

January 2011

Comparison Of Ct And Plain Film For The Postoperative Assessment Of Scaphoid Fracture Healing

Lauren Allyson Hackney
Yale School of Medicine, lauren.hackney@yale.edu

Follow this and additional works at: <http://elischolar.library.yale.edu/ymtdl>

Recommended Citation

Hackney, Lauren Allyson, "Comparison Of Ct And Plain Film For The Postoperative Assessment Of Scaphoid Fracture Healing" (2011). *Yale Medicine Thesis Digital Library*. 1556.
<http://elischolar.library.yale.edu/ymtdl/1556>

This Open Access Thesis is brought to you for free and open access by the School of Medicine at EliScholar – A Digital Platform for Scholarly Publishing at Yale. It has been accepted for inclusion in Yale Medicine Thesis Digital Library by an authorized administrator of EliScholar – A Digital Platform for Scholarly Publishing at Yale. For more information, please contact elischolar@yale.edu.

YALE UNIVERSITY SCHOOL OF MEDICINE

Comparison of CT and Plain Film for the Postoperative Assessment of Scaphoid Fracture Healing

A Thesis Submitted to the Yale University
School of Medicine in Partial Fulfillment of
the Requirements for the Degree of Doctor of
Medicine

Lauren A. Hackney

2011

COMPARISON OF CT AND PLAIN FILM FOR THE POSTOPERATIVE ASSESSMENT OF SCAPHOID FRACTURE HEALING. Lauren A. Hackney, Carrie R. Swigart, Seth D. Dodds. Department of Orthopaedics and Rehabilitation. Yale University School of Medicine, New Haven, CT.

Our study is designed to investigate the question of whether plain film or CT is a more suitable imaging modality for use in the postoperative assessment of scaphoid fracture healing. We have retrospectively collected data on 16 scaphoid fracture patients who have undergone surgical intervention as part of their management, and who had both plain film and CT imaging conducted within a relatively short time frame of five weeks as part of their follow-up. These imaging studies were then assessed by two observers who are hand surgeons at our institution, and were graded as healed or not healed. Of the 16 patients included in our study, 12 had plain film and CT that both provided the same assessment of healing; 8 of these were also in line with the assessment of healing based on clinical data. Three cases (3/16) had variable interpretation of healing by CT and plain film. All three of these cases involved surgical repair of nonunions, and each of the three cases, CT was able to detect radiographic signs of healing that were not seen by the observers on plain film. These results suggest that in the majority of cases, CT and plain film imaging offer similar assessments of healing of postoperative scaphoid fractures. In cases involving surgical repair of nonunions, CT can detect subtle radiographic signs of healing prior to the appearance of such signs on plain film.

Acknowledgements

I would like to thank Dr. Dodds and Dr. Swigart for their help and involvement with this project.

Table of Contents

Background and Epidemiology.....	1
Anatomy.....	2
Pathophysiology and Biomechanics	4
Clinical Presentation	4
Diagnostic Imaging.....	6
Treatment	13
Complications	18
Implications of Scaphoid Fracture Healing	19
Hypothesis and Aims	21
Methods	22
Results.....	24
Discussion.....	31
References.....	47

Introduction

Scaphoid fractures are among the most common upper extremity fractures to occur in adults. Prompt diagnosis and management can lead to adequate healing and the avoidance of post-traumatic complications, including nonunion and arthritis.

Background and Epidemiology

Acute scaphoid fractures were first described in 1881 by Cousin and Destot, without the use of radiographs or other imaging studies (1). In 1895, Etienne Destot, considered a pioneer of wrist orthopedics, first used a radiograph to view a fractured scaphoid (2). Since this time, imaging studies have been used routinely to elucidate areas of wrist malfunction and pain immediately following traumatic injury.

At present, recent data suggests that scaphoid fractures account for 2.9% of all fractures and 69% of all carpal injuries that occur in the adult population; they are second in frequency only to distal radius fractures (1, 3). Recent retrospective studies report incidences of these fractures ranging from 26 per 100,000 people to 121 per 100,000 person-years in a large military population (4).

In 2010, Van Tassel et al. utilized a large national population database to analyze the demographic distribution of the occurrence of acute scaphoid fractures. This study showed a gender breakdown of scaphoid fracture occurrence with a male predominance, reporting that 66.4% of scaphoid fractures occurred in males (4). Prior studies also highlighted a significantly higher rate of scaphoid fractures among the white population when compared to the African American population, with a relative risk of 1.32 (5).

The authors then stratified scaphoid fractures by age group. This distribution showed a peak incidence of scaphoid fractures in the second and third decades at 3.38 per 100,000, with a steady fall-off in incidence until the fifth and sixth decade. Finally, the authors undertook a stratification of scaphoid fractures by mechanism, finding that falls were responsible in 74.0% of patients, and that 34.15% of reported fractures resulted from sporting activities, with basketball and baseball being the most common culprits. Though scaphoid fractures remain relatively uncommon in the U.S. population, the incidence of 1.47 scaphoid fractures per 100,000 person-years reported by Van Tassel et al. indicates the persistent need for optimization of scaphoid fracture diagnosis and treatment to prevent adverse outcomes among such a young and active population (1, 4).

Anatomy

Any thorough understanding of the mechanism of scaphoid fractures and concepts of treatment must necessarily begin with an analysis of the anatomy of the scaphoid. One of the smallest bones in the human body, the scaphoid was aptly named after the Greek word for boat, *skaphos*, because of its tubular, twisted, S-shaped structure. Roughly 80% of the scaphoid's surface is covered with articular cartilage; this contributes to the difficulty in periosteal healing of scaphoid fractures and the decreased likelihood that such fractures will heal properly, while also limiting ligamentous attachments to the scaphoid and its vascular supply (1, 3). It is positioned in the carpus at 40 degrees to the coronal plane and 32 degrees to the sagittal plane (3) (Fig. 1).

The ulnar aspect of the scaphoid is concave, facilitating articulation with the sphere-like head of the capitate. A small, semi-lunar facet exists proximally to facilitate

articulation with the lunate. The articulation of the scaphoid with the radius occurs at the convex radial surface, in the proximal third of the scaphoid. The waist of the scaphoid is located distal to the radio-scaphoid articulation and is grooved on its palmar surface by the radioscapnocapitate ligament, which acts as a sling across the waist of the scaphoid (3).

Ligamentous attachments to the scaphoid include the radioscapnocapitate (RSC) ligament which attaches to the ulnar aspect of the scaphoid waist, and the dorsal intercarpal (DIC) ligament which is richly innervated by the posterior interosseous nerve and provides the primary vascular supply to the scaphoid. The RSC ligament originates from the radial styloid and effectively acts as a fulcrum around which the scaphoid rotates; it is believed to play a role in proprioception due to its high density of mechanoreceptors (3). Additionally, the scapholunate interosseous ligament connects the scaphoid to the lunate and is composed of both transverse and oblique collagen fibers that are critical in maintaining proper carpal kinematics at the scapholunate interval (3).

In 1980 a study of 15 fresh cadaver scaphoids elucidated details regarding the blood supply of the scaphoid (6). Through this study it was determined that 70-80% of the intraosseous vascularity and the entire vascularity of the proximal pole of the scaphoid was provided via branches of the radial artery. The distal tuberosity region of the scaphoid receives 20-30% of its supply from volar radial artery branches. The proximal pole of the scaphoid was found to be dependent on a single dominant intraosseous vessel for the majority of its blood supply and, as such, was concluded to be particularly vulnerable to avascular necrosis following traumatic injury to the scaphoid (6) (Fig. 2).

Pathophysiology and Biomechanics

The primary requirement for an acute fracture of the scaphoid is hyperextension at the wrist to greater than 95 degrees. The fracture begins at the volar waist and the forces propagate dorsally until a fracture occurs (7). Proximal pole scaphoid fractures specifically result from dorsal subluxation during forced hyperextension. Additional studies have reported axial loading and hyperflexion at the wrist as causative mechanisms for acute scaphoid fractures (8).

Scaphoid fracture displacement is directly related to three distinct forces: bending, shearing, and translational forces (3). When scaphoid fractures are left untreated, these forces produce variable action on the scaphoid waist and might ultimately lead to volar angulation; this deformation is known as the “humpback deformity” and is related to volar bone reabsorption resulting from persisting displacing forces that develop when a scaphoid fracture is left untreated.

Clinical Presentation

The assessment of a potential scaphoid injury must necessarily begin with a thorough evaluation of the clinical signs and symptoms relevant to the patient’s presentation. Both clinical history and clinical exam become instrumental to making the diagnosis, with over 90% of patients with a scaphoid fracture recalling a hyperextension injury (1). Other potential mechanisms of scaphoid fracture might involve higher energy falls with forced hyperextension or palmar flexion, collisions, or direct blows to the wrist (3). Main

examination techniques include palpation of the anatomic snuffbox as well as volar palpation of the distal tuberosity (9) (Fig. 3).

Additionally, care must be made to differentiate between acute and chronic scaphoid injury by inquiring about prior wrist trauma. Signs and symptoms of the two types of scaphoid injury may differ, with acute injury tending to present with swelling, limited range of motion, tenderness to palpation in the anatomic snuffbox, and pain with axial loading of the thumb. Chronic scaphoid injury is more likely to present with decreased wrist motion, weakness, difficulty performing pushups, and radial-sided wrist pain (3).

Several specific signs relevant to scaphoid injury have been pinpointed to be of particular efficacy in diagnosing a scaphoid fracture, but nonetheless some studies do call into question the utility of using such clinical signs in a diagnostic manner.

In 1994, Waizenegger et al. investigated 12 clinical features of scaphoid fractures in two groups of patients, one of which had radiographically-diagnosed scaphoid fractures and another of which had scaphoid fracture suspected but unconfirmed by radiographic imaging. The clinical signs that they assessed included mechanism of injury (impact on the palm with the wrist extended), swelling, pain, and discoloration of the snuffbox. Additional clinical tests that were assessed included pain with ulnar or radial deviation at the wrist, pain on resisted pronation or supination, pain with compression of the thumb, and pain with the “clamp” test in which the thumb and forefinger are used to compress the area of the scaphoid from both sides (10). The authors concluded that none of these twelve clinical signs or tests could be considered a reliable means of detecting or diagnosing a scaphoid fracture.

Despite the findings by Waizenegger et al., other studies have in fact demonstrated an important role for the clinical assessment of injuries to the scaphoid in determining the diagnosis and proper course of treatment. In 1998, Parvizi et al. evaluated the use of four clinical signs in assessing the existence of a scaphoid fracture. The signs they focused on included pain in the anatomic snuff box, tenderness over the scaphoid tubercle, pain on longitudinal compression of the thumb, and range of motion of the thumb. The study, which was a prospective evaluation of 215 patients with suspected scaphoid fractures, found that, while each test used alone was an inadequate indicator of a scaphoid fracture, all four tests used in combination within the first 24 hours following injury produced 100% sensitivity and 74% specificity in diagnosing a scaphoid fracture (11). Thus, these four clinical tests could be used in combination to achieve an accurate clinical diagnosis of a scaphoid fracture.

Diagnostic Imaging

The complicated three-dimensional shape of the scaphoid has long been implicated in the difficulty of evaluating fracture location and degree of displacement with acute scaphoid fractures. As a result, a wide variety of imaging modalities have been used in an attempt to more precisely evaluate scaphoid fracture location and severity, as well as assess proper healing after a fracture has been diagnosed and treated.

Plain radiographs are the initial imaging study of choice for suspected scaphoid fractures. The postero-anterior views typically used to assess scaphoid fractures often result in an image distorted by the flexion and normal curvature of the scaphoid, even when the wrist is in ulnar deviation at the time of the radiograph (9). In such imaging,

most of the anatomic features of the scaphoid, including the distal tubercle, are compressed into the distal half of the radiographic image, rendering the image difficult to analyze in the assessment of any potential fracture (9) (Fig. 4).

The plain film views that are typically used to assess the scaphoid vary in the anatomical region of the scaphoid that they highlight. The semipronated oblique and lateral views are optimal for analyzing the waist of the scaphoid, whereas the semisupinated oblique view is best for visualizing the dorsal ridge of the scaphoid (9). The lateral view of the scaphoid is a more difficult one on which to assess scaphoid injury due to the overlap of other carpal bones on this view; however, it is nonetheless useful in its ability to show perilunate fracture-dislocations as well as the overall alignment of the carpal bones (1).

Certain plain film views are also useful in highlighting scaphoid fracture displacement; these include flexion-extension and radioulnar deviation views of the wrist. Deformities observed in these views might more precisely indicate an unstable scaphoid fracture (1).

Other soft tissue signs seen on plain film have been used in an attempt to diagnose scaphoid fractures. These include the scaphoid and pronator fat stripes. The scaphoid fat stripe is a small, linear collection of fat that lies between the radial collateral ligament and the tendon sheaths of the abductor pollicis longus and extensor pollicis brevis. On oblique and postero-anterior views of the wrist the fat stripe is visualized as a thin lucent line that runs parallel to the lateral border of the scaphoid. Blood and edema along the lateral aspect of the scaphoid will accumulate in this area following acute traumatic injury, and this can alter the configuration of the fat stripe (12). These radiographic soft tissue signs

were concluded by Annamalai et al. in 2003 to be of minimal diagnostic value in the assessment of potential scaphoid fractures, due to inadequacies in both sensitivity and specificity (12).

Perhaps the next most frequently used imaging modality to visualize and assess scaphoid fractures is computed tomography. The process involves x-rays that are projected through the wrist while the source rotates around the patient; a computer is then used to generate a tomographic image (13). This imaging modality is useful in its ability to provide information concerning fracture plane orientation and location, fracture fragment displacement, and secondary degenerative changes in adjacent joints. The CT image can also be equally effective in casted and uncasted patients. Moreover, helical CT has the unique ability to trace a spiral curve around the patient's skin. In the case of scaphoid fractures, helical CT imaging is mostly used for the evaluation of complex fractures, healing fractures, and post-surgical fractures. It is a preferable imaging modality in the time required for the study, which can reduce unintentional intrascap motion while also providing a favorable study for ill patients. Helical CT imaging can also be used to generate multiplanar reconstructions from the original data, thus allowing any plane to be used to study a given fracture (13).

When using CT to analyze the scaphoid, it is crucial to use thin slices (2 mm or less) that are contiguous or overlapping; this is necessitated as a result of the scaphoid's small size and unusual geometry. Thick slices can cause undisplaced scaphoid fractures to be overlooked and are thus much less effective in this setting. Scans generated in this manner can be of most value when taken with the wrist in both ulnar and radial deviation. This positioning can allow for an accurate assessment of carpal displacement and

instability in addition to the typical visualization of the fracture line provided by CT-generated imaging (13).

Several studies have analyzed whether CT is a significantly superior imaging modality to plain films in the diagnosis of a scaphoid fracture. One study that analyzed the efficacy of radiographs and computed tomography in the assessment of scaphoid fracture displacement found that, while computed tomography improves the reliability of detecting scaphoid fracture displacement, its accuracy was somewhat limited. The study concluded that computed tomography was a useful modality to rule out scaphoid fracture displacement, but was less useful in diagnosing a displaced fracture (14).

Another study conducted by Temple et al. was designed to compare the efficacy of plain radiographs and computed tomography in assessing scaphoid fracture displacement among cadaver wrists with either no fracture, undisplaced fractures, or fractures with displacement of over 1 mm. The results of this study found that, while both CT scans in the sagittal plane and plain radiographs were both capable of detecting fractures with high degrees of interobserver and intraobserver reliability, both modalities fell short in detecting displacement greater than 1 mm (15). In this respect, while CT scans can be useful in generating images that show fracture location in greater detail than that of plain films, neither imaging modality is completely flawless. This is especially true with regards to their ability to assess certain important details—such as the degree of fracture displacement—that would certainly carry significant weight in determining management strategies for scaphoid fracture patients.

Additionally, some debate exists as to which imaging modality is optimal for the assessment of scaphoid fracture healing. One major study has determined that serial

radiographs that are typically used for assessment of healing have poor inter-observer agreement, even as late as 12 weeks post-injury (16). CT imaging provides enhanced resolution and more definitive information regarding healing, and so a significant debate exists as to whether the traditional use of serial plain films continues to hold value as a modality for assessing the healing of scaphoid fractures (3).

Magnetic resonance imaging is a favorable means of diagnosing scaphoid fractures because it can obtain images in any plane, is sensitive to edematous changes, and is free of streak artifacts that can obscure CT examinations. High resolution MRIs of the wrist are made possible with the use of surface coils, which are loops of conducting material that can be placed directly over the region of interest for increased magnetic sensitivity (13). One study conducted by Imaeda et al. elucidated the potential for MRI studies to diagnose scaphoid fracture lines as early as two days post-injury; additionally, these lines remained visible for several months longer than the lines seen on plain films (17) (Fig. 5).

Other studies, however, retain some skepticism with regards to the regular use of MRI for the diagnosis of a scaphoid fracture. For one, though MRIs have been shown to be 100% reliable in their ability to diagnose a scaphoid fracture, the high false positive rate associated with this imaging modality raises much concern (18). Some researchers point out that not all signal abnormalities detected on MRI represent true fractures; many may instead be related to artifact, normal variation, or bone bruising (19). Additionally, obtaining routine MRI for the assessment and diagnosis of scaphoid fractures would ultimately amount to an extremely resource-intensive endeavor.

One recent study conducted by Brydie et al. was designed to investigate the use of MRI to detect occult scaphoid fractures. In this study, 195 patients with clinically suspected scaphoid fractures and negative plain films underwent MRI within 14 days of the initial injury. The study ultimately concluded that nearly one fifth of patients with suspected scaphoid fractures and normal plain films had occult scaphoid fractures confirmed by MRI; another one fifth of patients had occult fractures of the distal radius or other carpal bones that were confirmed by MRI. The authors thus concluded that in the setting of negative or ambiguous plain films and clinical signs of a scaphoid fracture, MRI provides an early definitive diagnosis that can change patient management in over 90% of cases (20). This study certainly presents substantial evidence that MRIs to assess scaphoid fractures, when used sparingly in proper clinical settings, can possess much diagnostic utility.

The most commonplace role for the use of MRI in assessing scaphoid injury would be to reserve the use of MRI only if a fracture is clinically suspected in the setting of negative plain films. In this setting, MRI is considered by most to be the most reliable imaging modality for the diagnosis of both acute and occult scaphoid fractures, and is usually diagnostic within 24 hours of injury (3).

CT, MRI, and plain films are all useful imaging modalities for detecting morphologic changes in bone but do not provide information on osteoblastic activity of the wrist in patients with a clinically suspected scaphoid fracture. For this reason some recommend the use of radionuclide bone scintigraphy in the diagnostic assessment of a scaphoid fracture. One study by Tiel-van Buul et al. compared the use of repeated plain films up to 6 weeks after trauma, to three-phase bone scintigraphy performed 72 hours

after trauma, to assess potential scaphoid fractures in patients with clinical suspicion and initial negative plain films. The study reported an unacceptably high interobserver variability with the former method and concluded that bone scintigraphy would present a superior method for the detection of an occult fracture. The main issue presented with bone scintigraphy is that of a low specificity. It is especially difficult to localize an area of intense uptake to a specific carpal bone given the small anatomy involved in this region and the low resolution image generated through the use of scintigraphy (13). Newer technologies combining scintigraphy with plain radiography are perhaps on the horizon, and such innovations would certainly be necessary to allow bone scans to rival the other imaging modalities currently in use for scaphoid fracture assessment.

Finally, a relatively new but not yet commonplace method for visualizing scaphoid fractures has been developed in tomosynthesis. This method uses low-dose exposures from a linear x-ray tube that sweep toward a stationary digital detector in a selected body part. Up to 60 tomographic sections can be reconstructed from the multiple low-dose exposures with a selectable thickness ranging from 1 to 10 mm. The method has been used in mammography and abdominal imaging for many years, but has only recently received notice as a method of visualizing the scaphoid (21). Studies have shown that this imaging modality can detect cortical fractures and fractures of the trabecular bone in a similar manner to that of CT, and thus some recommend that it be used to augment plain films in the diagnosis of an occult scaphoid fracture (21). The commonplace use of tomosynthesis in the emergency room setting is a long way off, and the future role of this imaging modality in the scaphoid fracture diagnosis is still uncertain.

Much of the reasoning behind the use of such various imaging modalities to aid in the diagnosis of scaphoid fracture lies in the necessity to provide such a traumatic injury with rapid and appropriate treatment. Methods used to treat a diagnosed scaphoid fracture differ primarily depending on degree of displacement, severity of the fracture, and clinical and radiographic assessment of healing.

Treatment

Because the tenuous blood supply to the scaphoid leaves fractures of this bone at particularly high risk for non-union, it is crucial that any scaphoid fracture be primarily treated and followed by an orthopaedic surgeon or a hand surgeon. The typical scaphoid fracture classification system, the Herbert classification, divides fractures of this carpal bone into four different types, each with varying degrees of stability and probability of union. Type A fractures are defined as stable acute fractures; these are typically fractures through the tubercle or incomplete fractures through the waist of the scaphoid. Type B fractures are unstable and involve distal oblique fractures, complete waist fractures, proximal pole fractures, and trans-scaphoid perilunate fracture-dislocation. Type C and D scaphoid fractures refer to fractures with delayed union or non-union, respectively (22). The Herbert classification is a useful method for devising treatment strategies for acute scaphoid fractures (Fig. 6).

The initial emergency room management of suspected scaphoid fractures, regardless of initial radiographic findings, should involve immobilization in a short-arm thumb spica splint and arranged follow-up with an orthopaedic or hand surgeon within 7 to 10 days, during which reexamination and repeat radiographs can be performed as

needed. Significantly displaced fractures warrant urgent consultation with an orthopaedic or hand surgeon (23).

Distal pole and tubercle fractures are traditionally treated nonoperatively. The distal pole of the scaphoid is highly vascularized, and thus good clinical result is typically obtained for fractures of this area after 6 to 8 weeks of cast immobilization in a short-arm cast. Similarly, stable fractures or incomplete fractures of the scaphoid waist can be treated nonoperatively with a high expectation of adequate healing. Nondisplaced fractures of the scaphoid waist have an 88% to 95% rate of healing with cast immobilization that is started within three weeks of injury (24). Contrarily, fractures of the proximal pole of the scaphoid are much more prone to complications such as avascular necrosis and nonunion, presumably due to the more tenuous blood supply to this region of the scaphoid as well as the greater tendency towards instability of this fracture. Proximal pole fracture instability is attributed to the small size, interarticular location, and large moment arms across the fracture site (3). A general consensus exists to use operative methods for treatment of all proximal pole scaphoid fractures, regardless of degree of displacement.

When nonoperative treatment via cast immobilization is used for scaphoid fractures, some debate exists as to which size thumb spica cast is optimal to achieve healing. One study comparing short and long thumb spica casts for non-displaced scaphoid fractures showed a small difference favoring the above-elbow cast in order to prevent nonunion (25). Nevertheless, nonoperative treatment of even undisplaced or minimally displaced scaphoid fractures is falling out of favor due to the increased

necessity for prolonged follow-up, potential skin breakdown, prolonged immobilization until healing occurs, and a longer time to healing (26).

Though usually surgical intervention is not essential for non-displaced scaphoid fractures, recent data suggests that minimally invasive techniques using percutaneous screw fixation can lead to faster time to union than cast immobilization alone (9.2 weeks versus 13.9 weeks) (27). Additionally, operative methods can lead to a decreased rate of nonunion (27). Surgical treatment options involving percutaneous screw fixation traditionally result in patients being transitioned to a removable brace within two weeks, thus allowing for a more rapid recovery and return to function compared to casting.

Displaced or unstable scaphoid fractures refer to any scaphoid fracture in which the fracture fragments are displaced by more than 1 mm in any view (26). Unstable fractures also refer to those that become progressively displaced during a period of cast immobilization, regardless of initial non-displacement (26). Because displaced fractures are more likely to progress to nonunion or develop avascular necrosis, common practice is to address these fractures with a method of internal fixation.

Adequate bone healing requires viable bone cells, sufficient blood supply, and stability at the fracture site. To achieve fracture stability, various implants can be used to prevent shearing that disrupts the healing process (3). The most common of these is the headless compression screw introduced by Herbert and Fischer in 1984 (22). The headless screw is advantageous in that it can be inserted into the scaphoid below the articular cartilage that covers over 80% of the surface of the scaphoid (26). Though the Herbert screw can be inserted either dorsally or volarly, many surgeons prefer the dorsal approach especially for proximal pole fractures, due to the improved exposure of the

proximal pole and relative ease of screw insertion provided with this particular approach. The dorsal approach, however, does put the tenuous blood supply of the scaphoid at risk, especially in cases where the surgical exposure includes elevating the soft tissue attachments and dorsal blood supply off of the dorsal ridge of the scaphoid. Close follow-up is thus necessary to ensure that avascular necrosis does not develop (28).

A percutaneous technique of inserting cannulated Herbert screws has been developed relatively recently. With this method, reduction of displaced scaphoid fractures can be achieved with fluoroscopic or arthroscopic control. Multiple prospective randomized series have already reported union rates of 100% with this technique, thus suggesting a significant role for percutaneous screw fixation in the treatment of displaced and nondisplaced scaphoid fractures (29).

Scaphoid nonunions present a complication of scaphoid fractures that is usually addressed surgically, and most often using methods that are more complex than those used for initial scaphoid fractures. Scaphoid nonunion is defined as a nonhealed scaphoid that persists 6 months after the initial injury. Nonoperative management can be used for nondisplaced scaphoid nonunions, but entails prolonged cast immobilization for 4 to 6 months (26). Operative management for scaphoid nonunions has centered on the use of bone grafting techniques which can be used to correct the humpback deformity that commonly results from the development of a nonunion. Two of the main techniques studied include screw fixation in combination with wedge grafting, as well as iliac bone grafts combined with Kirschner-wire fixation (30, 31). The former technique is considered to be more technically difficult and, despite favorable clinical outcomes, the use of K-wire fixation and bone chip grafting is often preferred (26). Initial studies of the

use of iliac bone grafting and K-wire fixation to treat scaphoid nonunions have reported a 97% healing rate in an average of seventeen weeks. These results were unaffected by the preoperative existence of avascular necrosis or the location of the fracture, thus making this procedure particularly appealing for fractures of the proximal pole (31).

Nevertheless, considerable debate still exists as to the optimal treatment methods for scaphoid nonunions. Some have argued for the use of vascularized bone grafting including pronator quadratus pedicled bone graft, pedicled bone grafts based on the ulnar artery or palmar carpal artery, or radial styloid fasciosteal graft (26). Studies investigating the use of vascularized bone graft for scaphoid nonunions argue that such methods would be fundamentally better for the treatment of proximal pole fractures, particularly those affected by or at risk for the development of avascular necrosis. Though the balance of evidence does suggest that vascularized bone grafting techniques may be better for the treatment of nonunions affected by avascular necrosis of the proximal pole, successful outcomes from such techniques are not yet universal, thus warranting the continued debate on this subject (26).

Regardless of the operative technique used to repair acute scaphoid fractures or scaphoid nonunions, postoperative care must involve placement in a molded volar plaster splint for approximately four weeks. Hand therapy is a necessary component of treatment to regain motion and prevent wrist stiffness. Weight-bearing activity is not permitted initially, but discontinuation of the splint and full return to function are generally allowed only once healing has been demonstrated both clinically and radiographically (3).

Complications

As is the case with any serious fracture and especially one that occurs near a joint crucial for carrying out activities of daily living, failure to achieve sufficient union and healing can lead to severe consequences. Scaphoid fracture complications can be particularly prevalent if the initial management is inadequate. Delayed diagnosis and immobilization has been associated with rates of nonunion of up to 88% (32). The development of scaphoid fracture nonunion can have significant clinical consequences. A study on the natural history of scaphoid nonunions showed that the vast majority resulted in degenerative changes, including sclerosis, radioscaphoid arthritis, or generalized arthritis of the wrist (33). As mentioned earlier, the surgical treatment of scaphoid nonunions is significantly more complicated and often requires the use of advanced bone grafting techniques in order to be successful.

Since the integrity of the scaphoid is important for the stabilization of the carpal row via intercarpal and radiocarpal ligaments, scaphoid nonunion can severely compromise the overall stability of the wrist. An unstable fracture of the scaphoid can allow the proximal pole of the scaphoid to rotate with the lunate. In this setting, the distal pole of the scaphoid remains flexed, or attached to the trapezium and the trapezoid, resulting in the humpback deformity angulation through the fracture of the scaphoid (9).

Arthritic changes are the most commonly occurring complications of scaphoid nonunions, but one of the more serious consequences of a scaphoid nonunion is avascular necrosis. This is especially seen in proximal pole fractures of the scaphoid. Avascular necrosis can clinically present as increasing pain and decreased range of motion at the wrist. Many argue for the use of vascularized bone grafts to achieve maximal union rates

in the setting of avascular necrosis (88%, compared to 47% union for non-vascularized structural bone grafts) (30).

Fortunately the progression of a scaphoid fracture to nonunion is not in itself an ultimate diagnosis of wrist collapse and arthritis, and many of the operative techniques discussed earlier have been used successfully to facilitate nonunion repair and allow healing to proceed. Optimal results are always achieved, however, when scaphoid fracture or nonunion is promptly diagnosed and appropriately treated to completion, in order to allow full range of motion and return of function at the wrist, with minimal or no discomfort from the initial injury.

Implications of Scaphoid Fracture Healing

An important component of any scaphoid fracture assessment is the determination of proper healing. This has implications for both proper nonoperative treatment duration or extent of postoperative care, and most importantly governs when an individual can return to normal activities after suffering from a scaphoid fracture.

Healing mechanisms of a scaphoid fracture are identical to those of fractures in other areas of the body, and can involve either primary or secondary healing depending on the degree of displacement. Primary healing occurs when fracture surfaces are rigidly held in contact, allowing fracture healing to progress without the formation of a grossly visible callus (1). In the absence of rigid fixation at the fracture site, as can occur in displaced scaphoid fractures or fractures that are inadequately stabilized, secondary bone healing involving callus formation takes place. Secondary healing is a continuous process involving multiple stages and can take up to one year to reach completion (34). Though

any treatment that promotes scaphoid fracture healing can be considered successful, one that promotes primary healing is favorable since scaphoid fractures do not make callus, essentially rendering them unable to heal by secondary methods. Additionally, attempts at secondary healing are seldom successful in the setting of a scaphoid fracture, as the articular fluid creates a pseudarthrosis prior to bone healing

Imaging to monitor the progress of scaphoid healing is often necessary to prevent or promptly treat developing complications. Serial radiographs have typically been used to demonstrate adequate healing of scaphoid fractures but these are not without pitfalls—studies have shown poor inter-observer agreement in assessing scaphoid fracture union 12 weeks post-injury (16). Nevertheless, radiographs still remain the modality of choice to assess union, defined as “the restoration of bony architecture across the fracture site” (35). Radiographs are most commonly used in this context to identify trabeculae crossing the fracture line or sclerosis at the fracture line.

Magnetic resonance imaging has also proven useful in the assessment of scaphoid fracture healing. With this imaging modality, the appearance of healing is visualized as a “double line,” representing the fracture line coupled with the revascularization front. A failure of this front to proceed is almost always associated with eventual nonunion (36) (Fig. 7). MRI is also useful in that it can confirm bony union in a high percentage of patients deemed to be clinically non-united. Unlike other imaging studies, MRIs will continue to show an abnormal signal around a stable fracture even as healing progresses to union; the only definitive sign of union is the return of normal marrow continuity across the fracture line (37). In addition, an MRI scan would suffer from scatter if there was internal fixation present within the scaphoid. The MRI scan is thus a more clinically

appropriate study to identify the presence of a scaphoid fracture, rather than for the determination of healing.

CT scans are a more appropriate choice because reformatting of the imaging in multiple planes allows for a three dimensional assessment of the trabecular architecture of the scaphoid. CT imaging also has some scatter with internal fixation, but much less so than MRI. It is still possible to identify bridging trabeculae on CT even when an internal fixation device is present. Bridging bone across the fracture site visualized on CT provides evidence that radiographic healing has occurred. Most surgeons prefer to see at least 50% bridging bone prior to releasing patients to full activities. Even in the presence of radiographic healing, it is critical that the clinical exam support the assessment of a healed bone: the fracture site itself must be nontender and typical function must return to the extremity.

Hypothesis and Aims

Many surgeons delay a recommendation of full return to normal activities until both radiographic and clinical evidence of fracture healing are present (3). Unfortunately, much debate exists on the proper method to document radiographic healing, and to this date studies have not previously been done with regards to the optimal method to assess scaphoid fracture healing.

A firm knowledge of the assessment of healing would certainly help to minimize immobilization time, and perhaps to expedite surgical treatment in the case of prompt radiographic evidence of scaphoid nonunion. Additionally, evidence against the use of serial CT for the assessment of scaphoid healing would certainly prevent wasted

resources and unnecessary exposure to radiation, especially in a younger population. This study aims to provide preliminary results to suggest the optimal method for assessing scaphoid fracture healing, focusing on CT and plain films as the competing options for radiographic evidence.

It is possible that either plain films or CT imaging provides a superior means for the routine monitoring of scaphoid fracture healing post-operatively. Our hypothesis was that in surgically treated scaphoid fractures and nonunions, CT scans would be more likely to confirm radiographic evidence of healing than plain films once the scaphoid demonstrated clinical signs of healing. Using the physical exam finding of no scaphoid tenderness as the true positive for a healed scaphoid fracture, we suspect that CT scans would serve as a more accurate predictor of bridging bone than a plain film for operatively treated scaphoid fractures and nonunions. The purpose of our study was to provide recommendations for a specific post-operative radiographic protocol to efficiently monitor scaphoid fracture healing.

Methods

We collected retrospective data on sixteen patients from our institution who had suffered from an acute scaphoid fracture or non-union and undergone operative management to ensure proper healing. We specifically included patients in this study who had undergone multiple post-operative imaging studies for the assessment of healing progression, and who had a plain film and CT performed within a small enough time frame. Based on the retrospective nature of this investigation, five weeks or less between plain film and CT was chosen as an acceptable time frame by which to include patients.

The relevant imaging studies on these patients were collected, and their information anonymized to protect both patient confidentiality as well as to blind the observers. Two of the institution's hand surgeons were then asked to look at each patient's plain film and CT sequentially. The observers were blinded to the patient's identity as well as the attending surgeon involved in the operative management of each patient. They were also blinded to the clinical scenario involved with each patient's treatment and follow-up, knowing only that each patient had undergone operative management for a scaphoid fracture.

The observers were then asked to assess for fracture healing in each of the plain film and CT images. Responses were recorded as being either in support of or against fracture healing, with no recorded assessments on the degree of fracture healing or other factors observed in each image. Observers were not made aware of the other's response during data collection. Responses were collected and compiled into a database of included patients.

In cases where the radiology report of the imaging study specifically referred to the assessment of healing of the scaphoid fracture, this interpretation was included as a third observer interpretation. Reports that did not specifically refer to the degree of scaphoid fracture healing were not included. The assessments of each imaging study by the three observers were combined to reach a general consensus, which was then taken as the general radiographic assessment of healing.

In addition to radiographic data, clinical data was compiled on each patient included in this study. This clinical data was made to correspond chronologically with the time period encompassed by the imaging study for each patient. Specific clinical data

collected focused on the physical exam of the patient at the time of the imaging studies, especially in relation to the presence of tenderness in the anatomic snuffbox at the time of the visit. For the purposes of our study, clinical healing was defined as the absence of tenderness on clinical examination of the scaphoid. Clinical data was combined with radiographic assessment by the observers into an Excel spreadsheet to allow for all facets of patient data to be compared for each scaphoid fracture patient.

Results

A total of sixteen patients from our institution had both radiographic images and clinical data that could be compiled and analyzed for inclusion in our study. These patients all had fractures of the scaphoid; fifteen (14/16) had fractures of the scaphoid waist, and two (2/16) had proximal pole scaphoid fractures. All patients were followed up postoperatively with imaging studies obtained periodically. The average length of time in between surgery and analyzed plain film/CT was 104 days, with a range from 38 days after surgery to 330 days after surgery. Patients ranged in age from 15 to 42, with an average age of 26. Data on the included patients and their respective radiographic and clinical analyses are highlighted in Tables 1 and 2.

Of the patients included in our study, thirteen (12/16) had plain films and CT that warranted the same assessment by the observers with regards to fracture healing (Fig. 8 and Fig. 9). Nine of these cases (8/16) had plain films and CT both indicative of the same healing assessment and in line with the assessment of clinical healing. In five of these cases (5/16), the plain films and CT agreed in terms of providing the same assessment of healing, but this common assessment was not in line with the clinical data. In one of these

cases, CT and plain films indicated scaphoid fracture healing prior to a complete dissipation of scaphoid tenderness, which occurred two months following this imaging. In another case, plain films and CT both showed proper healing, but the patient still complained of tenderness at the distal pole of the scaphoid, later attributed to loosening of the scaphocapitate screw.



Figure 8a: Plain film showing clearly healed scaphoid fracture.

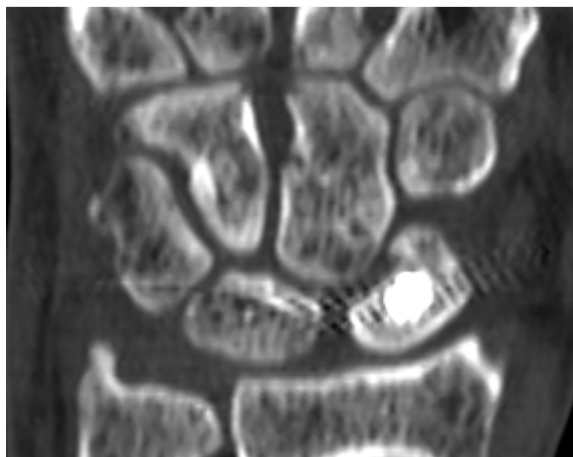


Figure 8b: CT scan from same patient also showing evidence of healing.



Figure 9a: Plain film showing nonhealing scaphoid fracture.



Figure 9b: CT of same patient also demonstrating a nonhealed scaphoid.

Three patients had plain films and CTs both showing inadequate healing in the absence of any scaphoid tenderness or clinical signs of incomplete healing. One of these cases involved surgical fixation of an early scaphoid nonunion. Despite radiographic evidence of failure to heal, the patient still did not complain of any scaphoid tenderness. Another patient had undergone wedge bone grafting as the operative procedure for scaphoid fracture repair. Though neither postoperative imaging study indicated healing, the patient again did not have any complaints of tenderness.

In three patients (3/16), the observer consensus indicated that the plain films and CT did not concur in the assessment of healing (Fig. 10). All three of these cases involved surgical nonunion repair of the scaphoid, and in all three cases the scaphoid was considered clinically healed. In two of these cases (2/16), the plain films failed to show signs of healing that were very clear on CT. In one case (1/16), healing that was detected on plain films was not evident on CT.



Figure 10a: Plain film showing a nonhealed scaphoid fracture.

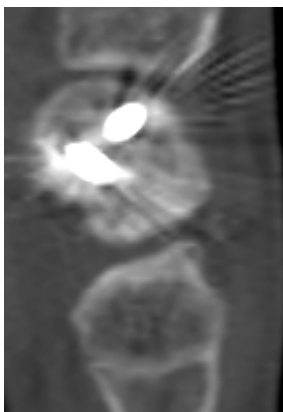


Figure 10b: CT scan of same patient showing no evidence of a persistent fracture line, demonstrating radiographic healing that is inconsistent with this patient's plain film.

Table 1: Patient demographics.

	Age	Sex	Side	Days between injury and surgery	Fracture type (Distal, waist, proximal)	Fracture displacement	Surgical repairs (internal fixation construct)
1	34	F	L	18	Transverse, mid-pole	Minimal	ORIF, Herbert screw (dual-threaded)
2	42	M	L		Mid-portion		Interfragmentary screw, K-wire
3	17	F	L	665		Mild ulnar displacement of proximal pole	Threaded metallic screw along long axis of scaphoid
4	27	M	R	46	Waist, transverse	Minimal	Dual threaded screw
5	25	M	L	6	Waist (between waist and proximal pole)	Minimal vertical	Dual threaded screw
6	19	M	R	45	Base, proximal one third	None	Dual threaded screw
7	34	M	L	>1000	Waist, oblique	None	Dual threaded screw
8	42	M	L	6	Waist		2 longitudinally oriented threaded screws
9	17	M	R	150	Waist		Longitudinally-oriented threaded screw + transverse screw
10	15	M	R	363	Waist		Interval threaded screws
11	28	M	R	464	Waist		Dual-threaded screw
12	17	M	L	112	Neck		Single threaded screw
13	19	M	L	124	Waist, horizontal	2 mm posterior gap	Dual-threaded screw
14	29	M	R	168	Waist	None	ORIF, dual-threaded screw
15	19	M	L	445	Waist		Dual-threaded screw
16	30	M	R	54	Waist, angulation	None	Dual-threaded screw

Table 2: Clinical results.

	Days between surgery and x-ray	Days between surgery and CT	Observer 1		Observer 2		Observer 3		Concensus		Clinically healed at time of x-ray/CT?	Imaging/clinical disparities
			Healing on x-ray	Healing on CT	Healing on x-ray	Healing on CT	Healing on x-ray	Healing on CT	Healing on x-ray	Healing on CT		
1	42	52	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes; no tenderness	
2	50	61	Yes	Yes	No	Yes	No	Yes	NO	Yes	Yes; no tenderness	*: Nonunion repair
3	182	150	No	No	No	Yes	No	No	NO	NO	Yes; minimal tenderness to deep palpation over proximal pole	*: Nonunion repair
4	61	84	No	No	Yes	No	Yes	Yes	Yes	NO	Yes; minimal tenderness	*: Nonunion repair
5	124	127	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes; continued clinical healing despite tenderness over scaphoid	
6	63	58	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes; decreased tenderness but still has wrist stiffness	
7	115	76	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No: tenderness	*: 2 months later tenderness resolved
8	330	349	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes; no tenderness in snuffbox	
9	241	251	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No; minimal tenderness at distal pole of scaphoid, less tenderness at waist of scaphoid	*: loosening of scaphocapitate screw
10	88	121	No	Yes	No	Yes	Yes	Yes	NO	Yes	Yes; no mention of tenderness but decreased ROM and wrist stiffness	*: Nonunion repair
11	78	71	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes; no tenderness	
12	60	83	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes; nontender scaphoid	
13	79	79	No	No	No	No	No	No	NO	NO	Yes; no mention of tenderness	*: fixation of early scaphoid nonunion
14	38	71	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes; 1-2/10 tenderness to palpation over snuffbox	
15	77	69	No	No	No	No	No	Yes	NO	NO	Yes; no tenderness	*: wedge bone graft
16	128	142	Yes	Yes	Yes	Yes			Yes	Yes	Yes; minimal tenderness dorsally	

Table 3: Statistical analysis of plain film interpretation with regards to clinical healing.

	Plain film showed healing	Plain film did not show healing
Clinically healed	9	5
Not clinically healed	2	0

Table 4: Statistical interpretation of CT efficacy.

	CT showed healing	CT did not show healing
Clinically healed	10	4
Not clinically healed	2	0

Tables 3 and 4 present a statistical analysis of the sensitivity and positive predictive values for both plain film and CT in the assessment of healing. According to this data, plain films could detect clinical healing, taken as our true positive, with 64% sensitivity, compared to a 71% sensitivity for CT in the detection of healing. Additionally, the positive predictive value for plain film in detecting healing of a postoperative scaphoid fracture was found to be 82% according to our data, compared with 83% for CT.

Discussion

Overall our study has helped to clarify the role of various imaging modalities in the postoperative assessment of scaphoid fracture healing. Prior to our study, there had been very limited exploration of this clinically important topic.

Magnetic resonance imaging has been investigated as a potentially useful method for assessing scaphoid fracture healing. The criterion used to assess fracture healing via MRI is the visualization of trabeculae crossing the fracture line or nonunion site. Traditionally, CT has been deemed the more accurate imaging method for assessing crossing trabeculae (38).

In 2000, McNally et al. conducted a study designed to investigate the ability of MRI to assess early union compared to plain radiographs. On MRI, bony union appears as at least partial normal marrow continuity across the fracture line. The authors reported that MRI can assess early union in as many as 45% of patients who were not considered to have a healed fracture clinically or radiographically. The study, which focused on patients who underwent nonoperative management for scaphoid fractures, showed that MRI can provide additional valuable information in this population. For one, by confirming bony union in a high proportion of patients deemed clinically non-united, MRI showed the potential to allow more rapid mobilization and return to normal function for this population (39). The study noted that clinical signs and plain radiographs remain the criteria in general use for deciding when to continue immobilization despite the poor predictive value of these techniques demonstrated in other studies (10, 39). This can result in up to 45% of patients undergoing prolonged periods of immobilization when plain films are used as the criteria for assessing radiographic healing (39).

The McNally study is only marginally applicable to the commonplace assessment of scaphoid fracture healing. The McNally study was limited only to patients with scaphoid fractures who had undergone nonoperative management. Since most severe or complicated scaphoid fractures undergo surgical intervention, this certainly weakens any

claim justifying the routine use of MRI to prevent overtreatment of scaphoid fractures. The McNally study also fails to address the presence of MRI image distortion resulting from scatter generated by internal fixation devices as a major limitation of this imaging modality for the assessment of postoperative scaphoid fracture patients. Additionally, as the McNally study highlighted, several patients who had both clinical and radiographic signs of healing had MRIs which demonstrated nonunion. The significance of this finding on MRI is certainly unclear but highlights that MRI, though perhaps possessing some utility in patients with clinically suspected nonunion at followup, is not the ideal choice of imaging study for patients with clinically united fractures (39).

The McNally study certainly made clear the reasons why we chose not to focus on the use of MRI to assess scaphoid fracture healing. For one, MRIs are far more resource-intensive than those used in our study, despite a lack of evidence demonstrating the cost-effectiveness of MRI in this setting. Additionally, the McNally study presented evidence against the efficacy of MRI for the assessment of all scaphoid fractures; even when used to assess the most straightforward scaphoid fractures, MRI was found to have a low specificity in highlighting scaphoid abnormalities relating to nonunion. Our study thus chose to focus on the more traditionally used imaging modalities, plain films and CT, for the postoperative assessment of scaphoid fracture healing.

Though there have been no previous studies investigating the use of CT for postoperative assessment of scaphoid fracture healing, one study has been conducted to investigate the use of CT for the assessment of scaphoid fracture healing after nonoperative management. This study, conducted by Geoghegan et al., concluded that CT scans conducted after four weeks of cast immobilization for acute nondisplaced

scaphoid fractures did indeed serve as a sufficient modality for assessing healing. In the Geoghegan study, the CT was used to assess fracture translation, percentage of bone contact, and overall estimate of fracture displacement, which were all considered to be individual radiographic predictors of bony union (40). The authors found that each of these individual characteristics had poor reproducibility in terms of potential to be used for the assessment of union. The assessment of union on a week 4 CT possessed a much improved inter-observer reproducibility in the Geoghegan study, and the authors thus concluded that CT was a suitable means to assess fracture union as early as four weeks after a scaphoid fracture managed nonoperatively (40).

Our study therefore is not the first used to investigate the use of CT in the assessment of scaphoid fracture healing. Previous investigation has also centered around the use of CT to assess scaphoid nonunions. In particular, CT has been widely used in the past to assess fracture configuration, bony deformity, and concurrent osteoarthritis in the setting of scaphoid nonunions (41). The greatest use of CT in the setting of scaphoid fractures is for preoperative planning, and little literature exists that is centered on the use of CT for the postoperative assessment of a scaphoid fracture.

Other previous studies have been conducted to assess the use of plain films in the follow-up of a scaphoid fracture. In 2005, Low et al. specifically focused on the use of plain films to follow up suspected scaphoid fractures with normal initial radiographs. The authors concluded that plain films used in this setting had poor sensitivity, poor negative predictive value, and poor reliability, and that as a result plain films alone should not be considered a valid diagnostic exam for occult scaphoid fractures (42).

In this sense, though previous literature has been written focusing on the use of both CT and plain films for scaphoid fracture assessment, very few studies have focused in detail on the use of these imaging modalities to assess healing of scaphoid fractures. Of those that have, none have focused on postoperative assessment of scaphoid fracture healing as is done in this study. Thus, our investigation elucidates some clinically relevant ideas that have not been investigated in the past.

The overall results of our study allow a conclusion to be drawn that plain films and CT both possess similar utility and accuracy for the postoperative assessment of scaphoid fracture healing. Though a previous study has suggested that plain films alone are not sufficiently accurate in diagnosing occult scaphoid fractures, the study did not investigate the use of this imaging modality for postoperative assessment of a known scaphoid fracture; thus, we do not believe that these results conflict with other studies that have been conducted on similar topics (42).

The basis behind this present study was that both imaging modalities are often used for the postoperative assessment of scaphoid fracture healing, often with a very subjective method of determining which modality to use at which time and in which patient. In theory, CT is considered the imaging modality that offers the better resolution image, visualization of finer detail, and better analysis of various characteristics of a scaphoid fracture (i.e. fracture displacement, fragmentation, etc.). Hand surgeons who routinely use CT for the postoperative assessment of scaphoid fracture patients argue that these qualities of the image assist in indicating whether a scaphoid fracture has sufficiently healed after a surgical intervention. Debate still exists as to whether CT is

helpful enough in this setting to warrant the additional use of resources and additional radiation exposure for this imaging modality as opposed to plain films.

The statistical results of our study indicate a slight benefit in terms of sensitivity for using CT as an imaging modality for the assessment of scaphoid fracture healing (71% vs. 64% sensitivity). Additionally, the positive predictive values for the two imaging modalities were also slightly in favor of CT for this purpose (82% vs. 83% positive predictive value). These numerical results must necessarily be interpreted in the context of our study, which involved a relatively small number of patients. Additionally, the specificity of both tests with respect to predicting scaphoid fracture healing was very low, suggesting that imaging studies alone cannot be used to assess for scaphoid fracture healing.

Overall, our results suggest that in the majority of cases, plain films and CT offer a similar degree of accuracy in the postoperative assessment of scaphoid fracture healing. Both imaging modalities allow for a sufficient assessment of bony bridging across the fracture site, and both modalities offer assessments that are in line with clinical healing in the majority of cases. Our study nevertheless revealed certain situations in which CT did prove to have a diagnostic advantage in terms of the radiologic assessment of healing. This included cases in which a patient had undergone surgical intervention for the repair of a scaphoid nonunion. In such cases, plain films were either ambiguous or not in line with clinical data suggestive of healing, and CT provided a more accurate and less ambiguous assessment of healing.

Assuming proper study validity, our results have important implications for the management of scaphoid fracture patients seen in follow-up. The results suggest that CT

is more sensitive than plain film for the detection of scaphoid fracture healing, but that the difference in sensitivity is not significant. In most cases, CT is not necessarily better as a routine imaging modality to assess for radiographic healing after operative management of an acute scaphoid fracture. Plain films may offer sufficient radiographic data for an accurate interpretation of the presence or absence of fracture healing in such cases. According to our data, however, this conclusion may not hold true for scaphoid nonunion repairs that are seen in follow-up. For scaphoid nonunion repairs, plain films often fail to highlight the radiographic signs of healing that are more subtle in this population. In this setting, the finer details and higher resolution images provided by CT would offer a better chance of obtaining an accurate assessment of healing, thus warranting the use of this imaging modality in this specific patient population.

Several limitations exist in our study that are worth noting in the interpretation of our results. The small sample size used in our study limits the strength and certainty with which we can draw conclusions, and a larger study with a greater sample size would certainly have been favorable. Additionally, our study analyzed patients who had undergone a CT and plain film study within a short time frame, taken to be five weeks. It would have been more ideal to analyze two studies that were conducted on the exact same day for patients seen in follow-up. Because of the retrospective nature of our study, this was not possible.

Also in line with the retrospective nature of our study was the inability to control for certain variables which may have affected healing assessments by CT and plain film. Our study did not control for the length of time in between the surgical intervention and the radiographic assessment; it is therefore possible that the utility of CT or plain film

assessment of scaphoid fracture healing is dependent on when in the healing process these imaging modalities are used. We also did not control for other factors that may influence the healing process, including age, smoking status, or prior wrist trauma. Our thinking was that any such factors affecting the healing process would present radiographic changes on both plain films and CT, and thus the effects of these factors would essentially cancel each other out with respect to our study.

We describe clinical exam as our true positive in this study. General practice is to take clinical exam findings in conjunction with imaging demonstrating healing as evidence that a fracture is sufficiently healed. In reality, neither alone is a reliable indicator of healing. Our questions revolved around whether plain film or CT was more accurate in predicting clinical healing or lack thereof. The method which we used to answer this question was to temporarily isolate one of these factors (clinical exam) as depicting the true state of the fracture in terms of healed or not healed. To do this we used scaphoid tenderness as an indicator of clinical healing. This does have inherent limitations but for the purpose of this study it allowed us to designate a fracture as healed or not healed prior to any imaging correlation.

One potential method to strengthen this study would be to include a retrospective assessment of healing. Because clinical healing is not a true gold standard and therefore a tenuous “true positive,” this provides an additional limitation to the study. In the future a true positive could be a retrospective assessment of whether the fracture was healed at the time of examination (for instance, if the clinical exam indicated that the scaphoid was nontender at this time, this could be further reinforced by making sure later clinical

examinations yielded a similar assessment, thus proving that the scaphoid was in fact clinically healed at this time).

Despite the various limitations of our study, the preliminary conclusions that we can draw from the collected data do make important suggestions that can potentially be used in the treatment of any scaphoid fracture patient. In the future, a prospective study evaluating the use of both plain films and CT in the postoperative scaphoid fracture patient could potentially provide solid evidence to lend even more credibility to these conclusions. While our study did not investigate the use of MRI data in the assessment of the postoperative scaphoid fracture patient, prior studies investigating the use of MRI for follow-up of scaphoid fracture patients have presented interesting findings with regards to the higher detail that MRI provides in visualizing a healing scaphoid fracture. Additional investigation into the significance of these finer details might also further elucidate the healing process of a scaphoid fracture, and which radiographic signs are most important for concluding that a scaphoid fracture has sufficiently healed.

Scaphoid fractures are among the most common fractures in adults, and this traumatic injury continues to affect many active individuals. Investigations into the best imaging modalities to be used in both diagnosing and managing a scaphoid fracture patient are not only warranted, but also necessary in order to allow the best possible outcome for this population.

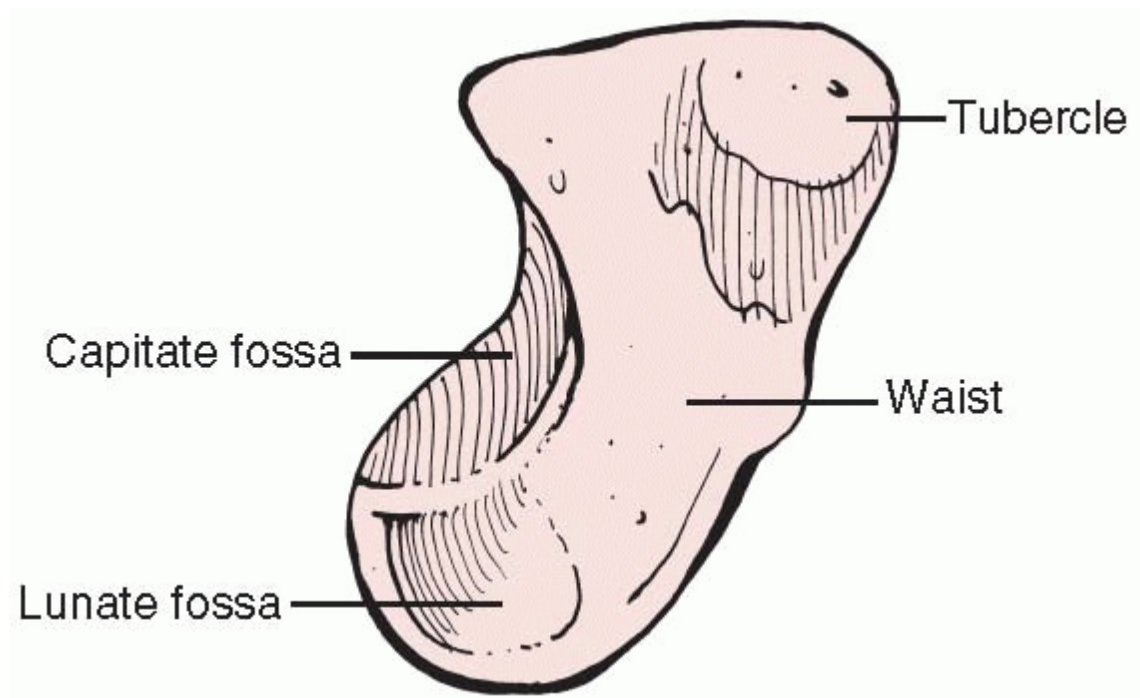


Figure 1: Anatomy of the scaphoid. From [1].

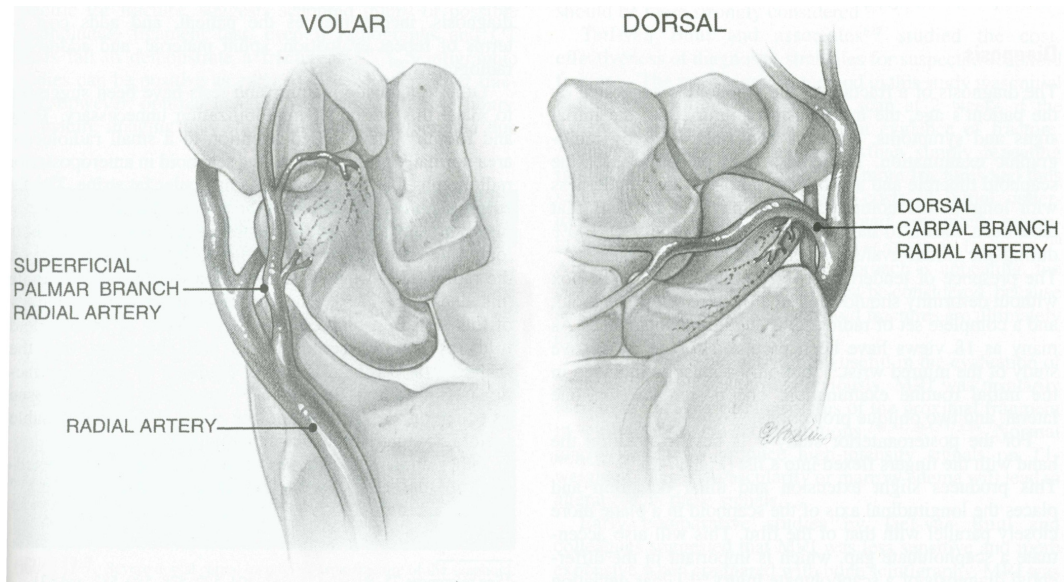


Figure 2: Vascular supply of the scaphoid. From [3].



Figure 3: The "anatomic snuffbox" can be examined for tenderness by deeply palpating the proximal pole of the scaphoid between the abductor pollicis longus and the extensor pollicis brevis tendons radially and the extensor pollicis longus tendon ulnarly, just distal to the radial styloid.



Figure 4: Plain posteroanterior radiograph with the wrist in ulnar deviation to bring the scaphoid into a profile of extension barely demonstrates a fracture line.



Figure 5a: Plain film of the wrist is completely normal on navicular view.

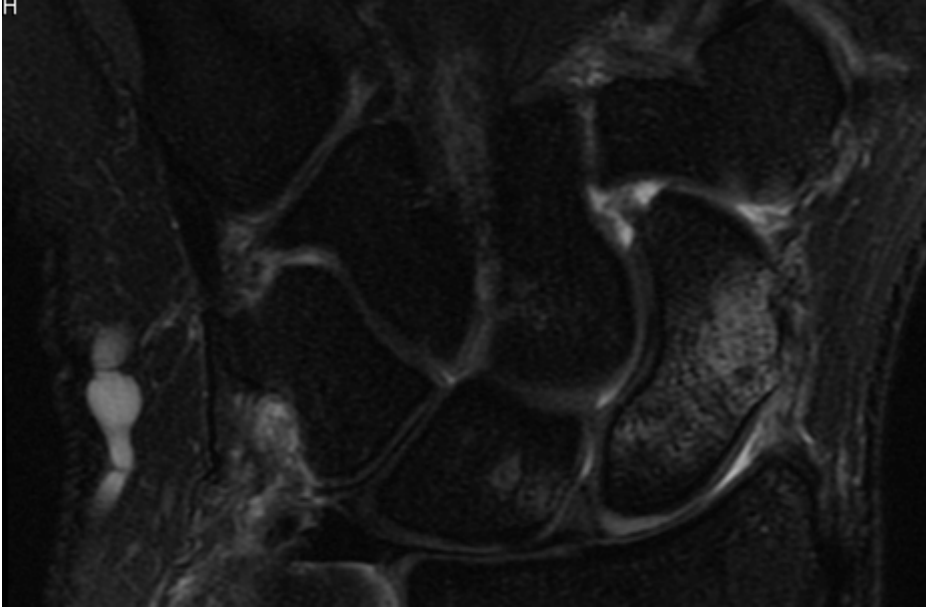


Figure 5b: MRI of the same patient showing increased edema and inflammation, indicative of a fracture.

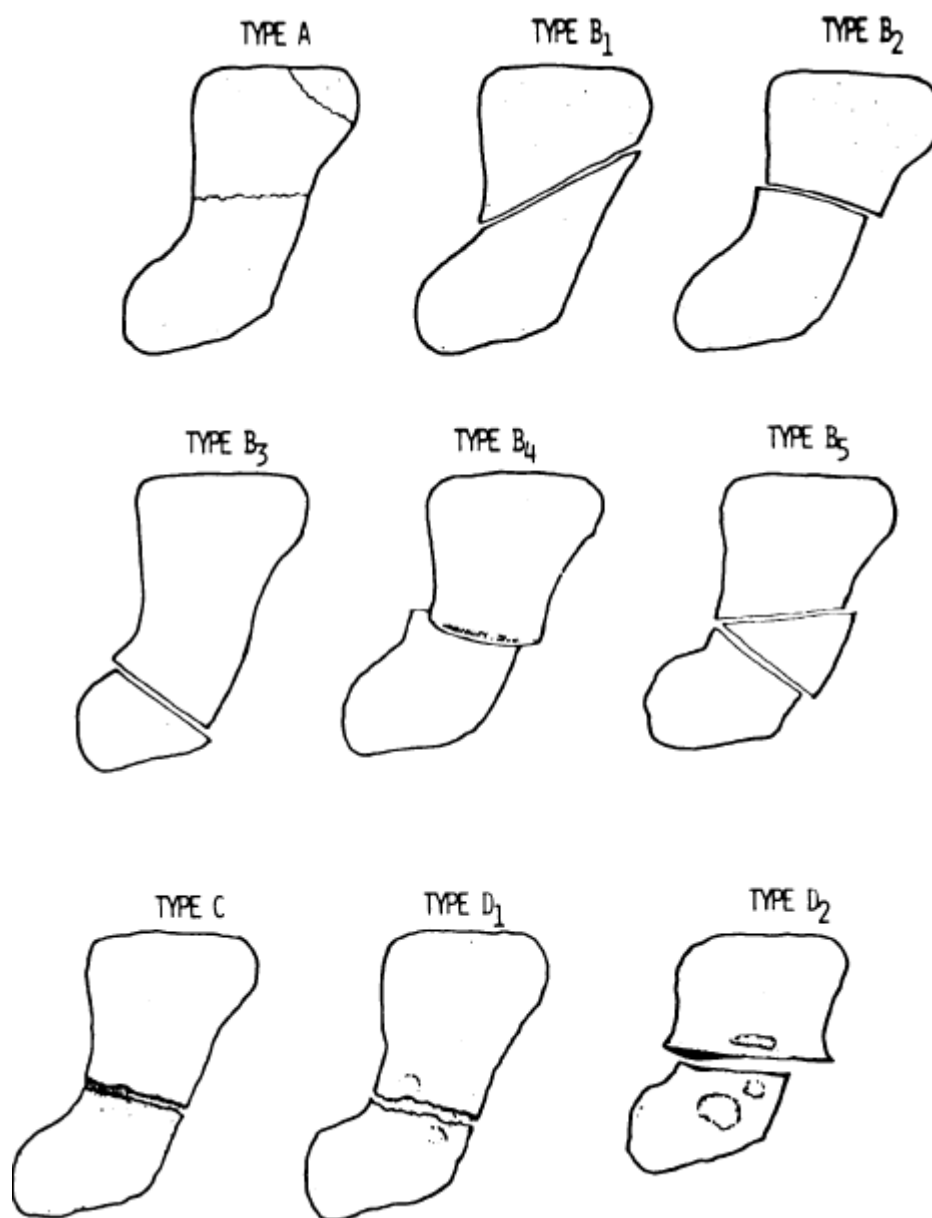


Figure 6: Herbert classification of scaphoid fractures based on radiographic appearance. From [22].



Figure 7: MRI shows the revascularization front as a white line on this T2-weighted image. From [36].

References

1. Gaebler C, McQueen MM. Carpus Fractures and Dislocations. In: Bucholz RW, Heckman JD, Court-Brown CM, Tornetta P, editors. *Fractures in Adults*. 7th ed: Lippincott Williams & Wilkins; 2009. p. 782-828.
2. Cooney WP. *The wrist: diagnosis and operative treatment*. 2nd ed. Rochester, MN: Lippincott Williams and Wilkins; 2010.
3. Geissler WB, Slade JF. *Green's Operative Hand Surgery*. 6th ed. Philadelphia, PA: Elsevier; 2011. p. 639-80.
4. Van Tassel DC, Owens BD, Wolf JM. Incidence estimates and demographics of scaphoid fracture in the U.S. population. *J Hand Surg Am*. 2010;35(8):1242-5.
5. Wolf JM, Dawson L, Mountcastle SB, Owens BD. The incidence of scaphoid fracture in a military population. *Injury*. 2009;40(12):1316-9.
6. Gelberman RH, Menon J. The vascularity of the scaphoid bone. *J Hand Surg Am*. 1980;5(5):508-13.
7. Weber ER, Chao EY. An experimental approach to the mechanism of scaphoid waist fractures. *J Hand Surg Am*. 1978;3(2):142-8.
8. Horii E, Nakamura R, Watanabe K, Tsunoda K. Scaphoid fracture as a "puncher's fracture". *J Orthop Trauma*. 1994;8(2):107-10.
9. Ring D, Jupiter JB, Herndon JH. Acute fractures of the scaphoid. *J Am Acad Orthop Surg*. 2000;8(4):225-31.
10. Waizenegger M, Barton N, Davis T, Wastie M. Clinical signs in scaphoid fractures. *J Hand Surg Br*. 1994;19(6):743-7.
11. Parvizi J, Wayman J, Kelly P, Moran C. Combining the clinical signs improves diagnosis of scaphoid fractures. A prospective study with follow-up. *J Hand Surg Br*. 1998;23(3):324-7.
12. Annamalai G RN. Scaphoid and pronator fat stripes are unreliable soft tissue signs in the detection of radiographically occult fractures. *Clin Radiol*. 2003;58(10):798-800.
13. Peterson D, Brandser E, Steyers C. Imaging scaphoid fractures and nonunions: familiar methods and newer trends. *Iowa Orthop J*. 1996;16:97-103.
14. Lozano-Calderón S, Blazar P, Zurakowski D, et al. Diagnosis of scaphoid fracture displacement with radiography and computed tomography. *J Bone Joint Surg Am*. 2006;88(12):2695-703.
15. Temple C, Ross D, Bennett J, et al. Comparison of sagittal computed tomography and plain film radiography in a scaphoid fracture model. *J Hand Surg Am*. 2005;30(3):534-42.
16. Dias J, Taylor M, Thompson J, et al. Radiographic signs of union of scaphoid fractures. An analysis of inter-observer agreement and reproducibility. *J Bone Joint Surg Br*. 1988;70(2):299-301.
17. Imaeda T, Nakamura R, Miura T, Makino N. Magnetic resonance imaging in scaphoid fractures. *J Hand Surg Br*. 1992;17(1):20-7.
18. Ring D, Lozano-Calderón S. Imaging for suspected scaphoid fracture. *J Hand Surg Am*. 2008;33(6):954-7.
19. Bhat M, McCarthy M, Davis TR, et al. MRI and plain radiography in the assessment of displaced fractures of the waist of the carpal scaphoid. *J Bone Joint Surg Br*. 2004;86(5):705-13.
20. Brydie A, Raby N. Early MRI in the management of clinical scaphoid fracture. *Br J Radiol*. 2003;76(905):296-300.

21. Geijer M, Borjesson AM, Gothlin JH. Clinical utility of tomosynthesis in suspected scaphoid fracture. A pilot study. *Skeletal Radiol*. 2010.
22. Herbert TJ, Fisher WE. Management of the fractured scaphoid using a new bone screw. *J Bone Joint Surg Br*. 1984;66(1):114-23.
23. Perron A, Brady W, Keats T, Hersh R. Orthopedic pitfalls in the ED: scaphoid fracture. *Am J Emerg Med*. 2001;19(4):310-6.
24. Cooney WP, Dobyns JH, Linscheid RL. Fractures of the scaphoid: a rational approach to management. *Clin Orthop Relat Res*. 1980;(149):90-7.
25. Gellman H, Caputo R, Carter V, et al. Comparison of short and long thumb-spica casts for non-displaced fractures of the carpal scaphoid. *J Bone Joint Surg Am*. 1989;71(3):354-7.
26. Kawamura K, Chung KC. Treatment of scaphoid fractures and nonunions. *J Hand Surg Am*. 2008;33(6):988-97.
27. McQueen M, Gelbke M, Wakefield A, et al. Percutaneous screw fixation versus conservative treatment for fractures of the waist of the scaphoid: a prospective randomised study. *J Bone Joint Surg Br*. 2008;90(1):66-71.
28. Chung KC. A simplified approach for unstable scaphoid fracture fixation using the Acutrak screw. *Plast Reconstr Surg*. 2002;110(7):1697-703.
29. Gutow AP. Percutaneous fixation of scaphoid fractures. *J Am Acad Orthop Surg*. 2007;15(8):474-85.
30. Merrell GA, Wolfe SW, Slade JF. Treatment of scaphoid nonunions: quantitative meta-analysis of the literature. *J Hand Surg Am*. 2002;27(4):685-91.
31. Stark HH, Rickard TA, Zemel NP, Ashworth CR. Treatment of ununited fractures of the scaphoid by iliac bone grafts and Kirschner-wire fixation. *J Bone Joint Surg Am*. 1988;70(7):982-91.
32. Langhoff O, Andersen J. Consequences of late immobilization of scaphoid fractures. *J Hand Surg Br*. 1988;13(1):77-9.
33. Mack G, Bosse M, Gelberman R, Yu E. The natural history of scaphoid non-union. *J Bone Joint Surg Am*. 1984;66(4):504-9.
34. Sfeir C, Ho L, Doll BA, et al. Fracture Repair. In: Lieberman JR, Friedlaender GE, editors. *Bone Regeneration and Repair: Biology and Clinical Applications*. Totowa, New Jersey: Humana Press; 2005. p. 21-44.
35. Dias JJ. Definition of union after acute fracture and surgery for fracture nonunion of the scaphoid. *J Hand Surg Br*. 2001;26(4):321-5.
36. Kulkarni RW, Wollstein R, Tayar R, Citron N. Patterns of healing of scaphoid fractures. The importance of vascularity. *J Bone Joint Surg Br*. 1999;81(1):85-90.
37. McNally E, Goodman R, Burge P. The role of MRI in the assessment of scaphoid fracture healing: a pilot study. *Eur Radiol*. 2000;10(12):1926-8.
38. Goldfarb CA, Yin Y, Gilula LA, et al. Wrist fractures: what the clinician wants to know. *Radiology*. 2001;219(1):11-28.
39. McNally EG, Goodman R, Burge P. The role of MRI in the assessment of scaphoid fracture healing: a pilot study. *Eur Radiol*. 2000;10(12):1926-8.
40. Geoghegan JM, Woodruff MJ, Bhatia R, et al. Undisplaced scaphoid waist fractures: is 4 weeks' immobilisation in a below-elbow cast sufficient if a week 4 CT scan suggests fracture union? *J Hand Surg Eur Vol*. 2009;34(5):631-7.
41. Smith M, Bain GI, Turner PC, Watts AC. Review of imaging of scaphoid fractures. *ANZ J Surg*. 2010;80(1-2):82-90.
42. Low G, Raby N. Can follow-up radiography for acute scaphoid fracture still be considered a valid investigation? *Clin Radiol*. 2005;60(10):1106-10.