of the proximal pole, instability of the fracture, and delay to surgery. Importantly, residual flexion deformity of the scaphoid did not have an effect on the outcome. Therefore, malunion was not thought to be a contributing factor to a poor result. This study, however, demonstrated that the length of immobilization negatively affects the functional outcome.⁵⁰

In a smaller study of 26 patients with nonunions who underwent bone grafting for scaphoid nonunions, 13 patients ultimately had lateral intrascaphoid angles greater than 45°. However, excellent function and high patient satisfaction was noted at 11 years' follow-up, with clinical outcomes indistinguishable between the groups who had normal alignment and those with malunion. It was thought, therefore, that osteotomy and surgical treatment of a malunion is not indicated for most of the patients with healed scaphoid fractures.⁵¹

The nondisplaced stable nonunion without degenerative changes (Mack-Lichtman type I)^{8,52,53} may be treated with bone grafting with or without hardware. Nonvascularized autogenous bone graft from the distal radius or iliac crest may be sufficient, although vascularized bone grafting should be considered in the presence of an avascular proximal pole as determined by MRI or intraoperative findings. In addition, there is the caveat that if the initial bone grafting fails future surgery is less likely to be successful.^{3,54-56} The fracture site should be freed from fibrous nonunion or interposed tissue, and

hardware may or may not be placed. Hardware placement provides additional stability but requires bony removal for placement. Kirshner wires may be used, but screw fixation may provide the advantage of compression of fracture fragments. Type II nonunions, which are unstable owing to fragment displacement, require one to address the nonunion and restore normal carpal stability to prevent the downward spiral from instability to collapse and arthritis.^{8,52,53} A corticocancellous wedge bone graft may be harvested from the iliac crest to correct alignment. Because of the instability, these fractures require fixation.

Scaphoid nonunion with accompanying mild arthritis are classified as Mack-Lichtman type III.^{8,52,53} Initial findings of radiocarpal arthritis include beaked changes to the radial styloid and narrowing of the joint space between the radius and scaphoid. Treatment includes addressing the nonunion as well as the arthritis. If the scaphoid can be salvaged, open reduction and internal fixation with bone graft are required. A radial styloidectomy may be performed if isolated radial styloid arthritis is present;⁵⁷ alternatively, excision of the distal scaphoid fragment may be performed if the scapholunate ligament is intact.^{53,58,59} However, significant arthritis of the scaphoid fossa and radial styloid is a contraindication to scaphoid salvage, and proximal row carpectomy and four-corner fusion are options.⁶⁰⁻⁶⁶

Mack-Lichtman types IV and V nonunions are those associated with midcarpal arthritis, without and with radiolunate arthritis, respectively.^{8,52,53} They require partial or complete wrist arthrodesis for optimal treatment.^{53,67}

In short, if degenerative arthritis is absent, and the carpus can be salvaged, one may consider bone grafting, either standard or vascularized, with or without internal fixation. However, if substantial degenerative arthritis is present, limited or complete wrist arthrodesis may yield a stable, painless result. Alternatively, proximal row carpectomy or anterior interosseous nerve (AIN) and posterior interosseous nerve (PIN) denervation neurectomy may be considered. Prior to surgery a trial of cast immobilization to simulate the fused wrist, or an AIN or PIN block may be helpful to clarify the possible effect of the desired procedure on the patient's symptoms.

Bone grafting

When the scaphoid is salvageable and bone grafting is attempted, one must consider the relative risks and benefits of nonvascularized or vascularized bone grafting. Nonvascularized bone grafting is probably sufficient for most waist fracture nonunions and those with preserved vascularity of the proximal pole. As noted previously, however, should standard bone grafting fail, future surgery is likely also to be unsuccessful.^{3,54-56} The benefits of

vascularized bone grafting for scaphoid nonunion include preservation of the blood supply, primary bone healing, and maintenance of structural integrity. Therefore, consideration of vascularized bone grafting is wise, particularly in the setting of osteonecrosis and proximal pole nonunions. Recently the Mayo Clinic documented the outcomes and complications of vascularized bone grafting for scaphoid nonunion in a series of 52 nonunions in 51 patients.⁶⁸ Two patients (two scaphoids) were lost to follow-up, with 50 patients and 49 scaphoids available for review. In this study, the 1,2-intercompartmental supraretinacular artery (1,2-ICRSA) was used as a reverse-flow vascularized bone graft for scaphoid nonunion.^{56,69,70} Previously published union rates for vascularized bone grafts in the scaphoid have ranged from 27% to 100%, although there are presently fewer than 10 such published studies in the literature with approximately 100 total patients.

In the Mayo Clinic study, there were 42 male patients and 9 female patients, with an average age of 23 years and a mean follow-up of 7.6 months. The nonunions were evenly divided between the proximal pole and the waist; and evidence of avascular necrosis was present in 24 scaphoids based on intraoperative surgical findings, MRI, and radiographs. Overall, 72% of the scaphoid fractures achieved union with vascularized bone grafting (36/50), and healing occurred at an average of 16 weeks (range 8–40 weeks). There was no change in carpal height from the preoperative to the postoperative radiographs. Factors adversely affecting the union rate included female sex (union rate: 30% vs. 82% in males); tobacco use (union rate: 81% in nonsmokers vs. 46% in smokers), and proximal pole avascularity [48% union rate in the presence of avascular necrosis (AVN) vs. 91% in the absence of AVN]. The type of internal fixation also influenced the union rate. Simple K-wire fixation resulted in a 53% union rate, whereas screw fixation resulted in an 88% union rate. Likewise, the presence of collapse or deformity adversely affected union rates. Carpal collapse with formation of a hump-backed deformity was present in 50% of the failures versus 11% of patients who went on to union. Interestingly, in this series of patients, the fracture-dislocation did not affect the union rate, with waist fractures achieving 70% union and proximal poles achieving 72% union. Prior surgery resulted in a healing rate of 64% compared to 73% in those with no previous operations. Complications in this series resulted in three infections, three patients with graft extrusion, two patients with graft resorption, and four patients with progressive degenerative changes that required further operative therapy. Five patients underwent subsequent surgeries including AIN and PIN neurectomy ($n = 2$), repeat autologous bone grafting ($n = 1$), scaphoid excision with four-corner fusion ($n = 1$), and total wrist fusion ($n =$

1).⁶⁸ Notably, the union rate was 100% in cases of nonunion in which AVN was absent and which underwent the vascularized bone grafting procedure with screw fixation.⁶⁸

Two studies in the literature showed relatively low healing rates of 60%⁵⁴ and 27%,⁷¹ respectively. In the study by Boyer et al.,⁵⁴ 10 proximal pole nonunions underwent vascularized bone grafting with a 60% union rate. The four failures occurred in patients who had previously undergone treatment with a bone grafting procedure, suggesting that prior surgery adversely affects the outcome of the 1,2-ICRSA bone graft.⁵⁴ In a second report by Straw et al.,⁷¹ 22 nonunions underwent the 1,2-ICRSA bone graft with only a 27% union rate ($n = 6$). Altogether, 16 of these patients had AVN of the proximal pole, and the K-wires that were used for fixation were removed at 8 weeks regardless of union status. Of those 16 patients with osteonecrosis of the proximal pole, only 2 had union, a 12.5% union rate, compared to 4 of 6 (67%) in the patients with a preserved vascular supply to the proximal pole.⁷¹ It could be concluded that a 1,2-ICRSA vascularized bone graft may not improve union rates in patients with significant AVN of the proximal pole fragment.⁷¹

Patients who overall are poor candidates for vascularized bone grafting are those with carpal collapse and scaphoids with a large defect or excessive comminution of the proximal fragment. Likewise, patients with radiocarpal arthritis may have a more disappointing outcome.⁵⁶ These series and the recent study from the Mayo Clinic present less optimistic results than a prior study by Steinmann et al. in which a 100% union rate was achieved in 14 patients at a mean 11.1 weeks.⁵⁶ The reasons for this increased failure rate are not entirely clear. However, it probably relates to broader acceptance of the procedure with resultant expanded indications for use of this vascularized bone grafting technique. Additionally, there is enthusiasm and willingness to try everything, including a vascularized bone graft prior to performing a salvage type procedure. The limitations of this larger, more recent study relate to its retrospective nature and the multiple surgeons involved. Factors overall that are thought to be associated with failure of 1,2-ICRSA in scaphoid nonunion include female sex, tobacco smoking, proximal pole AVN, humpback deformity, comminuted proximal pole and use of a K-wire or no metallic internal fixation.

Conclusions

In the authors' opinion, operative fixation of scaphoid fractures is the treatment of choice in cases of acute fracture in which the fracture is clearly visible on plain film radiographs, as we believe this implies that the

fracture is displaced. Several authors have demonstrated low morbidity and satisfactory outcomes following operative fixation.^{1,30,35-43} The surgical time is minimal, morbidity is minimal, and complications are infrequent. In addition, acute treatment may result in decreased risk of nonunion.

When a patient with clinical symptoms suggestive of scaphoid fracture is evaluated, initial radiographs are obtained at the time of presentation. If a scaphoid fracture is readily identified on plain films, it represents displacement, and acute operative treatment is recommended, with our preference being percutaneous placement of a cannulated screw. If no fracture is seen, and clinical findings suggest a scaphoid fracture, a MRI scan should be performed. If MRI reveals a fracture, nonoperative treatment may be undertaken with a short arm thumb spica cast with the wrist in neutral position, immobilizing the thumb to the interphalangeal joint, unless the fracture is at the proximal pole. This is maintained for 6 weeks with a CT scan obtained at this time point. If the CT scan remains suggestive of an unhealed fracture, cast immobilization is maintained for an additional 6 weeks. The exception to this involves cases in which a fracture of the proximal pole is identified on MRI. In these cases, percutaneous operative fixation should be undertaken to lessen the chance of nonunion. After operative fixation, the patient is placed in a volarly based thumb spica splint. If the patient is unlikely to comply with postoperative activity restrictions, a short arm thumb spica cast is placed. If the patient is reliable, a removable splint may be provided. Activity is restricted to not lifting >2 pounds and no repetitive use; utilizing the hand for activities of daily living and personal hygiene only is allowed. At 6 weeks, a CT scan is obtained to evaluate for evidence of union. If evidence of healing, such as disappearance of the fracture line, spot welding between fragments, or callous formation is present, immobilization is discontinued, with gradual return to activities. The literature suggests that partial union is often present but usually progresses to full union without the need for additional immobilization.⁷² If no evidence of healing is noted, immobilization is continued, with another CT scan obtained 4-6 weeks thereafter.

In the setting of an established scaphoid nonunion without significant arthritis, vascularized bone grafting with a technique such as the 1,2-ICRSA graft and fixation with metallic hardware, preferably a screw, is advised. When significant degenerative changes preclude scaphoid reconstruction, salvage procedures such as proximal row carpectomy, neurectomy, or limited or complete wrist arthrodesis are indicated.

In summary, scaphoid fractures are a common problem encountered in clinical practice. This article provides an algorithm for the diagnosis, evaluation, and

treatment of scaphoid fracture and possible sequelae, including nonunion.

References

- Herbert TJ, Fisher WE. Management of the fractured scaphoid using a new bone screw. *J Bone Joint Surg Br* 1984;66:114-23.
- Russe O. Fracture of the carpal navicular: diagnosis, non-operative treatment, and operative treatment. *J Bone Joint Surg Am* 1960;42:759-68.
- Cooney WP, Dobyns JH, Linscheid RL. Fractures of the scaphoid: a rational approach to management. *Clin Orthop* 1980; 149:90-7.
- Freedman DM, Botte MJ, Gelberman RH. Vascularity of the carpus. *Clin Orthop* 2001;383:47-59.
- Szabo RM, Manske D. Displaced fractures of the scaphoid. *Clin Orthop* 1988;230:30-8.
- Gelberman RH, Menon J. The vascularity of the scaphoid bone. *J Hand Surg [Am]* 1980;5:508-13.
- Gäbler C, Kukla C, Breitenseher MJ, Trattng S, Vécsei V. Diagnosis of occult scaphoid fractures and other wrist injuries: are repeated clinical examinations and plain radiographs still state of the art? *Langenbecks Arch Surg* 2001;386:150-4.
- Mack GR, Bosse MJ, Gelberman RH, Yu E. The natural history of scaphoid nonunion. *J Bone Joint Surg Am* 1984;66:504-9.
- Ruby LK, Leslie BM. Wrist arthritis associated with scaphoid nonunion. *Hand Clin* 1987;3:529-37.
- Desai VV, Davis TRC, Barton NJ. The prognostic value and reproducibility of the radiological features of the fractured scaphoid. *J Hand Surg [Br]* 1999;24:586-90.
- Linscheid RL, Weber ER. Scaphoid fractures and nonunion. In: Cooney WP, Linscheid RL, Dobyns JH, editors. *The wrist: diagnosis and operative treatment*. St Louis: Mosby; 1998. p. 385-430.
- Grover R. Clinical assessment of scaphoid injuries and the detection of fractures. *J Hand Surg [Br]* 1996;21:341-3.
- Parvizi J, Wayman J, Kelly P, Moran CG. Combining the clinical signs improves diagnosis of scaphoid fractures: a prospective study with follow-up. *J Hand Surg [Br]* 1998;23:324-7.
- Watson-Jones R. *Fractures and joint injuries*. 4th ed. Baltimore: Williams & Wilkins; 1952-1955. Vol 1: p. 86-9; Vol 2: p. 606-28.
- Brooks S, Cicutini FM, Lim S, Taylor D, Stuckey SL, Wluka AE. Cost effectiveness of adding magnetic resonance imaging to the usual management of suspected scaphoid fractures. *Br J Sports Med* 2005;39:75-9.
- Dorsay TA, Major NM, Helms CA. Cost-effectiveness of immediate MR imaging versus traditional follow-up for revealing radiographically occult scaphoid fractures. *AJR Am J Roentgenol* 2001;177:1257-63.
- Pillai A, Jain M. Management of clinical fractures of the scaphoid: results of an audit and literature review. *Eur J Emerg Med* 2005;12:47-51.
- Kukla C, Gaebler C, Breitenseher MJ, Trattng S, Vécsei V. Occult fractures of the scaphoid: the diagnostic usefulness and indirect economic repercussions of radiography versus magnetic resonance scanning. *J Hand Surg [Br]* 1997;22:810-3.
- Nielsen PT, Hedeboe J, Thommesen P. Bone scintigraphy in the evaluation of fracture of the carpal scaphoid bone. *Acta Orthop Scand* 1983;54:303-6.
- Brismar J. Skeletal scintigraphy of the wrist in suggested scaphoid fracture. *Acta Radiol* 1988;29:101-7.
- Brøndum V, Larsen CF, Skov O. Fracture of the carpal scaphoid: frequency and distribution in a well-defined population. *Eur J Radiol* 1992;15:118-22.
- Brydie A, Raby N. Early MRI in the management of clinical scaphoid fracture. *Br J Radiol* 2003;76:296-300.

23. Leslie IJ, Dickson RA. The fractured carpal scaphoid. Natural history and factors influencing outcome. *J Bone Joint Surg Br* 1981;63:225–30.
24. Mittal RL, Dargan SK. Occult scaphoid fracture: a diagnostic enigma. *J Orthop Trauma* 1989;3:306–8.
25. Amrani KK. Radiology corner: diagnosing radiographically occult scaphoid fractures. What's the best second test? *J Am Soc Surg Hand* 2005;5:134–8.
26. Breitensteiner MJ, Metz VM, Gilula LA, Gaebler C, Kukla C, Fleischmann D. Radiographically occult scaphoid fractures: value of MR imaging in detection. *Radiology* 1997;203:245–50.
27. Raby N. Magnetic resonance imaging of suspected scaphoid fractures using a low field dedicated extremity MR system. *Clin Radiol* 2001;56:316–20.
28. Thorpe AP, Murray AD, Smith FW, Ferguson J. Clinically suspected scaphoid fracture: a comparison of magnetic resonance imaging and bone scintigraphy. *Br J Radiol* 1996;69:109–13.
29. Fowler C, Sullivan B, Williams LA, McCarthy G, Savage R, Palmer A. A comparison of bone scintigraphy and MRI in the early diagnosis of the occult scaphoid waist fracture. *Skeletal Radiol* 1998;27:683–7.
30. Bond CD, Shin AY, McBride MT, Dao KD. Percutaneous screw fixation or cast immobilization for nondisplaced scaphoid fractures. *J Bone Joint Surg Am* 2001;83:483–8.
31. Gellman H, Caputo RJ, Carter V, Aboulafia A, McKay M. Comparison of short and long thumb-spica casts for non-displaced fractures of the carpal scaphoid. *J Bone Joint Surg Am* 1989;71:354–7.
32. Skirven T, Trope J. Complications of immobilization. *Hand Clin* 1994;10:53–61.
33. Dias JJ, Wildin CJ, Bhowal B, Thompson JR. Should acute scaphoid fractures be fixed? A randomized controlled trial. *J Bone Joint Surg Am* 2005;87:2160–8.
34. Rettig ME, Kozin SH, Cooney WP. Open reduction and internal fixation of acute displaced scaphoid waist fractures. *J Hand Surg [Am]* 2001;26:271–6.
35. Saedén B, Törnkvist H, Ponzer S, Höglund M. Fracture of the carpal scaphoid: a prospective, randomized 12-year follow-up comparing operative and conservative treatment. *J Bone Joint Surg Br* 2001;83:230–4.
36. Chen ACY, Chao EK, Hung SS, Lee MSS, Ueng SWN. Percutaneous screw fixation for unstable scaphoid fractures. *J Trauma* 2005;59:184–7.
37. Filan SL, Herbert TJ. Herbert screw fixation of scaphoid fractures. *J Bone Joint Surg Br* 1996;78:519–29.
38. Haddad FS, Goddard NJ. Acute percutaneous scaphoid fixation using a cannulated screw. *Chir Main* 1998;17:119–26.
39. Haddad FS, Goddard NJ. Acute percutaneous scaphoid fixation: a pilot study. *J Bone Joint Surg Br* 1998;80:95–9.
40. Herbert TJ. Experience with the Herbert screw in the treatment of scaphoid fractures. *J Hand Surg [Br]* 1989;14:463.
41. Herbert TJ. Use of the Herbert bone screw in surgery of the wrist. *Clin Orthop* 1986;202:79–92.
42. Trumble TE, Gilbert M, Murray LW, Smith J, Rafiqah G, McCallister WV. Displaced scaphoid fractures treated with open reduction and internal fixation with a cannulated screw. *J Bone Joint Surg Am* 2000;82:633–41.
43. Wu WC. Percutaneous cannulated screw fixation of acute scaphoid fractures. *Hand Surg* 2002;7:271–8.
44. Adolfsson L, Lindau T, Arner M. Acutrak screw fixation versus cast immobilization for undisplaced scaphoid waist fractures. *J Hand Surg [Br]* 2001;26:192–5.
45. Drac P, Manak P, Labonek I. Percutaneous osteosynthesis versus cast immobilization for the treatment of minimally and non-displaced scaphoid fractures: functional outcomes after a follow-up of at least 12 month. *Biomed Pap Med Fac Univ Palacky Olomouc Czech Repub* 2005;149:149–51.
46. Merrell GA, Wolfe SW, Slade JF III. Treatment of scaphoid nonunions: quantitative meta-analysis of the literature. *J Hand Surg [Am]* 2002;27:685–91.
47. Perlik PC, Guilford WB. Magnetic resonance imaging to assess vascularity of scaphoid nonunions. *J Hand Surg [Am]* 1991;16:479–84.
48. Trumble TE. Avascular necrosis after scaphoid fracture: a correlation of magnetic resonance imaging and histology. *J Hand Surg [Am]* 1990;15:557–64.
49. Singh AK, Davis TRC, Dawson JS, Oni JA, Downing ND. Gadolinium enhanced MR assessment of proximal fragment vascularity in nonunions after scaphoid fracture: does it predict the outcome of reconstructive surgery? *J Hand Surg [Br]* 2004;29:444–8.
50. Inoue G, Shionoya K, Kuwahata Y. Herbert screw fixation for scaphoid nonunions: an analysis of factors influencing outcome. *Clin Orthop* 1997;343:99–106.
51. Jiranek WA, Ruby LK, Millender LB, Bankoff MS, Newberg AH. Long-term results after Russe bone-grafting: the effect of malunion of the scaphoid. *J Bone Joint Surg Am* 1992;74:1217–28.
52. Mack GR, Kelly JP, Lichtman DM. Scaphoid non-union. In: Lichtman DM, Alexander AH, editors. *The wrist and its disorders*. Philadelphia: Saunders; 1997. p. 234–67.
53. Markiewicz AD, Stern PJ. Current perspectives in the management of scaphoid nonunions. *Instr Course Lect* 2005;54:99–113.
54. Boyer MI, von Schroeder HP, Axelrod TS. Scaphoid nonunion with avascular necrosis of the proximal pole: treatment with a vascularized bone graft from the dorsum of the distal radius. *J Hand Surg [Br]* 1998;23:686–90.
55. Bynum EB, Culp RW, Bonatus TJ, Alexander CE, McCarroll HR. Repeat Russe bone grafting after failed bone graft surgery for scaphoid non-union. *J Hand Surg [Br]* 1995;20:373–8.
56. Steinmann SP, Bishop AT, Berger RA. Use of the 1,2 intercompartmental supraretinacular artery as a vascularized pedicle bone graft for difficult scaphoid nonunion. *J Hand Surg [Am]* 2002;27:391–401.
57. Nakamura T, Cooney WP III, Lui WH, Haugstvedt JR, Zhao KD, Berglund L, et al. Radial styloidectomy: a biomechanical study on stability of the wrist joint. *J Hand Surg [Am]* 2001;26:85–93.
58. Garcia-Elias M, Lluch A. Partial excision of scaphoid: is it ever indicated? *Hand Clin* 2001;17:687–95.
59. Malerich MM, Clifford J, Eaton B, Eaton R, Littler JW. Distal scaphoid resection arthroplasty for the treatment of degenerative arthritis secondary to scaphoid nonunion. *J Hand Surg [Am]* 1999;24:1196–205.
60. Cohen MS, Kozin SH. Degenerative arthritis of the wrist: proximal row carpectomy versus scaphoid excision and four-corner arthrodesis. *J Hand Surg [Am]* 2001;26:94–104.
61. Imbriglia JE, Broudy AS, Hagberg WC, McKernan D. Proximal row carpectomy: clinical evaluation. *J Hand Surg [Am]* 1990;15:426–30.
62. Kirschenbaum D, Schneider LH, Kirkpatrick WH, Adams DC, Cody RP. Scaphoid excision and capitulate arthrodesis for radioscaphoid arthritis. *J Hand Surg [Am]* 1993;18:780–5.
63. Tomaino MM. Intercarpal fusion for the treatment of scaphoid nonunion. *Hand Clin* 2001;17:671–86.
64. Tomaino MM, Delsignore J, Burton RI. Long-term results following proximal row carpectomy. *J Hand Surg [Am]* 1994;19:694–703.
65. Tomaino MM, Miller RJ, Cole I, Burton RI. Scapholunate advanced collapse wrist: proximal row carpectomy or limited wrist arthrodesis with scaphoid excision? *J Hand Surg [Am]* 1994;19:134–42.
66. Wyrick JD, Stern PJ, Kiefhaber TR. Motion-preserving procedures in the treatment of scapholunate advanced collapse wrist: proximal row carpectomy versus four-corner arthrodesis. *J Hand Surg [Am]* 1995;20:965–70.
67. Schuind F, Haentjens P, Van Innis F, Vander Maren C, Garcia-Elias M, Sennwald G. Prognostic factors in the treatment of carpal scaphoid nonunions. *J Hand Surg [Am]* 1999;24:761–76.

68. Shin AY, Chang M, Moran SL, Steinmann SP, Bishop AT. Outcomes and complications of 1,2-intercompartmental supraretinacular arterial vascularized bone grafting of scaphoid nonunions. Podium presentation, 59th Annual Meeting of the American Society for Surgery of the Hand, New York, September 2004.
69. Steinmann SP, Bishop AT. A vascularized bone graft for repair of scaphoid nonunion. *Hand Clin* 2001;17:647-53.
70. Zaidenberg C, Siebert JW, Angrigiani C. A new vascularized bone graft for scaphoid nonunion. *J Hand Surg [Am]* 1991;16:474-8.
71. Straw RG, Davis TRC, Dias JJ. Scaphoid nonunion: treatment with a pedicled vascularized bone graft based on the 1,2 intercompartmental supraretinacular branch of the radial artery. *J Hand Surg [Br]* 2002;27:413-6.
72. Singh HP, Forward D, Davis TR, Dawson JS, Oni JA, Downing ND. Partial union of acute scaphoid fractures *J Hand Surg [Br]* 2005;30:440-5.