Vascularized Bone Grafts and Their Applications in the Treatment of Carpal Pathology

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ABSTRACT

Vascularized bone grafts (VBGs) are techniques in the management of certain types of carpal pathology. VBGs have traditionally been advocated for conditions including delayed and nonunion of fractures and avascular necrosis. The most common indications for VBG have been for scaphoid nonunion, lunatomalacia (Kienböck's disease), and osteonecrosis of the scaphoid (Preiser's disease). Advantages over NVBG have been established. VBGs provide improved blood flow, osteocyte preservation, and accelerated healing rates. Local pedicled VBGs are the most commonly used methods. They are technically less demanding than are free VBGs and are associated with less morbidity. Commonly used donor grafts arise from the dorsal vasculature of the wrist and include the 1,2 intercompartmental supraretinacular artery (1,2 ICSRA), the 2,3 ICSRA, the fourth extensor compartment artery (fourth ECA), and the fifth ECA. A 4 + 5 ECA combination graft has been described to provide a longer pedicle. In managing osteonecrosis, most surgeons would agree that VBG should be reserved for carpal bones with an intact cartilaginous shell and no collapse. In treating scaphoid pathology, indications for VBG include fractures/nonunions with proximal pole avascular necrosis and/or small proximal pole fragments.

KEYWORDS: Vascular bone grafting, osteonecrosis, nonunion

The concept of vascularized bone grafting has been shown to be effective in facilitating healing of difficult fractures, avascular necrosis, and nonunions of bone. This treatment modality has been used in multiple areas of the body susceptible to the above maladies. Multiple types of bone grafting exist. NVBGs can be categorized as autograft versus allograft, cancellous, and cortical. Vascularized bone grafts are categorized as free or pedicled grafts. Free vascularized bone grafts involve removal of bone from its original (donor) blood supply, transplanting it to the affected area, and anastomosing the graft to the local blood supply. Historically, free vascularized bone graft (VBG) applications for the upper extremity have included reconstructions after

tumor resection, significant infections, or trauma.^{1,2} Although not very common, free VBG has been reported in the treatment of conditions such as scaphoid and avascular necrosis (AVN) of the scaphoid and lunate bones.³⁻⁵

Pedicled vascularized bone grafts maintain the vascular blood supply of the donor bone graft and place the graft to the affected area. This necessitates that the donor bone be in proximity to the accepting bone graft site. Pedicled grafts can be simply bone or may include bone, muscle, fascia, and/or skin. They remain the most commonly used method of vascular bone grafting in the wrist. In addition to their applications in the upper extremity, pedicled vascular bone grafts

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have been used in the treatment of fractures/nonunions of the femoral neck and hip, tibia, and mandible.⁶⁻⁹

Despite the fact that vascular bone grafts have been shown to provide better healing rates, they are technically more demanding and carry an increased risk of donor-site morbidity. The purpose of this article is to review VBG applications in the treatment of carpal pathology, specifically scaphoid fracture and nonunion, Preiser's disease, and Kienböck's disease (Fig. 1).

BASIC SCIENCE OF VASCULARIZED BONE GRAFTING

VBGs help facilitate bone healing and revascularize bone without creeping substitution and thus accelerate fracture healing.^{10,11} Osteocytes are preserved,^{12,13} and this results in accelerated graft consolidation.¹⁴⁻¹⁶ It has been clearly established that vascular bone grafts offer superior biological and mechanical properties over nonvascular bone grafts.¹⁷⁻¹⁹ Postimplant remodeling is minimized, and this preserves bone mass, which minimizes osteopenia and maintains bone strength after grafting.²⁰⁻²²

Animal models have demonstrated superior blood flow from pedicled bone grafts when compared with nonvascular grafting.²³⁻²⁵ Tu et al demonstrated blood

flow from pedicled VBG increases over time compared with nonvascular bone graft and undisturbed radius.^{23,24} Immediately after elevation of the graft in a canine model, the blood flow rate was $8.42 \text{ mL min}^{-1} 100 \text{ g}^{-1}$ versus $16.53 \text{ mL min}^{-1} 100 \text{ g}^{-1}$ for the undisturbed radius. At 2 weeks after elevation, the rate increased significantly for the VBG to $33.72 \text{ mL min}^{-1} 100 \text{ g}^{-1}$, whereas the rate for nonvascularized bone graft (NVBG) was $0.62 \text{ mL min}^{-1} 100 \text{ g}^{-1}$ and the undisturbed radius remained unchanged. The authors also concluded that venae comitantes within each graft maintain flow. Sunagawa et al reported union rates of 73% with VBG versus 0% for NVBG in a scaphoid nonunion canine model.²⁵

ANATOMY AND NOMENCLATURE

Many of the sources for pedicled bone grafts for carpal pathology are based on the distal radius. Zaidenberg et al initially described the use of a pedicled dorsal radius VBG for scaphoid pathology.²⁶ Sheetz et al helped clarify and laid the groundwork for an anatomically based classification of potential donor grafts.²⁷ The types of grafts from the dorsal distal radius can be grouped into two broad categories: within and superficial to the extensor retinaculum. The vessels arise from the radial and ulnar anterior interosseous and posterior interosseous vessels. They give rise to three dorsal arches: (1) a dorsal intercarpal arch, (2) a dorsal radiocarpal arch, and (3) a dorsal supraretinacular arch. The extensor retinaculum vessels are subclassified as either within a compartment or extensor compartmental (EC) versus vessels between compartments or intercompartmental (IC). Vessels on the surface of the retinaculum are called supraretinacular (SR). Four main vessels can be used as pedicled VBGs: 1,2 intercompartmental supraretinacular artery (1,2 ICSRA; intercompartmental [between first and second compartments], supraretinacular (superficial to extensor retinaculum)); 2,3 ICSRA; fourth extensor compartment artery (fourth ECA); and fifth

Figure 1 Schematic of the primary dorsal distal radius blood supply and possible VBG donor sites. (From Sheetz KK, Bishop AT, Berger RA. The arterial blood supply of the distal radius and the ulna and its potential use in vascularized pedicled bone grafts. *J Hand Surg [Am]* 1995;20:906, Fig. 4c. Figure used with permission.)

Table 1 Extraosseous Vessel Characteristics with Regard to Presence of the Artery and Nutrient Vessels into the Radius

Artery	Artery Present (%)	Nutrient artery?
1,2 ICSRA	94	Yes
Second EC br.	56	Yes
2,3 ICSRA	100	Yes
Second EC br.	91	Yes
Fourth ECA	100	Yes
Fifth ECA	100	No
Fourth EC br.	39	Yes

Source: From Sheetz KK, Bishop AT, Berger RA. The arterial blood supply of the distal radius and the ulna and its potential use in vascularized pedicled bone grafts. *J Hand Surg [Am]* 1995;20:907, Table 1. Used with permission.
EC br., extensor compartment branch.

Table 2 Extraosseous Vessel Characteristics: The Number of Nutrient Arteries and Their Diameters

Artery	No. Nutrient Arteries	Nutrient Artery Diameter (mm)
1,2 ICSRA	3.2	< 0.10
Second EC br.	1.0	0.16
2,3 ICSA	1.8	0.11
Second EC br.	1.4	0.19
Fourth ECA	3.2	0.16
dRCA	2.6	0.18

Source: Adapted from Sheetz KK, Bishop AT, Berger RA. The arterial blood supply of the distal radius and the ulna and its potential use in vascularized pedicled bone grafts. *J Hand Surg [Am]* 1995;20:908, Table 2. Used with permission.
EC br., extensor compartment branch; dRCA, dorsal radio carpal arch.

ECA. The details of the frequency of nutrient vessels are illustrated in Table 1, Table 2, and Table 3.

Additional dorsal VBG donor sites have included the index finger and thumb metacarpal bone. This graft is based on the dorsal index finger metacarpal artery as the pedicle. Nutrient vessels in the bone have allowed for both proximal and distal bone grafts to be harvested. Their use has been described in the treatment of thumb defects, Kienböck's disease, and scaphoid nonunion.^{28–30} The use of a pedicled thumb metacarpal VBG is based on the first dorsal metacarpal artery. It has been described in the treatment of scaphoid nonunion.³¹

The palmar blood supply to the distal radius is illustrated in Fig. 2. The radial and ulnar vessels give rise to a palmar carpal arch. In addition, a palmar metaphyseal arch is frequently noted. Although pedicled vascular bone grafts from the volar side of the wrist are less used than are dorsal grafts, multiple descriptions of their use have been published. The most commonly described is the pronator pedicled bone graft.^{32–34} Kuhlmann et al described both a volar carpal artery pedicled VBG and a vascularized pisiform bone graft for both nonunion of the scaphoid and Kienböck's disease.^{35,36} Volar distal ulna VBG has also been described.³⁷

VASCULAR BONE GRAFTS IN THE TREATMENT OF SCAPHOID PATHOLOGY

Scaphoid fractures are the most common carpal bone injury.³⁸ Its blood supply arises primarily from the dorsal radial artery. Two and three different vascular systems have been used to delineate its blood supply.^{39–42} A dorsal vascular component to the scaphoid is well established, and these feed into the scaphoid from the distal aspect and run in a retrograde fashion. A volar and laterally based arterial system that enters at the scaphoid tubercle level exists. Based on this arterial pattern, the blood supply of the proximal pole is tenuous and vulnerable to nonunion and avascular necrosis after fractures.

Table 3 Nutrient Artery Characteristics: The Distances of the Nutrient Vessels from the Joint Line and Percentage That Penetrate the Cancellous Bone

Artery	Distance from Joint Line (mm)	Percentage Penetrating Cancellous Bone (%)
1,2 ICSRA	15	6
Second EC br.	21	57
2,3 ICSRA	13	22
Second EC br.	18	48
Fourth ECA	11	45
dRCA	4	79

Source: Adapted from Sheetz KK, Bishop AT, Berger RA. The arterial blood supply of the distal radius and the ulna and its potential use in vascularized pedicled bone grafts. *J Hand Surg [Am]* 1995;20:908, Table 2. Used with permission.
EC br., extensor compartment branch; dRCA, dorsal radio carpal arch.

Figure 2 The volar blood supply of the distal radius. The radial and ulnar vessels communicate to form a metaphyseal arch. rPCA, radial half of the palmar arch; uPCA, ulnar half of the palmar arch; pMeta, palmar metaphyseal arch; RA, radial artery; UA, ulnar artery; Ant Int A, anterior interosseous artery. (From Sheetz KK, Bishop AT, Berger RA. The arterial blood supply of the distal radius and the ulna and its potential use in vascularized pedicled bone grafts. *J Hand Surg [Am]* 1995;20:906, Fig. 4b. Figure used with permission.)

Nonunion rates after scaphoid fracture have been reported to occur in 5 to 15% of fractures.⁴³ Increased rates have been associated with fracture displacement, treatment delay, location (proximal) of the fracture, avascular necrosis, and concomitant carpal instability.⁴⁴ Traditional bone grafting treatments for scaphoid nonunion are in part dependent on the degree of deformity of the scaphoid and include inlay bone grafting, wedge grafting, and cancellous bone grafting and fixation.^{45–48}

Indications for VBG for Scaphoid Nonunion

The indications for VBG in the treatment of scaphoid nonunion continue to evolve. The advantages of VBG for scaphoid nonunion include increased blood supply to nonunion site, expedited bone healing, and diminished risk of fracture. A potential disadvantage is that the distal radius bone may be inferior in quality and strength compared with iliac crest. Factors favorably affecting the success of VBG include anatomic restoration of the scaphoid, vascularity of the fracture fragments, larger size of the proximal pole, and stable fixation. Most surgeons would agree that fractures/nonunions with proximal pole AVN and/or small proximal pole fragments are fairly well established indications for pedicled VBG. Additional indications for vascularized bone grafting may include patients who have failed prior surgery.

Technique

The technique for vascularized bone grafting in the treatment of scaphoid nonunion is illustrated in Fig. 3. The patient is placed supine on the operating room table while placing his or her arm on the hand table. A tourniquet is used but inflated only to 200 mm Hg. This will allow for better visualization of the donor vessels. In addition, an Esmarch is not used to exsanguinate the extremity. A curvilinear incision is made centered over the dorsal-radial wrist. Care is taken to protect the superficial branch of the radial nerve. The 1,2 ICSRA is identified between the first and second dorsal compartments. Sharp dissection of the soft tissues in line with the vessel is performed. The fracture or nonunion site is visualized, and feasibility of VBG is determined. The appropriate size of bone graft is raised with the nutrient vessel in the center. Care must be taken to elevate the soft tissues in line with the graft while avoiding injury to the pedicle. The bone is then prepared to accept the graft. It can be laid dorsally or volarly in a wedge shape to correct a humpback deformity. The graft is finally secured with fixation. Our preference is with a compression screw. Postoperatively, the patient is placed into a thumb spica splint/cast. The wrist and thumb are immobilized until evidence of radiographic and clinical healing.

Outcomes of VBG in the Treatment of Scaphoid Nonunions

The earliest reports of vascular bone grafting for scaphoid nonunion were based on the volarly based distal radius, pronator muscle pedicle. Multiple investigators reported good outcomes with overall excellent union rates with this graft.^{32,34,36,49} Braun initially reported a series of scaphoid nonunions treated with this graft in 1983.³² All of the patients treated went on to heal. Kuhlmann et al treated three patients with scaphoid nonunion with this volar radial graft.³⁶ The technique was technically demanding and included two incisions. All patients healed, had improved grip and range of motion, and returned to work. Kawai and Yamamoto published their results of eight patients who underwent a similar VBG technique for old scaphoid fractures and nonunions.³⁴ All fractures went on to heal at an average of 8.5 weeks. All of the patients were pain-free, had improved range of motion, and returned to their prior occupations.

Zaidenberg et al later introduced the dorsal distal radius graft that has gained in popularity over the past 15 years.²⁶ This graft has been classified as the 1,2 ICSRA graft.²⁷ Zaidenberg referred to it as the ascending irrigating branch of the radial artery. Their series included 11 patients with scaphoid nonunion with and without avascular necrosis. All patients healed at an average of 6 weeks. Rest pain improved in all wrists, but five patients complained of some pain with activity. Average grip strength improved as well. Subsequent studies have reported similar outcomes.^{44,50–53} Uerpaiojkit et al reviewed 10 patients, five with concomitant AVN, and all went on to heal at an average of 6.5 weeks.⁵³ Functional parameters including grip, pinch, and range of motion all improved. Steinmann et al reviewed 14 patients with AVN treated at the Mayo Clinic with 1,2 ICSRA pedicled bone graft.⁴⁴ Eight were difficult proximal pole nonunions, eight wrists had sclerosis consistent with AVN, and four demonstrated some evidence of degenerative changes on plain film. All of the patients went on to heal at an average 11 weeks, and nine had a good/excellent result. The authors did conclude that early arthritic changes were a poor prognostic sign. These sentiments were echoed by Malizos et al.⁵⁰ They reviewed 22 wrists that underwent VBG. Again, universal healing was noted within 6 to 12 weeks. Sixteen patients had no pain, and six had mild pain with activity. The authors reiterated that patients with degenerative disease fared worse. A recent follow-up study from the same group included 30 patients at a minimum 2-year follow-up.⁵² The average nonunion chronicity was 3.3 years. Twenty underwent dorsal bone grafting, whereas 10 were treated with palmar-based VBG. All of the fractures healed by 12 weeks. Ninety percent of patients reported complete pain relief, and 77% good or excellent results were achieved. The Mayo Modified

Wrist Score significantly improved. The authors concluded that pedicled VBGs were a reliable method of treating scaphoid nonunion. Waters and Stewart demonstrated that adolescents can go on to heal with VBG for problematic proximal pole nonunions and AVN.⁵⁴ They reviewed three patients who healed at an average of 3.4 months. Chen et al reviewed the outcomes of using dorsal distal radius pedicled VBG in nonunions that have a concomitant humpback deformity.⁵¹ The authors reviewed 11 patients treated over a 4-year period. All of the nonunions healed at an average 13 weeks with revascularization of the proximal pole. Ten patients had good or excellent outcomes. The authors concluded that in addition to helping promote healing and restor-

ing the blood supply to the proximal pole, pedicled VBG can correct humpback deformity and resultant carpal instability.

As previously mentioned, alternative bone graft donor sites about the wrist have also been used in treating scaphoid nonunion and avascular necrosis, and these have been taken from the palmar carpal arteries and distal radius,^{55,56} dorsal distal radius capsular based graft,⁵⁷ and dorsal metacarpal arteries.^{28,31,58,59} Implanting a vascular pedicle into a nonvascular bone graft has also been reported.⁶⁰ The reported union rates are favorable and outcomes generally successful.

Unfortunately, not all reports on the use of VBG have been favorable.^{61–63} Boyer et al reviewed 10 patients

Figure 3 Schematic demonstrates the technique of dorsal distal radius VBG for scaphoid nonunion. (A) A curvilinear incision is made in line with the scaphoid on the radial side of the wrist. (From Shin AY, Bishop AT, Berger RA. Vascularized pedicled bone grafts for disorders of the carpus. *Tech Hand Upper Extrem Surg* 1998;2:94–109, Fig. 7. Figure used with permission.) (B) The 1,2 ICSRA is identified between the first and second dorsal compartments. The superficial branch of the radial nerve (SBRN) is safely retracted. (From Shin AY, Bishop AT, Berger RA. Vascularized pedicled bone grafts for disorders of the carpus. *Tech Hand Upper Extrem Surg* 1998;2:94–109, Fig. 8. Figure used with permission.) (C) The first and second dorsal compartments are opened at the level of the bone graft site to create a cuff or retinaculum that contains the 1,2 ICSRA. (From Shin AY, Bishop AT, Berger RA. Vascularized pedicled bone grafts for disorders of the carpus. *Tech Hand Upper Extrem Surg* 1998;2:94–109, Fig. 9. Figure used with permission.) (D) The fracture or nonunion site is visualized after dorsal capsulotomy. (From Shin AY, Bishop AT, Berger RA. Vascularized pedicled bone grafts for disorders of the carpus. *Tech Hand Upper Extrem Surg* 1998;2:94–109, Fig. 10. Figure used with permission.)

Figure 3 (Continued) (E) The nonunion site is debrided and bone ends prepared. A burr can be used to create a slot in preparation of the donor graft. (From Shin AY, Bishop AT, Berger RA. Vascularized pedicled bone grafts for disorders of the carpus. *Tech Hand Upper Extrem Surg* 1998;2:94–109, Fig. 11. Figure used with permission.) (F) The bone graft is elevated after a series of osteotomies with the nutrient artery centered in graft. After completing a proximal osteotomy, the radial and ulnar osteotomies can be performed. Then the distal edge can be gently levered to prevent risk of injury to the pedicle. (From Shin AY, Bishop AT, Berger RA. Vascularized pedicled bone grafts for disorders of the carpus. *Tech Hand Upper Extrem Surg* 1998;2:94–109, Fig. 12. Figure used with permission.) (G) Schematic illustrates the bone graft placement in the slot. It is then secured with supplemental fixation. (From Shin AY, Bishop AT, Berger RA. Vascularized pedicled bone grafts for disorders of the carpus. *Tech Hand Upper Extrem Surg* 1998;2:94–109, Fig. 13. Figure used with permission.) (H) Schematic demonstrated how the VBG can be used as a wedge graft in cases of humpback deformity. (From Shin AY, Bishop AT, Berger RA. Vascularized pedicled bone grafts for disorders of the carpus. *Tech Hand Upper Extrem Surg* 1998;2:94–109, Fig. 19. Figure used with permission.)

treated with 1,2 ICSRA for scaphoid nonunion and AVN.⁶¹ Only six patients went on to heal, and only five returned to their previous employment. Among the four failures, all had previous surgery, and three subsequently underwent partial wrist fusion. The authors also concluded that a risk factor for failure is a history of prior surgery. Straw and colleagues reviewed the outcomes of 22 patients who underwent vascularized bone grafting with the 1,2 ICSRA and a single K-wire fixation.⁶² Their overall union rate was only 27%. Sixteen patients in their

series had proximal pole osteonecrosis, and only two of those went on to heal. The authors concluded that proximal pole AVN was a risk factor for failure. Although the authors fail to mention it in their study, prior reports of poorer healing rates with K-wire stabilization, when compared with other methods of fixation, have been published.^{63,64} More recently, Chang et al reviewed 49 patients who underwent dorsal pedicled VBG using the 1,2 ICSRA for scaphoid nonunion.⁶³ They found that nearly 30% (14 patients) had failed to heal and attempted

to correlate the failures with potential risk factors. Female gender, tobacco use, and proximal pole AVN were associated with poorer outcomes. In addition, the presence of a humpback deformity was higher in the patients that did not heal. Fractures fixed with K-wires alone also fared worse. Interestingly, the fracture location was not a factor in predicting outcome. In addition to the nonunion rates, the authors also noted a 16% complication rate including: infection, graft extrusion, and hardware failure.

In summary, scaphoid nonunion can be a challenging problem to the hand surgeon. A meta-analysis evaluating the treatments for scaphoid nonunion demonstrated significantly better success in achieving union with VBG (88%) versus traditional bone grafting (47%).⁶⁴ Although vascularized bone grafting has demonstrated promise in the treatment of scaphoid nonunion and AVN, we are still in the process of better defining the indications for this technique. Not all reports have been favorable. With improved prospective, randomized studies, we can better evaluate the usefulness of these grafts.

VASCULARIZED BONE GRAFTING IN THE MANAGEMENT OF KIENBÖCK'S DISEASE

Kienböck's disease is defined as avascular necrosis of the lunate bone. As the disease progresses, a predictable pattern of collapse and arthritis can occur.⁶⁵⁻⁶⁷ The cause and pathogenesis are not completely understood but are likely multifactorial. Anatomic, vascular, and traumatic factors have been implicated. Although somewhat debated, there appears to be a relationship between ulna minus variance and osteonecrosis of the lunate.^{68,69} The shortened ulna is thought to allow for increased forces and load transmission across the radiolunate joint.^{70,71}

The anatomy and blood supply of the lunate can be variable. Tsuge and Nakamura suggested a correlation between smaller lunate size and the development of Kienböck's disease.⁷² Most lunate bones have both a dorsal and volar blood supply.⁷³ However, intraosseous vascularity demonstrates a 20% incidence of a single nutrient artery and/or poorly organized intraosseous anastomoses, which may predispose patients to the development of avascular necrosis.⁷⁴ There is a relationship between repetitive microtrauma and fracture and the development of osteonecrosis. However, it is unclear as to whether it is a cause or effect. Investigators have noted that more than 80% of lunates with Kienböck's disease had fractures.^{65,75}

The natural history of Kienböck's disease is poorly understood partly due to the fact that there are so few studies examining benign neglect. Whereas most experts agree that lunate collapse and arthritis is inevitable, a clinical correlation is not absolute. One study examining 20 years average follow-up of conservatively treated

Kienböck's disease found that 80% had no pain or pain only with significant activity.⁶⁶ However, two thirds of the wrists developed radiographic evidence of arthritis. Another report on nonoperative treatment of Kienböck's disease determined that it was generally unsuccessful, with 60% of patients having persistent pain with 7 of 25 wrists requiring a change of occupation.⁷⁶

A staging system for Kienböck's disease was originally proposed by Stahl and based on anteroposterior radiographic findings.⁷⁷ This was later modified by Lichtman to include four stages and has become the most commonly used system for grading disease progression (Table 4).^{67,78} Despite flaws in quantifying collapse on plain films, the staging system is helpful in guiding treatment.

Multiple treatments for Kienböck's disease have been described. The decision of best treatment is based on several factors including stage of the disease, duration of patient symptoms, the patient's anatomy, and surgeon preference. Described treatment options have included immobilization, lunate excision/replacement, joint-leveling (unloading) procedures, radial osteotomy, capitate shortening, vascularized and nonvascular bone grafting, partial wrist arthrodesis, proximal row carpectomy, and complete wrist fusion.^{75,77,79-89} Partial wrist fusion, proximal row carpectomy, and complete wrist arthrodesis have been used for late-stage disease.⁹⁰ Unfortunately, many reports in the literature are retrospective, and it is somewhat difficult to determine the optimal treatment for varying stages of Kienböck's disease.

Traditional treatments for Kienböck's disease can be very effective. Joint-leveling procedures for patients with negative ulnar variance can reduce the loads across the radiolunate joint.^{86,87} Good results for stage 1 to 3 disease including improved pain, strength, and range of motion have been published with radial-shortening or ulnar-lengthening procedures.^{75,85,88,89,91} Increased nonunion rates have been associated with ulnar-lengthening procedures.⁷⁵ For patients with ulna neutral variance,

Table 4 Stahl-Lichtman⁶⁸ Classification for Kienböck's Disease

Stage 1	Plain radiograph: normal Bone scan: positive MRI: positive
Stage 2	Plain radiograph: Increased density of lunate without collapse
Stage 3	Lunate collapse with partial or complete sclerosis (a) proximal row remains aligned (b) proximal row becomes malaligned and destabilized
Stage 4	Lunate disintegrated, degenerative changes in the radiocarpal joint and/or midcarpal joint

lateral closing wedge osteotomies or partial wrist arthrodesis have been advocated.^{92–95} Both procedures have shown efficacy in unloading the lunate and improving patient outcomes.

Indications for Vascularized Bone Grafting for Kienböck's Disease

Vascularized bone grafting in the treatment of Kienböck's disease has gained popularity as a means to address the vascular insufficiency. A variety of donor sources have been suggested including the second dorsal metacarpal artery, a pedicled vascular pisiform, the pronator quadratus bone flap, select dorsal distal radius pedicled grafts, nonvascularized bone grafting with core revascularization, and free vascularized iliac crest bone grafting.^{3,96–109} Although indications continue to evolve, most surgeons would agree that VBG should be reserved for patients with intact cartilaginous shell and absence of degenerative changes. In addition to being a standalone procedure, vascularized bone grafts can be performed in conjunction with traditional treatments for Kienböck's disease.

Technique

Whereas multiple graft sources have been described, because it provides for a longer pedicle, our preference is to use the 4 + 5 ECA pedicle from the dorsal distal radius. The technique is summarized in Fig. 4. A dorsal longitudinal incision is used centered over the lunate and distal radius. The interval between the fourth and fifth extensor compartment is used to allow for exposure to the extensor compartment vessels. The fourth and fifth vessels are identified and ligated proximally where they communicate. The lunate is then cored-out in preparation for bone graft insertion. The appropriately sized graft is harvested and contoured to fill the defect. The cortical portion of the graft should structurally support the lunate to help prevent recurrent collapse.

The lunate is vulnerable to recurrent collapse during the revascularization process.¹¹⁰ Previous studies have demonstrated that early loading may be detrimental to the revascularization of the graft and the ongoing revascularization process.^{3,107,111–113} To minimize this potential problem, we prefer to unload it for 8 to 12 weeks after surgery. This can be achieved with either pinning of the scaphocapitate interval with two percutaneous 0.062-in. K-wires or with application of an external fixator across the wrist.

Outcomes of Vascularized Bone Grafts for Kienböck's Disease

Early reports of VBG for Kienböck's disease included the use of a scaphoid tubercle on an abductor pollicis

brevis muscle pedicle.⁹⁹ Braun later reviewed eight patients treated with pronator quadratus muscle–distal radius bone pedicle grafting and found that they all healed, and arrest of lunate collapse occurred in four wrists.³² Other early vascularization attempts have included the use of dorsal metacarpal artery pedicles.^{98,100,104} Hori et al reported eight of nine patients treated in this fashion had improvement using a dorsal metacarpal arteriovenous pedicle.⁹⁸ The authors noted radiographic and neovascularization and resolution of sclerosis. However, there also appeared to be possible further fragmentation of the lunate bone. Tamai et al reported that with use of an arteriovenous (AV) pedicle, a loss of carpal height was noted in 31% of wrists.¹⁰⁴ Bone grafting and core revascularization with an AV pedicle insertion has been described.⁹⁶ The surgeons performed 28 procedures with an average 6.7-year follow-up. All of the patients subjectively improved. Lunate collapse did progress in 15%, and there was only an average 4.7% loss of carpal height. Unfortunately, arthrosis did progress in 64% of cases. The authors concluded that AV pedicle implantation was not superior to VBG. Several authors have reported on the use of a vascularized pedicled pisiform for Kienböck's disease as well.^{101–103} Despite less than 2-year follow-up, these investigators generally reported overall good results. Daecke et al recently reexamined outcomes with a vascularized pisiform graft.¹⁰⁵ They evaluated 23 patients with an average 12-year follow-up. Pain improved in 20 patients, and patient outcome measures were favorable. Grip and range of motion also significantly improved. A joint-leveling procedure was also performed in patients with negative ulnar variance. Sixteen patients maintained their lunate height. Among 20 patients with follow-up x-rays, the Lichtman stage in 11 remained unchanged, improved in 3, and worsened in 6. Seven patients had evidence of arthritis. The authors concluded that long-term outcomes of pisiform VBG provided good patient satisfaction and functional outcomes.

Like treatment for scaphoid nonunion, applications of dorsal distal radius pedicled grafts have gained popularity over the past decade.^{107,108,114} Technically, the dorsal approach and harvesting of the distal radius bone graft is less demanding than are some of the previously mentioned techniques. As previously mentioned, our preferred graft is the 4 + 5 ECA vessels. Retrograde flow of the fifth ECA is directed in an orthogonal direction into the fourth ECA after ligation of the posterior branch of the anterior interosseous artery. Overall, this allows for a longer and larger-diameter pedicle. In addition, the relatively ulnar location of the vessel allows for arthrotomy to access the lunate with less risk of injury to the pedicle. Moran et al published encouraging outcomes using this technique.¹⁰⁷ The authors examined

Figure 4 Vascular bone grafting procedure with 4 + 5 ECA vessels. (A) After a longitudinal incision centered over the lunate and distal radius, the interval between the fourth and fifth compartments is used. (From Shin AY, Bishop AT, Berger RA. Vascularized pedicled bone grafts for disorders of the carpus. *Tech Hand Upper Extrem Surg* 1998;2:94–109, Fig. 21. Figure used with permission.) (B) The fifth extensor compartment artery (ECA) is identified and traced proximally to its origin from the anterior interosseous artery. (From Shin AY, Bishop AT, Berger RA. Vascularized pedicled bone grafts for disorders of the carpus. *Tech Hand Upper Extrem Surg* 1998;2:94–109, Fig. 22. Figure used with permission.) (C) A ligament sparing capsulotomy is performed to expose the carpus. (From Shin AY, Bishop AT, Berger RA. Vascularized pedicled bone grafts for disorders of the carpus. *Tech Hand Upper Extrem Surg* 1998;2:94–109, Fig. 23. Figure used with permission.)

Figure 4 (Continued) (D) This schematic demonstrates the technique of preparing the lunate for VBG. Necrotic bone is removed using a burr or curette while leaving the shell intact. (From Shin AY, Bishop AT, Berger RA. Vascularized pedicled bone grafts for disorders of the carpus. *Tech Hand Upper Extrem Surg* 1998;2:94–109, Fig. 24. Figure used with permission.) (E) The appropriately sized bone graft is then raised and set into the lunare bone defect. The cortical strut is oriented in a proximal to distal direction to help prevent collapse. (From Shin AY, Bishop AT, Berger RA. Vascularized pedicled bone grafts for disorders of the carpus. *Tech Hand Upper Extrem Surg* 1998;2:94–109, Fig. 25. Figure used with permission.)

26 patients treated with this method with an average 31-month follow-up. Pain relief was accomplished in 92% of the wrists. There was also a significant increase in grip strength from 50% of the contralateral extremity to 89%. Only 23% of patients had radiographic evidence of continued collapse of the lunate after surgery. Follow-up magnetic resonance imaging (MRI) was performed at an average 20 months after surgery on 17 wrists, and 71% of them had evidence of revascularization. Two patients were deemed failures and underwent total wrist arthroplasty.

Unfortunately, few good comparison studies are published comparing types of vascularized bone grafting for Kienböck's disease. Moran et al reviewed 48 patients with vascularized bone grafting from a variety of volar and dorsal aspects of the wrist.¹⁰⁶ Evaluation revealed no significant differences in objective or subjective outcomes between types of grafting. Pain improved in nearly all (98%) of the patients. Grip significantly improved, whereas there was no significant improvement in range of motion. Radiographic evidence of revascularization was noted in ~60% of lunates, and revascularization did correlate with improved patient outcome measures.

In summary, vascularized bone grafting compares favorably with existing treatments for treatment of precollapse Kienböck's disease. Overall patient satisfaction is good with generally improved functional parameters. The technique can be used in conjunction with established procedures such as joint-leveling surgeries. With improved studies, better understanding of its role in the treatment of Kienböck's disease can be achieved. Although there does not appear to be clear evidence of the superiority of one type of grafting over another, the

dorsal distal radius grafts, specifically 4 + 5 ECA, are technically feasible and remain our preference.

VASCULARIZED BONE GRAFTING IN THE MANAGEMENT OF PREISER'S DISEASE

Preiser's disease is defined as osteonecrosis of the scaphoid that is not related to prior fracture or nonunion. Its incidence is much less common than is Kienböck's disease. The etiology may be traumatic or atraumatic. Although there is no universally accepted etiologic theory, it is thought to be due to a disruption in the vascular supply to the scaphoid.^{41,42,115} Reported associated risk factors have included corticosteroid use, microtrauma, terminal vessel occlusion, progressive systemic sclerosis, scaphoid hypoplasia, and systemic lupus erythematosus.^{116–124} An etiologic classification has been proposed that includes (1) traumatic, (2) systemic, (3) congenital, and (4) idiopathic.¹²³

Herbert and Lanzetta proposed a radiographic classification system that is illustrated in Table 5.

Table 5 The Herbert⁵² Classification for Stages of Preiser's Disease

Stage 1	Plain radiograph: normal Bone Scan: positive MRI: positive
Stage 2	Plain radiograph: Increased density of proximal pole; generalized osteoporosis
Stage 3	Fragmentation of the proximal pole with or without pathologic fracture
Stage 4	Carpal collapse; osteoarthritis

Radiographic presentation is similar to that of lunate osteonecrosis. In early disease, plain radiographs are normal. MRI and bone scan are more sensitive in detecting marrow changes consistent with AVN. As the disease progresses, sclerosis of the scaphoid develops. This is followed by fragmentation, collapse, and subsequent arthritis.¹²³

The treatment of Preiser's disease remains controversial. In part, the treatment is based on the stage of disease. Because there are so few reported cases of Preiser's disease and its treatment, little can be concluded about the optimal treatment. Treatments for early disease have included immobilization,^{123,125} drilling of the proximal pole,¹²³ arthroscopic debridement¹²⁶ and vascularized bone grafting,^{98,127} excision of part or all of the scaphoid with and without silicone replacement,¹²⁸ and radial osteotomy.¹²⁸ For cases involving fragmentation, collapse, and arthritis, reported treatments include excision and replacement,^{128,129} limited carpal arthrodesis and scaphoidectomy,¹³⁰ proximal row carpectomy,^{116,122} and complete wrist fusion.¹²³ Scaphoid salvage may be attempted in early disease and is predicated on an intact cartilaginous shell and lack of significant arthritic changes at the radiocarpal and midcarpal joints.

Indications for Vascularized Bone Grafting for Preiser's Disease and Technique

Although the indications continue to evolve, we currently restrict the use of VBG in the treatment of scaphoid osteonecrosis to patients with early-stage disease (Herbert¹²⁸ stage I or II) and in patients without signs of radiocarpal arthritis and no evidence of carpal instability. The technique is similar to that described for the treatment of scaphoid nonunion. We prefer the use of the 1,2 ICSRA pedicled graft. If evidence of radiocarpal arthritis is detected at the time of surgery, it may be reasonable to consider a salvage procedure such as a scaphoidectomy and four-corner arthrodesis or proximal row carpectomy. Treatment of Preiser's disease with a VBG is technically more demanding in that it is often difficult to remove all of the necrotic bone without injuring the cartilage shell. Large bone grafts are typically necessary to fill the bony defect. Because of more extensive dissection to visualize the disease and fill the defect, the patients tend to be immobilized for longer periods of time after surgery (average 2 to 3 months). Thus, it is not unusual for patients to have resultant limited range of motion. Unloading the scaphoid after VBG remains somewhat debated. The indication would be similar to the reasons described for Kienböck's disease. However, no proven benefit to using external fixation postoperatively has been demonstrated.^{131,132}

Outcomes of Vascularized Bone Grafting for Preiser's Disease

There is no universally accepted choice for VBG donor site in the treatment of Preiser's disease. In the early 1980s, Braun reported use of a pedicled bone graft from the palmar portion of the radius for revascularization of the scaphoid with good results.³² Kawanishi et al also reported two cases of vascularized bundle implantation for the treatment of Preiser's disease also with good results.¹³³

Kalainov presented a series of 19 patients with Preiser's disease, 9 of which underwent vascularized grafting.¹³¹ The authors proposed two different types of patients based on MRI findings. Type I patients had global ischemia of the scaphoid. In type II disease, the patients had more localized proximal pole ischemia. Patients with type II disease had better overall outcomes; Modified Mayo Wrist scores were 86 compared with 50 in the type I patients. All patients with type I Preiser's disease went on to experience fragmentation and collapse of the scaphoid regardless of treatment.

Moran et al reviewed the Mayo Clinic experience with eight patients who underwent vascularized bone grafting for the treatment of Preiser's disease.¹³² The average follow-up period was 36 months. MRI demonstrated involvement of the entire scaphoid in all patients. Postoperative grip and motion were limited compared with those of the unaffected extremity. Functional outcomes were adequate and somewhat better than those of previous reports.^{122,128,131} Although pain significantly improved, it did not resolve. To date, no patient has required salvage procedures. Postoperative MRI evaluation did show marrow changes consistent with revascularization, but this was typically incomplete.

In summary, Preiser's disease is fortunately less common than is Kienböck's disease and osteonecrosis of the scaphoid associated with fracture or nonunion. Outcomes with VBG for the management of this difficult problem have shown some promise compared with traditional treatment options. Whereas revascularization after VBG appears to occur, patient outcomes are not as predictable.

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