Scaphoid blood flow and acute fracture healing

A DYNAMIC MRI STUDY WITH ENHANCEMENT WITH GADOLINIUM

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We have investigated whether assessment of blood flow to the proximal scaphoid can be used to predict nonunion in acute fractures of the scaphoid. We studied 32 fractures of the scaphoid one to two weeks after injury, by dynamic fat-suppressed T1-weighted gradient-echo MRI after the intravenous administration of gadopentetate dimeglumine (0.1 mmol/kg body-weight). Steepest slope values (SSV) and percentage enhancement values (%E) were calculated for the distal and proximal fragments and poles. All the fractures were treated by immobilisation in a cast, and union was assessed by CT at 12 weeks.

Nonunion occurred in four fractures (12%), and there was no statistically significant difference between the proximal fragment SSV and %E values for the fractures which united and those with nonunion. The difference between the proximal pole SSV and %E values for the union and nonunion groups reached statistical significance ($p < 0.05$), but with higher enhancement parameters for the nonunion group. Our results suggest that poor proximal vascularity is not an important determinant of union in fractures of the scaphoid.

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Traumatic disruption of the precarious vascular anatomy of the scaphoid, causing impaired proximal blood supply, is implicated as a cause of nonunion of a fracture of the scaphoid.¹ Conventional methods for assessing vascularity of the scaphoid, such as plain radiography and bone scintigraphy are unreliable² and therefore the true incidence of

proximal avascularity after a fracture is unknown. Sclerosis of the proximal fragment develops only after several weeks and probably indicates revascularisation and deposition of new bone after an ischaemic episode rather than ongoing avascular necrosis.³ Green⁴ observed that radiologically dense proximal fragments often bleed at operation and others have shown that rotation of the proximal fragment of the scaphoid after fracture can mimic the appearance of sclerosis on plain radiography.⁵ The absence of an accurate method for assessing blood flow of the scaphoid has precluded any prospective analysis of the influence of vascularity on the healing capacity of acute fractures.

Unenhanced MRI can detect long-standing and established avascular necrosis of bone, but not early devascularisation or different degrees of ischaemia and the vascular status of the scaphoid in acute fractures has not been widely studied.⁶ Enhanced MRI (dynamic and static) after injection of gadolinium may demonstrate changes in tissue perfusion, and is increasingly used to evaluate the vascularity of various tissues and organs, including bone marrow.

Patients and Methods

We enrolled 32 patients (2 women and 30 men) with a mean age of 32 years (18 to 66) into the study. They all had an isolated radiologically visible acute fracture of the scaphoid (29 waist, 2 proximal, 1 distal). The initial radiological assessment consisted of a standard four-view scaphoid series (posteroanterior, posteroanterior oblique, lateral and Ziter). Approval of the Ethics Committee had been obtained and the patients gave their written consent.

All patients were treated conservatively for eight to 12 weeks in a well-fitting Colles-type cast with the wrist in slight extension. This type of cast is as effective as a conventional scaphoid cast and obviates the need for restriction of the thumb.⁷ This is our standard management of all acute fractures of the scaphoid unless there is an associated carpal dislocation or significant displacement of the fracture.

MRI protocol. The MRI protocol was established as a reproducible technique during a preliminary pilot study. All MRI of the fractured wrists was undertaken one to two weeks after injury on a 1.5 Tesla superconducting system (Magnetom Vision; Siemens, Erlangen, Germany). The

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Fig. 1

MRI showing the sagittal localiser with required slice orientation to achieve a true coronal image of the scaphoid.

patients were positioned supine on the scanner couch with both arms extended alongside the trunk. The fractured wrist remained in plaster and was placed in a pronated position. A small flexible surface coil was wrapped around the plaster cast. Immobilisation of the fractured wrist was aided by Velcro straps. Before each patient was advanced into the magnet bore, a 19-gauge plastic cannula was placed in a contralateral cubital vein and connected to extension tubing

150 cm long which had been filled with physiological saline. With this arrangement, the patient did not have to be moved out of the magnet for injection of contrast.

The following MR sequences were performed from a sagittal localiser (Fig. 1) and obtained in the true coronal plane of the fractured scaphoid.

1) Static T1-weighted spin-echo sequence (TR/TE 450/12, 10 cm field of view (FOV), 3 mm sections with no gap, 3 excitations, 256×256 matrix). This sequence was used to verify the correct positioning of the slice before the injection of contrast.

2) Dynamic fat-suppressed single-slice T1-weighted FLASH gradient-echo sequence (TR/TE 33.7/6.0, 16 cm FOV, 6 mm section, 1 excitation, 179×256 matrix, flip angle 90°). Phase-encoding was orientated in a cephalad-caudad direction to prevent pulsation artefact from the radial artery obscuring the adjacent scaphoid. The temporal resolution was 13 seconds. A total of 25 sequential images was obtained over five to six minutes synchronous with the intravenous administration of 0.1 mmol/kg body-weight of gadopentetate dimeglumine (Magnevist; Schering, Berlin, Germany). Intravenous administration was by rapid manual injection of the bolus over two to three seconds followed by a saline flush. Injection began immediately after acquisition of the first sequential image.

Fig. 2

Images from the dynamic sequence are shown on the left. The pixel intensity curve generated from a single pixel in the distal pole (represented by the white box on each image) is shown in the upper right. From this curve the steepest slope (shown by the dashed line) is calculated. Also the %E in the 20th image after the bolus arrival is calculated. The gradient images and enhancement images (bottom right) are generated by calculating the steepest slope values and enhancement values for every pixel in the image.

Fig. 3

Diagram showing the scaphoid ROIs which are a) the distal fragment, b) the proximal fragment, c) the distal pole and d) the proximal pole.

3) Static fat-suppressed T1-weighted spin-echo sequence after injection of gadolinium (TR/TE 450/12, 10 cm FOV, 3 mm sections with no gap, 3 excitations, 256×256 matrix). This sequence was acquired approximately ten minutes after the bolus of gadopentetate dimeglumine had been given.

Analysis of dynamic MR data. The dynamic data were transferred to a workstation and analysed on a pixel basis using software developed in-house. Image registration minimised the effect of any movement of the patient and principal components analysis was used to improve the signal-to-noise ratio.⁸

Two enhancement parameters, steepest slope value (SSV) and percentage enhancement (%E), were calculated for each pixel time-signal intensity curve (Fig. 2). The SSV was the maximum gradient between two consecutive pixels on the pixel curve. The %E varies with time and it is therefore important to standardise the definition of the time of arrival of contrast agent in the wrist. The arrival point was defined as the beginning of the pixel curve upslope (typically on the second or third sequential image), and the %E was calculated using the 20th image after this arrival point.

The enhancement parameters were subsequently displayed as parametric images (gradient and enhancement images) where the gray-scale value of each pixel was equal to the numerical value of the spatially corresponding enhancement parameter (Fig. 2). Four regions of interest (ROI) were then manually delineated using a cursor and these were applied to the parametric images. The four ROIs were: a) the distal fragment of the scaphoid; b) the proximal fragment of the scaphoid; c) the distal pole of the scaphoid; and d) the proximal pole of the scaphoid (Fig. 3). All ROIs were drawn inside the cortical margins of the scaphoid to avoid including surrounding tissues. The mean pixel values for each of the four ROIs were calculated for the two enhancement parameters.

Subjective visual assessments of contrast enhancement were also made from the static images after injection of gadolinium.

Follow-up and fracture outcome. All the patients were reviewed regularly and immobilisation in plaster was con-

tinued for at least eight weeks. Healing of the fracture was assessed by high-resolution CT on a helical CT scanner (Somatom Plus; Siemens) 12 weeks after injury. The patients were positioned prone on the scanner couch with the injured wrist placed above the head. Thin (1 to 2 mm) sections were directly acquired in both the coronal and sagittal planes of the fractured scaphoid by appropriate positioning of the wrist with respect to the scanner gantry.

Finally, the quantitative and qualitative assessments of gadolinium enhancement were correlated with the outcome of the fracture.

Results

Nonunion occurred in four (3 waist and 1 proximal) of the 32 fractures (12%). All cases of nonunion were subsequently confirmed at operation during fixation by a Herbert screw and bone grafting.

In all fractures, enhancement of the distal scaphoid generally exceeded proximal enhancement with a spectrum of enhancement defects of the proximal fragment and proximal pole (Table I). In six cases, there was no enhancement of the proximal pole, which indicated severe ischaemia or avascularity. This difference between distal and proximal enhancement was statistically significant for the SSV and %E values for both the fragments and poles (Mann-Whitney U test, $p < 0.001$).

The %E and SSV values for the proximal fragment and proximal poles, according to the union and nonunion groups, are shown in Figures 4 and 5. There was no statistically significant difference between the proximal fragment SSV and %E values for the two groups. The differences between the proximal pole SSV and %E values were just statistically significant (Mann-Whitney U test, $p < 0.05$), but the enhancement values were higher for the nonunion group than for the union group. Thus poor proximal enhancement did not correlate with nonunion. It is of interest that the six fractured scaphoids with apparently avascular proximal poles (0% enhancement) all united.

Discussion

In recent years, enhanced MRI after injection of gadolinium (dynamic and static) has become established as a non-invasive means of estimating vascularity of bone marrow.⁹⁻¹⁷ A decrease in perfusion is manifested as a decrease in enhancement since the amount of gadolinium delivered to the intravascular space and subsequently to the extracellular space and tissue interstitium is reduced. Since proximal hypovascularity is widely thought to contribute to nonunion of a scaphoid fracture, it is logical to apply enhanced MRI to the study of fractures of the scaphoid and there have been provisional reports by two groups of workers.¹⁸⁻²⁰ Both groups reported that distal enhancement predominates over proximal enhancement after fracture of

Table I. The SSV and %E results for the proximal and distal pole and the proximal and distal fragment of 32 patients with acute fractures of the scaphoid

	Proximal pole	Distal pole	Proximal fragment	Distal fragment
Median %E (range)	44 (0 to 318)	234 (41 to 422)	133 (13 to 344)	253 (86 to 474)
Median SSV (range)	28 (11 to 365)	158 (25 to 335)	85 (16 to 365)	208 (56 to 387)

Fig. 4

Graph showing the %E values in the union and nonunion groups for the proximal pole and proximal fragment. A value of 0 indicates avascularity; thus six scaphoids had avascular proximal poles and all of these united.

Fig. 5

Graph showing the SSV in the union and nonunion groups for the proximal pole and proximal fragment. Values approaching 0 indicate a very slow uptake of gadopentetate dimeglumine.

the waist of the scaphoid, but neither addressed the relationship between scaphoid enhancement and healing of the fracture. Eustace and Denison²¹ also briefly mentioned the potential of dynamic MRI to identify perfusion abnormalities in acute fractures of the scaphoid.

Precise positioning of the slice through the scaphoid is critical to the dynamic imaging and was achieved in our study by the use of a sagittal localiser and a preliminary T1-weighted spin-echo sequence for verification of the slice. Exact positioning of the slice ensures that the measured enhancement is attributable to vascularity of the scaphoid bone alone, rather than incorporation of an element of enhancement from the adjacent soft tissues which are extremely vascular in the immediate period after injury. The 6 mm single slice would have encompassed virtually the entire volume of the scaphoid. Previous investigators have also emphasised the importance of imaging in which scanning follows the precise planes of the scaphoid.²²

Figure 4 shows that, although six proximal poles showed no enhancement and thus appeared to be avascular, there was

at least some enhancement of all the proximal fragments. This difference probably arose because the ROI of the proximal fragment included the site of the fracture, which would be expected to be vascular. Alternatively, as the MR assessments were carried out one to two weeks after injury, this difference between the proximal poles and the fragments could be due to early revascularisation of the distal edge of the proximal fragment at the site of the fracture.

Fat suppression was applied successfully to both the dynamic and static images after injection of gadolinium and it improved the visual clarity of marrow enhancement by nullifying the high signal of marrow fat.

Under normal circumstances even healthy bone marrow may sometimes fail to show detectable enhancement.^{10,23,24} Yellow marrow usually shows less enhancement than red marrow¹⁴ and it is generally recognised that fatty marrow has some of the lowest enhancement values amongst normal tissues.²⁵ The scaphoid lies peripherally in the appendicular skeleton and, in adults, its marrow is overwhelmingly fatty rather than haemopoietic. The detec-

Fig. 6a

Fig. 6b

Static-enhanced T1-weighted spin-echo images with fat suppression of two fractures of the waist of the scaphoid showing a) poor enhancement of the proximal fragment, and b) good enhancement of the proximal fragment. Such observations support the idea of the variable proximal extension of the arterial foramina along the waist of the scaphoid.

Fig. 7a

Fig. 7b

Coronal CT scans obtained at 12 weeks after injury showing that a) the fracture in Figure 6a, which had poor proximal enhancement, had healed uneventfully and b) that the fracture in Figure 6b, which had good proximal enhancement, had progressed to nonunion. There is increased density in the proximal fragment in (a).

tion of bone-marrow enhancement was not difficult in this study as the scaphoid is hyperaemic after fracture.

The blood supply of the scaphoid is distally based and vulnerable to interruption in the event of a fracture.²⁶⁻²⁸ The arteries supplying the proximal portion of the scaphoid enter the waist of the scaphoid along the dorsal ridge and run proximally, supplying the proximal 70% to 80% of the bone. Although small vessels are noted on the surface of the proximal pole in relation to the attachment of soft tissues, detailed examinations have failed to show any vessels penetrating the cortex of the scaphoid in this area.²⁸ The wide spectrum of enhancement of the proximal scaphoid which we observed (Fig. 6) could be explained by the relative positions of the fracture of the waist of the scaphoid and the nutrient foramina on the dorsal ridge which are subject to considerable individual variability. Since 13% of scaphoid bones have no vascular foramina, 20% have only one vascular foramen, and the remaining 67% have two or more foramina proximal to the waist, the loss or otherwise of the blood supply of the proximal scaphoid depends not only on the site of the fracture, but also on the relative positions of the fracture and the arterial foramina on the dorsal ridge in individual patients.²⁹ Our results therefore give credence to the idea of inconsistency in the arrangement of the arterial foramina along the dorsal ridge and variation in how far they reach proximally along the waist.^{3,28-30}

Our rate of nonunion of 12% is similar to that reported by other studies (10% to 13%) in which fractures of the scaphoid were treated conservatively.³¹⁻³³ Since it is well recognised that it is difficult to assess union of a fracture on plain radiographs taken at 12 weeks after injury,³⁴ we used high-resolution CT to determine the outcome. This technique is very accurate for assessing union of a scaphoid fracture,³⁵⁻³⁷ and all the cases of nonunion in our study were additionally confirmed during subsequent bone-grafting procedures.

The lack of correlation in our study between poor proximal scaphoid enhancement shortly after fracture and eventual nonunion (Figs 6 and 7) does not support the hypothesis that ischaemia of the proximal scaphoid predisposes to nonunion. Since some of the fractures which united showed no enhancement of the proximal pole initially, it would appear that even initially avascular bone can revascularise with subsequent union. If there is proximal avascularity the healing response should presumably originate solely from the vascularised distal fragment by creeping substitution.³⁸ This is consistent with the observation of revascularisation advancing into devitalised proximal fragments on MRI.⁶

Although the number of cases of nonunion in our study is small, and the study thus has limited statistical power, we consider it improbable that poor proximal enhancement is a determinant of nonunion. Other factors, such as displace-

ment or soft-tissue interposition, may determine the outcome of these fractures. Although a previous study concluded that displacement of the fracture, as assessed on plain radiographs, does not influence the rate of union of fractures of the scaphoid,³⁹ the plain radiological features of a fracture correlate poorly with the operative findings during fixation.⁴⁰ It is thus possible that more accurate assessment of displacement, by CT or MRI, may predict the likelihood of union.

The assessment of the vascularity of the proximal scaphoid by dynamic gadolinium enhancement MRI does not predict whether a fracture will, or will not, unite after conservative treatment. It therefore cannot be used to identify fractures with a poor prognosis which may be better treated by internal fixation.⁴⁰

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