

The outcome of bone graft surgery for nonunion of fractures of the scaphoid

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Abstract

Data on 806 patients undergoing bone graft surgery for a scaphoid fracture nonunion were retrospectively collected at 19 centres in the United Kingdom. Each centre contributed at least 30 cases. Sufficient data were available in 462 cases to study factors that influenced the outcome of surgery. Overall union occurred in at least 69%, and nonunion in at least 22%, with 9% of cases having 'uncertain union status'. Union appeared to be adversely influenced by smoking and the time between acute scaphoid fracture and nonunion surgery, with adjusted odds ratios of 1.8 and 2.4, respectively, but neither achieved the pre-determined significance level of 0.003. The type of bone graft (vascular vs non-vascular; iliac crest vs distal radius) did not appear to influence outcome. Further large multicentre prospective studies with clear definitions of 'union' and other factors are needed to clarify whether modification of surgical technique can influence union.

Level of evidence: IV

Keywords

Scaphoid fracture, nonunion, bone graft surgery, outcome

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Introduction

Symptomatic scaphoid fracture nonunion is typically treated operatively with bone grafting and internal fixation, unless significant wrist arthritis has developed as a consequence of the nonunion. Previous small studies suggest that the outcome of bone grafting and fixation of scaphoid fracture nonunion is affected by patient factors, including smoking (Little et al., 2006), fracture factors, such as the site of fracture (proximal pole or waist), the time interval between the acute fracture and the nonunion surgery (Inoue et al., 1997; Merrell et al., 2002; Nakamura et al., 1993; Trezies et al., 2000) and bone graft factors, including the donor site and graft vascularity (Braga-Silva et al., 2008; Goyal et al., 2013).

Two recent systematic reviews have investigated factors, which affect the outcome of scaphoid fracture nonunion surgery and how successful it is in achieving union. One (Pinder et al., 2015) found high frequencies of union with both vascularized and non-vascularized

bone grafts but did not consider confounding factors. The other (Ferguson et al., 2016) resolved that it was difficult to draw any conclusions, because most studies contained few cases, confounding factors were rarely considered and there were inconsistencies between studies, including the definition of union and variable length of follow-up after surgery, which sometimes was only a few weeks.

This retrospective study investigated the outcome of the treatment of scaphoid fracture nonunion by bone grafting in 19 centres within the United Kingdom.

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Methods

This study was defined as a multicentre retrospective evaluation of service by the Research and Innovation Department of the Nottingham University Hospitals NHS Trust, and thus did not require ethical committee approval. This definition of the study was confirmed at each recruiting centre. Surgeons at 19 centres throughout the United Kingdom agreed to provide data on patients with scaphoid fracture nonunions treated with surgery to achieve union and thus improve wrist function. A trainee surgeon at each centre identified patients who had undergone such surgery before October 2014 by searching hospital records starting in September 2014 and working backwards in time, until a minimum of 30 cases were identified. Cases of revision bone grafting and fixation after a previous failed bone graft procedure were excluded. Relevant data on these cases were extracted from the hospital case notes and radiographs during October to December 2016. Thus, the minimum time between surgery and data collection from the medical records was 2 years. For this study, a nonunion was defined as a fracture that had not united within 12 weeks of the acute injury based on plain radiographs or computed tomography (CT) scans. It was also decided that a minimum radiological follow-up of 12 weeks after the nonunion was required to determine whether a scaphoid fracture had, or had not, united.

Eligibility

Data was collected on 806 cases. Specific cases were excluded for the following reasons.

- Patient age <16 ($n=27$).
- Age at surgery not recorded ($n=10$).
- Nonunion part of a trans-scaphoid perilunate dislocation ($n=2$).
- Site (waist, distal or proximal pole) was not recorded ($n=8$).
- Type of bone graft not recorded ($n=11$).
- Was treated with synthetic bone graft ($n=1$).
- Time from acute fracture to nonunion surgery could not be calculated ($n=93$).
- Bone graft surgery occurred within 12 weeks of the acute fracture ($n=65$).
- Time from surgery to last radiological follow-up not recorded ($n=17$).
- Less than 12 weeks postoperative radiological follow-up ($n=120$).

This left 462 cases, as some had more than one reason for exclusion. These 462 fracture nonunions were categorized as proximal if within the proximal

20% of the length of the scaphoid and distal if within the distal 20% of the length of the scaphoid. Those in the central 60% of the scaphoid were categorized as nonunion of the waist of the scaphoid.

The outcome of the 'nonunion' surgery was union status. This was categorized as united, persistent nonunion or 'uncertain whether united', based on the impressions of the treating surgical team as recorded in the medical notes. The trainee assessor at each of the 19 centres also assessed the last available post-operative radiographs, CT or magnetic resonance imaging (MRI) of each patient and categorized the outcome as united, persistent nonunion or 'uncertain whether united'. This was according to the absence or presence of adverse features, such as: a gap at the fracture site or graft interface; lucency around, or movement (backing out) of, the implant; and displacement of the graft or the fracture (Dias, 2001).

Analysis

This study was designed as hypothesis-generating research, so no sample size calculation was done. Descriptive statistics are provided as frequencies with percentages (%). Age was skewed so the geometric mean and 95% confidence intervals (CI) are reported and compared using natural-log transformed data in a one-way analysis of variance (ANOVA) with Bonferroni correction. Proportional differences were examined using the chi-squared or Fisher's exact tests as appropriate. Agreement between the surgeon and the trainee assessor was determined using Cohen's kappa.

Union as diagnosed by the treating surgeon was the outcome of interest. Uncertain cases were classified as persistent nonunion. Logistic regression was used to estimate the odds ratio (OR) and 95% CI for persistent nonunion after surgery. To adjust for known confounders, multivariable logistic regression was used with the pre-selected co-variables of age as a continuous measure, and smoking, fracture pattern, method of fixation and time from acute fracture to nonunion surgery as categorical co-variables. We chose to examine the type of bone graft used through effect modification. Separate logistic regressions were also used to estimate the outcomes for patients with proximal pole and waist fracture nonunions; there was insufficient data to model distal pole fractures separately. All models were internally validated by lossless non-parametric bootstrapping by resampling with replacement, with 1000 iterations (Collins et al., 2015). All tests were two-sided. To improve the reliability of our results, the family-wise error rate was revised from $p < 0.05$ to $p < 0.003$ (Sidak, 1967).

Results

The baseline characteristics of the patients and their nonunions, treatments and outcomes are summarized in Table 1. The surgery was unsuccessful, leaving persistent nonunion in 22% of patients

($n=104$). In another 41 (9%) of cases, there was uncertainty as to whether the nonunion had united or not. Non-vascularized bone graft was the most common method of grafting for every type of scaphoid fracture and was used with increasing frequency

Table 1. Summary of patient characteristics.

| | Total ($n=462$) | Proximal pole ($n=119$) | Waist ($n=316$) | Distal pole ($n=27$) |
|---|----------------------|------------------------------|----------------------|---------------------------|
| Mean age (95% CI) | 26 (26 to 28) | 26 (24 to 27) | 26 (25 to 26) | 26 (23 to 29) |
| Sex (%) | | | | |
| Female | 33 (7) | 5 (4) | 24 (8) | 4 (15) |
| Male | 427 (93) | 114 (96) | 290 (92) | 23 (85) |
| Smoker at the time of surgery (%) | | | | |
| Yes | 125 (27) | 30 (25) | 90 (29) | 5 (19) |
| No | 185 (40) | 40 (41) | 125 (40) | 12 (44) |
| Unable to ascertain from notes | 152 (33) | 41 (34) | 101 (32) | 12 (44) |
| Time from acute fracture to nonunion surgery (%) | | | | |
| 3–6 months | 99 (22) | 25 (21) | 68 (21) | 6 (22) |
| 6–12 months | 135 (29) | 40 (34) | 91 (29) | 4 (15) |
| 1–2 years | 125 (27) | 30 (25) | 86 (27) | 9 (33) |
| More than 2 years | 103 (22) | 24 (20) | 71 (23) | 8 (30) |
| Type of bone graft used (%) | | | | |
| None | 36 (8) | 18 (15) | 18 (6) | 0 (0) |
| Non-vascularized distal radius/ulna graft | 136 (29) | 36 (30) | 89 (28) | 11 (41) |
| Non-vascularized iliac crest graft | 193 (42) | 25 (21) | 155 (49) | 13 (48) |
| Vascularized local bone flap (pedicle) | 91 (20) | 38 (32) | 50 (16) | 3 (11) |
| Free vascularized bone flap | 6 (1) | 2 (2) | 4 (1) | 0 |
| Type of fixation (%) | | | | |
| No fixation | 4 (1) | 0 | 4 (1) | 0 |
| Kirschner wire(s) | 35 (8) | 1 (1) | 32 (10) | 2 (7) |
| Cannulated screw | 422 (91) | 117 (98) | 280 (89) | 25 (93) |
| Non-cannulated screw | 1 (0) | 1 (1) | 0 | 0 |
| Postoperative follow-up (%) | | | | |
| 3–6 months | 179 (39) | 38 (32) | 127 (41) | 14 (52) |
| 6–12 months | 149 (32) | 39 (33) | 104 (33) | 6 (22) |
| 1–2 years | 91 (20) | 27 (23) | 58 (18) | 6 (22) |
| More than 2 years | 43 (9) | 15 (13) | 27 (9) | 1 (4) |
| Union as stated in the medical records (%) | | | | |
| Not united | 104 (22) | 32 (27) | 65 (21) | 7 (26) |
| Uncertain | 41 (9) | 8 (7) | 31 (10) | 2 (7) |
| United | 317 (69) | 79 (66) | 220 (69) | 18 (67) |
| Radiographs unavailable | 1 (0) | 1 (0) | 0 (0) | 0 (0) |
| Union as assessed by trainee (%) | | | | |
| Not united | 114 (25) | 36 (30) | 72 (23) | 6 (22) |
| Uncertain | 29 (6) | 6 (5) | 23 (7) | 0 (0) |
| United | 306 (66) | 73 (61) | 214 (68) | 19 (70) |
| Radiographs unavailable | 13 (3) | 4 (3) | 7 (2) | 2 (7) |
| Imaging technique used to diagnosis postoperative union | | | | |
| Plain radiographs | 331 (72) | 83 (70) | 288 (91) | 20 (74) |
| CT | 120 (26) | 32 (27) | 82 (26) | 6 (22) |
| MRI | 6 (1) | 3 (3) | 3 (1) | 0 (0) |
| Uncertain | 5 (1) | 1 (0) | 3 (1) | 1 (4) |

CI: confidence interval; CT: computed tomography; MRI: magnetic resonance.

from the proximal pole (51%), to the waist (77%), to the distal pole (89%).

Plain radiographs were the most commonly employed test for union ($n=321$, 60%). Comparison of assessments of postoperative union by the treating surgical team and the trainee assessors in this study showed excellent agreement (90%, $k=0.8$, $p<0.001$).

Descriptive statistics of the variables associated with persistent nonunion are reported in Table 2. Table 3 shows the unadjusted (univariable) and adjusted (multivariable) ORs, which suggest that smoking and delays to nonunion surgery are associated with a worse outcome. Smoking at the time of surgery nearly doubled the odds of a persistent

nonunion (i.e. treatment failure); this association remained strong in our multivariable modelling, and was also independent of age, time from injury to surgery and the method of fixation. Similarly, delay of 1–2 years from injury to nonunion surgery was independently associated with 40% higher odds of persistent nonunion, whereas a delay of more than 2 years increased the odds by 140%. The variability of these estimates suggests that the longer the delay, the lower the probability of achieving union. Using effect modifiers in our multivariable model, the use of vascularized bone (as either a local or free flap) did not significantly alter the odds of achieving union for smokers ($p=0.5$), proximal pole

Table 2. Postoperative union and baseline factors ($n=462$).

| | Union ($n=317$) | Persistent nonunion ($n=104$) | Uncertain ($n=41$) | <i>p</i> -value |
|---|----------------------|------------------------------------|-------------------------|-----------------|
| Mean age (95% CI) | 25 (24 to 26) | 27 (26 to 28) | 25 (22 to 28) | 0.3 |
| Sex (%) | | | | |
| Male | 287 (91) | 100 (96) | 40 (98) | 0.13 |
| Female | 28 (9) | 4 (4) | 1 (2) | |
| Smoker at the time of surgery (%) | | | | |
| No | 134 (43) | 39 (38) | 12 (29) | 0.01 |
| Unable to tell | 106 (34) | 24 (23) | 17 (42) | |
| Yes | 73 (23) | 40 (39) | 12 (29) | |
| Fracture pattern (%) | | | | |
| Proximal pole | 79 (25) | 32 (31) | 8 (20) | 0.6 |
| Waist | 220 (69) | 65 (73) | 31 (76) | |
| Distal pole | 18 (6) | 7 (7) | 2 (5) | |
| Time from acute fracture to nonunion surgery (%) | | | | |
| 3–6 months | 72 (23) | 19 (18) | 8 (20) | 0.05 |
| 6–12 months | 104 (33) | 23 (22) | 8 (20) | |
| 1–2 years | 82 (26) | 29 (28) | 14 (34) | |
| >2 years | 59 (19) | 33 (32) | 11 (26) | |
| Type of bone graft used (%) | | | | |
| No bone graft | 23 (7) | 9 (9) | 4 (10) | 0.3 |
| Non-vascularized distal radius/ulna bone graft | 92 (29) | 30 (29) | 14 (34) | |
| Non-vascularized iliac crest bone graft | 129 (41) | 43 (41) | 21 (51) | |
| Vascularized local bone flap (pedicle) | 69 (22) | 20 (19) | 2 (5) | |
| Free vascularized bone flap | 4 (1) | 2 (2) | 0 (0) | |
| Type of fixation (%) | | | | |
| None | 2 (1) | 2 (10) | 0 (0) | 0.7 |
| Kirschner wire(s) | 24 (8) | 7 (7) | 4 (10) | |
| Screw | 291 (92) | 95 (91) | 37 (90) | |
| Imaging technique to diagnose postoperative union (%) | | | | |
| Plain radiographs | 221 (71) | 76 (73) | 34 (83) | 0.4 |
| CT | 87 (28) | 26 (25) | 7 (17) | |
| MRI | 4 (1) | 2 (2) | 0 (0) | |

CI: confidence interval; CT: computed tomography; MRI: magnetic resonance imaging.

Table 3. Risk factors for persistent nonunion after surgery ($n=462$).

| | Univariable OR (95% CI) | Adjusted OR (95% CI) | p -value ^a |
|-----------------------------|----------------------------|-------------------------|-------------------------|
| Age | 1.0 (1.0 to 1.0) | 1.0 (1.0 to 1.0) | 0.3 |
| Male | 2.4 (0.8 to 7.1) | 2.3 (0.8 to 7.1) | 0.1 |
| Current smoker | | | |
| No | 1 (referent) | 1 (referent) | 0.01 |
| Unclear | 0.8 (0.4 to 1.4) | 0.7 (0.4 to 1.3) | |
| Yes | 1.9 (1.1 to 3.2) | 1.8 (1.0 to 3.1) | |
| Time from injury to surgery | | | |
| 3–6 months | 1 (referent) | 1 (referent) | 0.01 |
| 6–12 months | 0.8 (0.4 to 1.6) | 0.9 (0.4 to 1.7) | |
| 1–2 years | 1.3 (0.7 to 2.6) | 1.4 (0.7 to 2.8) | |
| >2 years | 2.1 (1.1 to 4.1) | 2.4 (1.2 to 4.8) | |
| Fracture location | | | |
| Distal pole | 1 (referent) | 1 (referent) | 0.3 |
| Waist | 0.8 (0.3 to 1.9) | 0.7 (0.3 to 1.9) | |
| Proximal pole | 1.0 (0.4 to 2.7) | 1.1 (0.4 to 3.0) | |
| Fixation | | | |
| Screw | 1 (referent) | 1 (referent) | 0.4 |
| Kirschner Wires | 0.9 (0.4 to 2.1) | 0.8 (0.3 to 2.1) | |
| None | 3.0 (0.4 to 22) | 4.0 (0.5 to 31) | |

^aDerived from multivariable logistic regression.
CI: confidence interval; OR: odds ratio.

nonunion ($p=0.2$) or nonunion treated more than 1 year after the acute fracture ($p=0.2$). Resampling did not change any of these estimates. We recommend caution in interpreting these models because, while they appear clinically significant, they are not statistically significant according to the family-wise error rate of $p < 0.003$.

When examining the different fracture patterns individually, we again identified smoking and delays to nonunion surgery as potentially significant factors. Concerning proximal pole fractures, our bootstrapped multivariable logistic regression identified the patient's smoking status as the only factor potentially associated with persistent nonunion (OR 4.3 [95% CI 1.2 to 15]; re-sampled $p=0.03$). Similarly, concerning waist fractures, our bootstrapped multivariable logistic regression suggested that the time between acute fracture and nonunion surgery was independently associated with treatment failure whereby a delay of 1–2 years increased the odds by twofold (OR 2.1 [95% CI 1.5 to 13]) and delays over 2 years increased the odds by fourfold (OR 4.4 [95% CI 1.5 to 13]; re-sampled $p=0.007$). However, these estimates should be interpreted with caution because they are not statistically significant with respect to the family-wise error rate of $p < 0.003$.

Discussion

Shortcomings of the existing evidence on outcomes of scaphoid fracture nonunion surgery include the lack of large prospective studies and a multitude of small studies, which have used different criteria to define union and nonunion, failed to consider the impact of confounders, such as smoking, and used different types of bone graft according to characteristics of the nonunion, such as site, deformity and vascularity. This has resulted in different studies coming to different conclusions about which factors influence the success of bone graft surgery. This study also has many of these shortcomings as it was a retrospective survey of practice in 19 centres within the United Kingdom. However, 462 of the 806 collected cases satisfied our preselected definitions of nonunion (fracture not united after 12 weeks), and had sufficient follow-up (more than 12 weeks) to analyse the influence of factors, such as smoking and time since acute fracture on outcome with adjustment for confounders.

Union occurred in 69% of cases after bone graft surgery in the 19 centres overall. This is lower than reported in many single centre studies and less than the 79% union recently reported for low-intensity pulsed ultrasound (LIPUS) (Seger et al., 2018). It is

also lower than the overall frequency of union in over 80% reported by two systematic reviews (Ferguson et al., 2016; Pinder et al., 2015). This might indicate surgical failings, but all the 19 centres regularly manage this clinical problem. It could also be an underestimate due to us categorizing some fractures as having 'uncertain union status'. If all these fracture nonunions had actually united, then overall 78% would have been classed as united. It is perhaps surprising that other studies have not reported difficulties determining whether union had, or had not, occurred in some instances. Other possible explanations are the use of different criteria for defining union (Dias, 2001), different lengths of follow-up or even reporting bias, in which only case series with high percentages of unions have been submitted for publication.

A recent meta-analysis found that smokers have twice the risk of experiencing a nonunion after a number of trauma and elective orthopaedic operations (Pearson et al., 2016). Its mechanism for inhibiting fracture healing is not known but could be due to nicotine (Feitelson et al., 2003; Gaston and Simpson, 2007) or carbon monoxide (Sorensen et al., 2009) within the inhaled smoke. Two studies reported 82% and 88% union after bone graft surgery for scaphoid fracture nonunion in non-smokers compared with 40% and 57% in smokers, respectively (Dinah and Vickers, 2007; Little et al., 2006). Our data suggest that smoking is probably associated with a doubling of the odds of persistent nonunion after bone graft surgery, which is consistent with these two studies.

Separate analysis of proximal pole and waist fractures suggested that smoking may particularly affect the outcome of proximal pole fracture nonunion (non-smokers vs smokers: 77% vs 43%; $p=0.01$). However, this finding is not significant, given the revision of our family-wise error rate ($p < 0.003$). Also, it was based on univariate analyses, which do not take into account confounding factors, such as time since the acute fracture.

Merrell et al. (2002) reported union of scaphoid fracture nonunions in 90% after surgery within a year and 80% after surgery more than 1 year after injury. Another study of 160 patients found that one of the factors associated with poorer outcomes was delay before surgery (Inoue et al., 1997). Nakamura et al. (1993) found delays to surgery of over 5 years were associated with poorer outcomes after nonunion surgery, as did Inaparthi and Nicholl (2008). However, others have found no impact from delay (Trezies et al., 2000). Our data suggest that the outcome of bone graft surgery is time dependant, as the odds of treatment failure

are 40% higher for patients with a delay of 1 to 2 years and 140% higher for those with a delay of more than 2 years, compared to those who underwent surgery within 3 to 6 months of the acute fracture. We recommend that future researchers measure time on a continuous scale (e.g. in days, weeks or months) rather than categorizing data into time blocks. This will allow a more accurate estimation of the impact of specific delays on the likelihood of union.

The type of bone graft used for scaphoid fracture nonunion surgery remains a subject of debate and may depend on characteristics of the nonunion, including the vascularity of the proximal fracture fragment and deformity at the nonunion. Current reports show tendencies to use tricortical wedge (corticocancellous) bone grafts for unstable nonunion, vascularized bone grafts for nonunion with evidence of avascular necrosis of the proximal fragment and cancellous bone graft for stable nonunion (Merrell et al., 2002; Munk and Larsen, 2004; Uesato et al., 2017). Our study did not distinguish between different corticocancellous and cancellous non-vascularized grafts, but a recent review by Sayegh and Strauch (2014) suggested the former resulted in better restoration of the height of the scaphoid and carpal alignment, and significantly better Mayo wrist scores. They found that cancellous grafts were associated with shorter time to union, but there was no difference in the overall percentages of union between these grafts. Our data suggest that non-vascularized iliac crest bone graft is the most common choice for scaphoid nonunion surgery in the United Kingdom. Vascularized bone grafts appear to be used most frequently for proximal pole (32%), rather than waist (17%) nonunions. Our univariate analyses suggested that vascularized local bone graft may influence the union of proximal pole (vascularized vs non-vascularized: 82% and 58%; $p=0.04$), but not waist fracture nonunion, though again these findings were not statistically significant. Furthermore, analysis of the whole group of 462 scaphoid fractures (distal pole, waist and proximal pole) revealed no benefit to vascularized bone grafts. This is in agreement with the findings of recent systematic reviews that reported similar union results for vascularized and non-vascularized bone grafts (92% and 88%, respectively) (Ferguson et al., 2016; Pinder et al., 2015). We did not, however, independently assess the preoperative rationale for the use of vascularized grafting or any preoperative imaging for evidence of avascular necrosis (AVN). This, therefore, may introduce a risk of selection bias affecting any benefit of vascularized grafting in the setting of AVN.

We also found no benefit of iliac crest bone graft over a graft from the distal radius, which concurs with one systematic review (Pinder et al., 2015). Harvest of iliac crest bone graft may cause complications, and for this reason, use of non-vascularized bone from the distal radius might be the preferred choice when restoration of scaphoid height is not required, or the nonunion is within the proximal pole (Arrington et al., 1996; Goulet et al., 1997). However, we accept our study analyses are probably underpowered to detect differences in outcomes between the different types of bone grafts.

AVN of the proximal fracture fragment is thought to increase the failure rate of bone graft surgery, although ischaemia alone, without AVN of the proximal fragment, may not influence the success of grafting (Rancy et al., 2018). The reference standard to assess vascularity is intra-operative assessment of punctate bleeding from the proximal fracture fragment (Green, 1985). It can be assessed preoperatively with MRI, but its value in predicting the outcome of surgery is uncertain (Cerezal et al., 2000; Singh et al., 2004). AVN of the proximal fragment was not studied in this evaluation of service as the presence of punctate bleeding is frequently not recorded in the operation notes and MRI is not normally used preoperatively in the United Kingdom. Also, cases of AVN causing collapse and fragmentation of the proximal pole would have been excluded from our study as they are not suitable for bone graft reconstruction of the scaphoid.

There is no consensus on the definition of a scaphoid fracture nonunion, which makes comparisons between published articles impossible. A recent systematic review (Ferguson et al., 2016) looked at 144 studies of scaphoid nonunion and found that only 17 defined the time since the acute fracture after which a failure of union indicated a nonunion. The time intervals suggested ranged from 12 weeks to 1 year. In this study, we required a minimum period of 12 weeks after acute fracture, in keeping with current practice and other researchers (Murase et al., 2005; Schuind et al., 1999). Many surgeons feel that union is unlikely to occur 12 weeks or more after injury, either spontaneously or with further immobilization of the wrist in plaster, and patients are reluctant to tolerate long periods in a cast. Every case that was included in our study had the diagnosis of nonunion confirmed at the time of surgery.

There is also no consensus on the definition of radiological union after scaphoid fracture nonunion surgery. One systematic review found that the radiological features used to diagnose a nonunion, such as absence of bridging trabeculae, both before or after bone graft surgery, were not described in any of the

144 studies (Ferguson et al., 2016). Plain radiographs are most commonly used and the absence of a complete gap between the fracture fragments on any image, as well as no evidence of loosening of the fixation screw or wires (if present) suggest union, such that nonunion is a diagnosis by exclusion (Dias, 2001). Persistent nonunion may give the appearance of bridging trabeculae due to overlap of the distal and proximal fracture fragments unless the X-ray beam for at least one view is in the plane of the fracture. The timing of the radiographs is also important, as graft resorption may make a nonunion evident at 12 weeks after surgery, whereas radiographs taken at 6 weeks (before bone graft resorption) may suggest union. It was for this reason we excluded all cases with a radiological follow-up of less than 12 weeks from our analyses. CT scanning probably allows a more reliable assessment of union, but the presence of a metallic fixation device (screw or wires) may distort the images and make this assessment difficult.

This study was a retrospective service evaluation, and thus has several failings, including a high percentage of case exclusions ($344/806 = 43\%$) for the reasons previously given. A systematic review of scaphoid fracture nonunion surgery revealed that the outcome of bone graft surgery had been reported in 5464 cases in 144 studies of ten or more cases published in peer reviewed journals before 2015 (Ferguson et al., 2016). Therefore, despite the number of exclusions, our 462 cases are equal to 7.8% of the previously reported outcomes of scaphoid fracture nonunion surgery.

Another issue with the present study is the possibility that the different centres involved used different criteria for determining whether the surgery had succeeded in achieving union because the primary outcome in this study was the conclusion of the treating surgical team. Despite the potential for bias, this outcome was selected as it allowed consideration of the clinical, as well as the radiological presentation. An assessment of the postoperative imaging of the scaphoid fracture nonunions by the trainee assessors in each centre that used defined criteria (Dias, 2001) demonstrated 95% agreement with the conclusions of the treating surgical team. Although the trainee assessors were not blinded to the treating surgical team's assessment of union when making their assessments, this instils some confidence in the accuracy of the assessments of union, especially as we included an additional, 'uncertain', category of 'union state' for cases where the observers felt unable to categorize the outcome as 'united' or 'not united' with reasonable certainty. Future prospective studies should be designed to allow longer follow-up

or further imaging with CT scans to elucidate the outcome of these cases.

In conclusion, this study suggests that the previously published values for union (>80%) after bone grafting of scaphoid fracture nonunions may not reflect the outcome of current practice in the United Kingdom. It supports the hypotheses that both smoking and the time interval between acute fracture and nonunion surgery influence the outcome of bone graft surgery. Both these factors are often beyond the control of the surgeon and will act as confounders during data analysis. Any conclusions regarding the impact of variations of surgical technique on the outcome of bone graft surgery for scaphoid nonunion must be considered unsound, and potentially incorrect, if these factors are not considered.

Future studies of the outcome of bone graft surgery for scaphoid fracture nonunion should be prospective to allow complete data collection and sufficiently large to allow for the management of potential confounders, such as smoking. They should also report their definitions of a nonunion and union after surgery and have a standardized imaging protocol for assessing union and nonunion. Ideally these definitions and imaging requirements should be standardized for all future studies as previously suggested (Ferguson et al., 2016). Only when the results of such studies are available will we know whether surgical techniques can be modified to improve the outcome of bone graft surgery for scaphoid fracture nonunion.

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