Received: 17 May 2017 | Revised: 2 July 2017 | Accepted: 25 August 2017
DOI: 10.1002/micr.30233

RESEARCH ARTICLE

WILEY MICROSURGERY

Vascularized thumb metacarpal periosteal pedicled flap for scaphoid nonunion: An anatomical study and pediatric case report

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Funding information
This research received no specific grants from any funding agency in the public, commercial, or not-for-profit sectors.

Confidentiality: The authors declare that patient confidentiality was maintained throughout the duration of this study and afterwards.

Vascularized Thumb Metacarpal Periosteal Pedicled Flap for Scaphoid Nonunion: An Anatomical Study and Pediatric Case Report.

Purpose: Through an anatomical review, the primary aim of this study was to delineate the dorsal thumb metacarpal (TM) periosteal branches of the radial artery (RA). In addition, we report here the clinical utility of a vascularized TM periosteal pedicled flap (VTMPF), supplied by the first dorsal metacarpal artery (FDMA), in a complex case of scaphoid nonunion.

Methods: Ten latex-colored upper limbs from fresh human cadavers were used. Branches of the RA were dissected under 3x loupe magnification, noting the periosteal branches arising from the FDMA. The VTMPF was measured for both length (cm) and width (cm).

Results: The FDMA provided a mean 12 periosteal branches (range 9 to 15), with a mean distance between branches of 0.5 cm (range 0.2–1.1), allowing for the design of a VTMPF which measured a mean 4 cm in length and 1.2 cm in width. We used a VTMPF to treat recalcitrant scaphoid nonunion, with a volar defect of 0.7 cm, in a 16-year-old boy. No bone graft was used. The patient experienced no postoperative complications. Successful consolidation was achieved three months after surgery, confirming the flap's survival. At 14-months of postoperative follow-up, the patient's VAS pain rating was 0 out of 100, and his DASH questionnaire score was 5. The patient had painless range that was 95% that of the contralateral limb. The patient's pinch and grip strengths were 6.5 kg and 28 kg, respectively (95% of unaffected side).

Conclusions: VTMPF may be considered a valuable and reliable surgical option for scaphoid nonunion in complex clinical scenarios.

To whom it may concern: we, the authors of this article, hereby state that no part of the work has either been submitted for publication or published elsewhere. We also state that the content of this article has been reviewed and approved by all the authors, in full belief that it has been written honestly and without plagiarism.

1 | INTRODUCTION

Though most pediatric scaphoid fractures have a good prognosis with conservative management (Weber, Fricker, & Ramseier, 2009), scaphoid nonunion has been reported (Ahmed, Ashton, Tay, & Porter,

TABLE 1 Anatomical study of dorsal thumb metacarpal periosteal branches based on radial artery

		Periosteal Branches		Septocutaneous Perforator Branches		Muscular Branches	
		FDMA	RB of FDIA	FDMA	RB of FDIA	FDMA	RB of FDIA
Number	Mean	12	5	3	2	6	6
	Range	9–15	4–7	2–4	1–3	5–7	5–8
Distance between branches (cm)	Mean	0.6	0.7	1.4	2.4	0.9	0.8
	Range	0.2–1.1	0.2–1.2	0.8–1.8	2.1–4.3	0.7–1.2	0.6–0.9
Distribution (Number)	Radial	Mean: 9	Mean: 3			Abductor Pollicis Brevis Muscle	First Dorsal Interosseous Muscle
		Range: 7–12	Range: 2–4				
	Ulnar	Mean: 3	Mean: 2				
		Range: 2–5	Range: 1–3				

FDMA: First Dorsal Metacarpal Artery.
RB of FDIA: Radial Branch of First Dorsal Intercarpal Artery.

2014; Behr et al., 2014; Elhassan & Shin, 2006; Reigstad, Thorkildsen, Grimsgaard, Reigstad, & Rokkum, 2013). Since this lesion is a rarity, however—with a nonunion rate of just 0.8% (Elhassan & Shin, 2006)—management experience is limited and optimal treatment remains controversial (Elhassan & Shin, 2006). Available treatment options include cast immobilization, bone grafting with K-wire fixation, bone grafting without osteosynthesis, headless compression screw fixation with or without bone grafting, and vascularized bone grafting (Ahmed et al., 2014; Behr et al., 2014; Chloros et al., 2007; Elhassan & Shin, 2006; Hamdi & Khelifi, 2011; Reigstad et al., 2013; Weber et al., 2009).

Vascularized periosteal flaps have gained special attention in reconstructive surgery, because of how effective they are at promoting healing when used to treat complex bone nonunion in pediatric patients, owing to their high angiogenic and osteogenic potentials (Qi et al., 2008; Soldado et al., 2012, 2015). We anatomically studied how the radial artery (RA) vascularizes the thumb metacarpal (TM) periosteum to assess the potential for developing a new vascularized periosteal flap to manage selected cases of pediatric scaphoid nonunion. We sought a technique that was less technically demanding and associated with less donor-site morbidity than prior techniques. We also sought a procedure that would be distinct from what has been described previously for scaphoid nonunion treated with vascularized TM bone flaps supplied by the FDMA, as previously described by Bertelli, Tacca, and Rost (2004). Afterwards, we used this vascularized TM periosteal pedicled flap (VTMPF) successfully to reconstruct recalcitrant nonunion of the scaphoid in a 16-year-old boy in the context of avascular necrosis of the proximal pole and nonunion that had persisted for more than four years.

2 | MATERIALS AND METHODS

For this study, 10 upper limbs (5 right and 5 left) from fresh adult human cadavers were used (mean age 72 years). In all specimens, we performed anterograde arterial injection of colored natural latex through the brachial artery at the level of the elbow. The branches of the radial artery were dissected under 3× loupe magnification, noting the muscular, the cutaneous and the periosteal branches arising from the radial artery to the dorsal aspect of the thumb metacarpal (TM). Also noted were the distance (in centimeters, cm) between the periosteal branches and the base of TM, and the distribution of the branches (medial/lateral). The VTMPF was measured for length (cm) and width (cm).

3 | RESULTS

The anatomical findings are summarized in Table 1. The RA was located running from volar to dorsal in the anatomical snuffbox, proximal to the trapeziometacarpal joint, under the insertion of the abductor pollicis longus (APL) and extensor pollicis brevis (EPB) tendons. Two arteries were identified in all dissections, stemming from the radial artery and reaching the dorsal aspect of the TM. The first of them—named the first dorsal metacarpal artery (FDMA) (Bertelli et al., 2004)—emerged a mean 2 mm (range 1–3 mm) ulnar to the APL, traversing under the APL from the ulnar to radial side at the base of the TM as it ran along the radial aspect of the insertion of the APL tendon, over the fascial layer of the abductor pollicis brevis (APB) muscle. The FDMA, which averaged 1 mm in diameter at the base of the TM and a mean length of 0.52 cm (range 0.44 to 0.61 cm), ran along the dorsal aspect of the insertion of the APL tendon. The artery then continued its course along the volar third of the dorsal side of the TM, in close contact with the periosteum. The FDMA reached the radial side of the metacarpal head and, at this level, anastomosed with the radial palmar collateral artery of the thumb. The FDMA gave off a mean 12 periosteal branches (range 9 to 15), with a mean distance of 0.6 cm between these branches (range 0.2 to 1.1 cm) and a mean length of 6 mm (range 4 to 8 mm). Of these periosteal branches, roughly 75% were radial, while 25% were ulnar. Both of the more distal branches ran in a radial direction in 100% of the dissections. The FDMA primarily provided a mean six muscular branches (range 5 to 7) to the APB muscle. There was a mean of three cutaneous branches (range 2 to 4). One of these

FIGURE 1 Dissection of the posterior compartment of thumb metacarpal (TM). Periosteal branches originating in the radial artery (#) between the APL () and ECRL () muscles were found running transversely across the periosteum of the dorsal aspect of the TM (*). Detail of the periosteal branches arising from the FDMA (white arrow) and RB of the FDIA (black arrow) to the TM (*). (**) Second metacarpal. (<>) First dorsal interosseous muscle

three arose at the level of the base of the TM (proximal or distal to the EPB tendon); another at the level of the middle third of the TM (2 to 3 cm from the metacarpophalangeal joint), and a third at the level of the distal third of the TM.

The second artery, named the radial branch (RB) of the first dorsal intermetacarpal artery (FDIA) (Bertelli et al., 2004), arose from the RA a mean 13 mm (range 11 to 16 mm) distal to the FDMA. The RB of the FDIA, which averaged 0.8 mm in diameter and a mean length of 0.41 cm (range 0.36 to 0.48 cm), traversed under the EPL at the base of the TM as it ran along the ulnar aspect of the dorsal side of the TM. The artery then continued its course along the ulnar third of the dorsal side of the TM. The RB of the FDIA reached the ulnar side of the metacarpal head and ended as an axial vessel, which continued as the ulnar collateral dorsal artery. There were a mean five periosteal branches (range 4 to 7), with a mean distance of 0.7 cm between branches (range 0.2 to 1.1 cm) and a mean length of 5 mm (range 4 to 6 mm). Of these five, three generally were radial (60%) and two ulnar (40%). In all of the dissections, the more proximal periosteal branch had a radial direction, running over the insertion of the APL tendon until it anastomosed with the first dorsal metacarpal artery (FDMA)—proximally at the base of TM, and distally at the head of the TM to form a vascular arch (Figure 1). There were a mean six muscular branches from the RB of the FDIA (range 4 to 9) to the first dorsal interosseous muscle (range 5 to 8). In five of the dissections, cutaneous perforating branches were located near the head of the TM and the junction of the proximal and middle thirds of the TM.

Each of these arteries was accompanied by a vein along its entire course. The periosteal branches from the FDMA and the RB of the

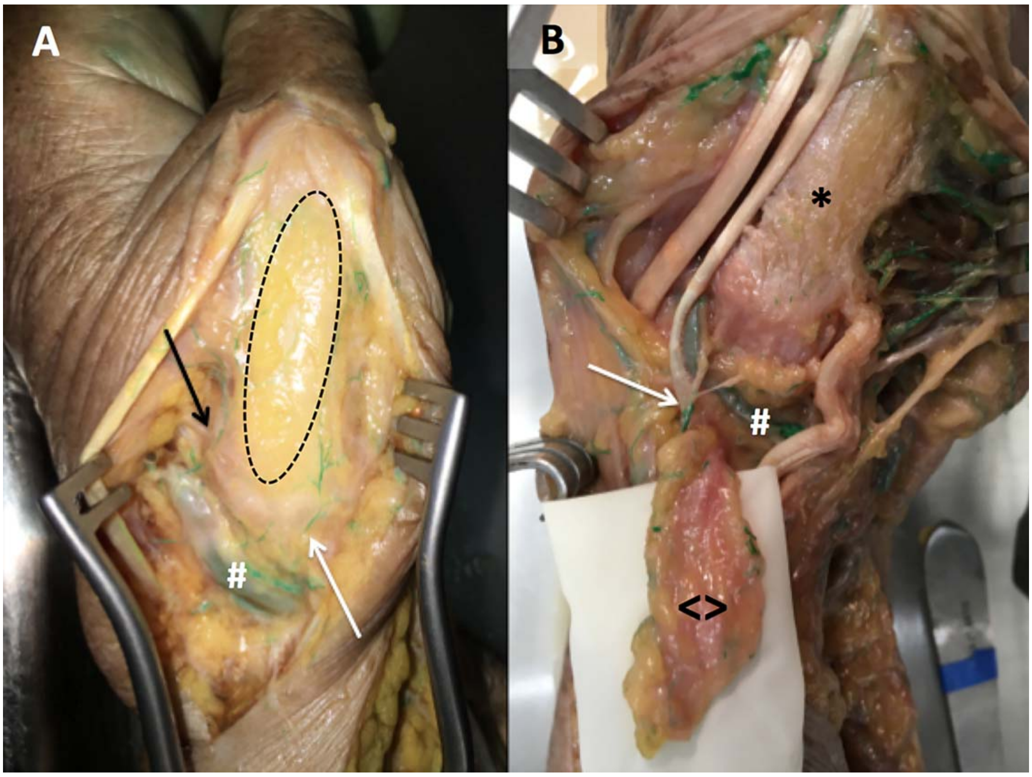

FIGURE 2 A: Before harvesting, showing the vascularized TM periosteal pedicled flap (VTMPF) (black oval) supplied by the FDMA (white arrow) and the RB of the FDIA (black arrow). B: After harvesting the VTMPF (<>) from the TM (*), it was designed to be a pedicled flap in an anterograde fashion. (#) Radial artery

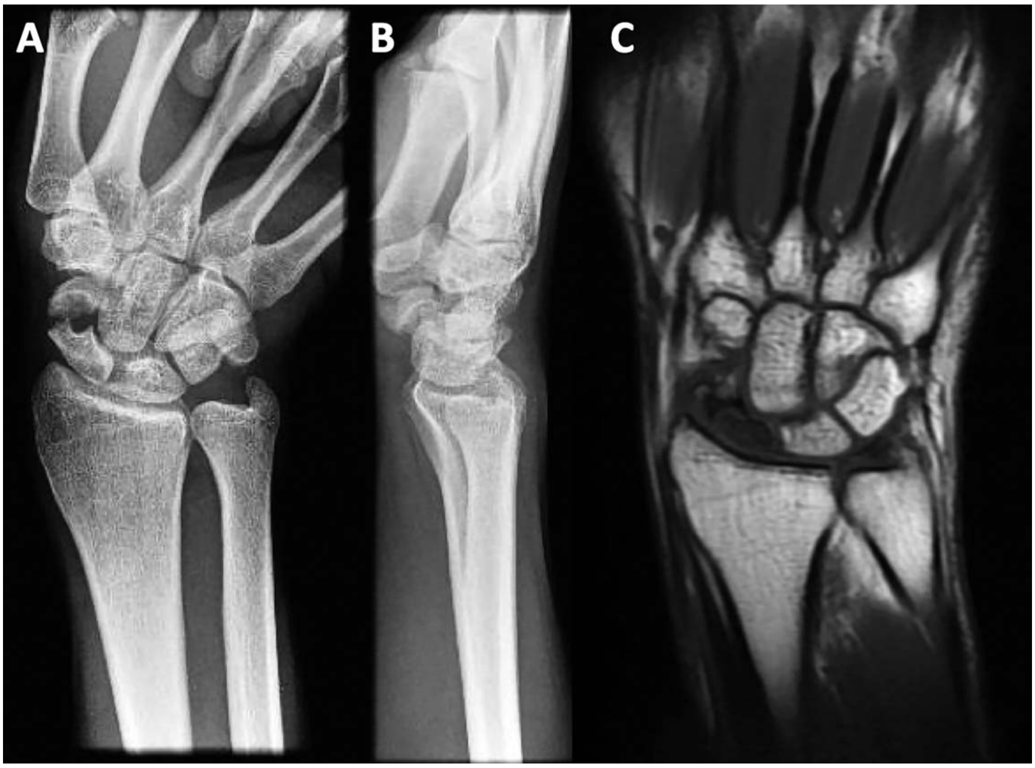

FIGURE 3 (A) Anteroposterior and (B) lateral radiographs and (C) a coronal MR image at four years of follow-up, showing recalcitrant nonunion and avascular necrosis of the scaphoid

FDIA anastomosed in the superficial layer of the dorsal periosteum, forming a vascular network.

The proposed periosteal graft was harvested from the complete dorsal aspect of the TM, producing a pedicle that had a minimum length of approximately 15 mm (range 12 to 17 mm). Alternatively, the graft could be harvested partially at the distal side of the thumb; in this latter case, the pedicle was larger, up to a length of approximately 40 mm (range 36 to 44 mm). Before harvesting, the mean size of the flap was 12 cm^2 (range 10.8 to 14 cm^2). The periosteal flap measured a mean 6 cm in length (range 5.5 to 6.4 cm) and 2 cm in width (range 1.8 to 2.2 cm). After harvesting, the mean two-dimensional area of the flap was 10.5 cm^2 (range 8.5 to 12.6 cm^2) due to elastic retraction (Figure 2).

4 | CASE REPORT

A 16-year-old, right-handed boy was examined after sustaining a fall onto his right wrist. Four years prior to presenting to us, due a scaphoid fracture B2 (as prescribed by Filan & Herbert, 1996), the patient had undergone fixation of the scaphoid with a retrograde headless compression screw. Three years after that first surgery, the patient underwent corticocancellous bone grafting from the distal radius, fixed with two 2 mm Kirschner-wires for scaphoid nonunion D3[12]. When the patient presented to us, one year after his second surgery, radiographs and magnetic resonance imaging (MRI) showed recalcitrant nonunion D4[12] of the fracture localized in the middle third of the scaphoid, with a scapholunate angle of 70 degrees and avascular necrosis of the proximal pole (Figure 3). On a 10 cm visual analog scale (VAS), the patient rated his pain as 8, and had a quick DASH (Disabilities of the Arm, Shoulder and Hand) score of 68. The patient's range of movement included 30° and 40° of wrist flexion and extension, 20 and 10° of pronation and supination, and 10° and 5° of radial and ulnar deviation, respectively. Grip strength was 30% that of the opposite hand.

Nonunion was exposed using a volar approach. Sclerotic bone was debrided and excised at the nonunion site. A maneuver in accordance with that described by Lynch and Linscheid (1997) was performed. Humpback deformity was corrected, and the scapholunate angle and the scaphoid length were improved from 70° to 55° and from 20 mm to 23 mm (1 mm of difference with contralateral scaphoid), creating a volar defect of 7 mm at the nonunion site. This bone correction was stabilized with two retrograde 2 mm headless compression screws (Extremifix Cannulated Screw System^{TM}, OsteoMed©, Dallas, Texas, USA). As no bone graft was added to the nonunion site and a volar defect was created, the goal of the screw was to maintain and stabilize the reduction, without compression of the nonunion to not collapse or flexion the scaphoid. We putted a bone spreader in the nonunion site during the insertion of the screws to avoid the flexion of the scaphoid. Finally, the VTMPF was harvested through a separate incision over the TM. Periosteal flap vascularization was from the FDMA, and was constructed in an anterograde direction (Figure 4).

The harvesting technique we employed for the VTMPF adhered to most of the standard steps used to obtain a TM vascularized bone graft (Bertelli et al., 2004). This longitudinal skin incision ran from the dorsal

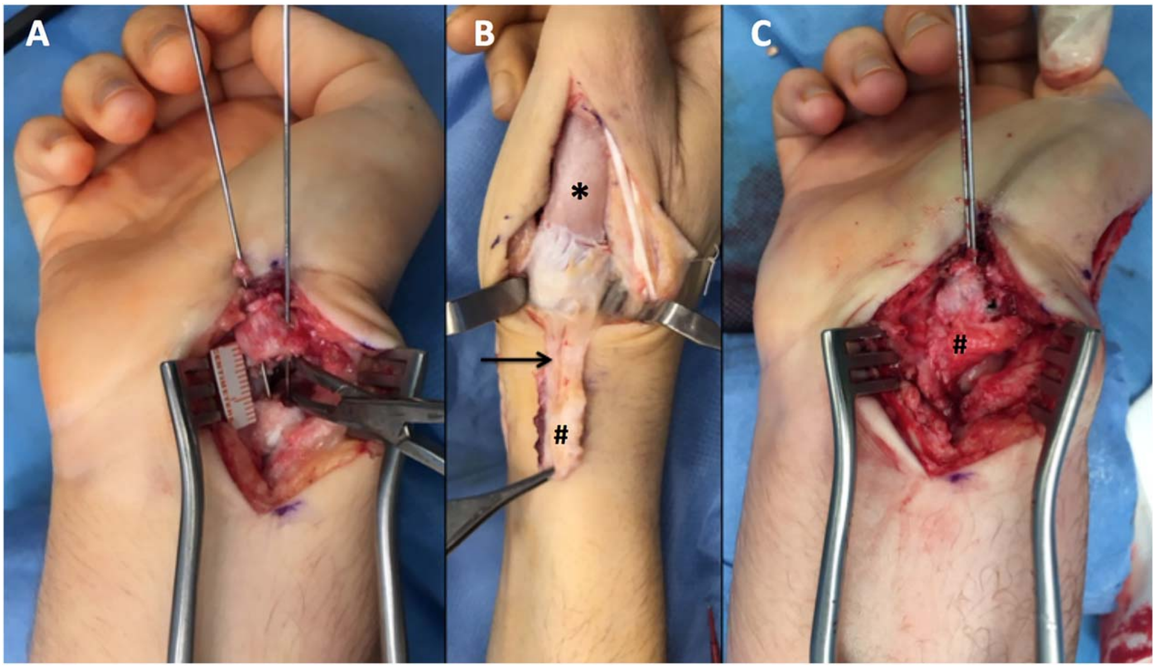

FIGURE 4 Scaphoid reconstruction. (A): Volar scaphoid approach to expose bone nonunion creating a volar defect. (B): VTMPF (#) after detachment from the TM, with previous transfer to the scaphoid. (Black arrow) FDMA. (C): Correction and fixation of scaphoid nonunion with two headless compression screws, and transversal placement of the flap (#) to bridge the nonunion

side of the thumb metacarpophalangeal joint to a point midway between the extensor pollicis longus (EPL) and EPB within the anatomical snuffbox. The skin was incised and the EPB tendon sheath opened and retracted in an ulnar direction. This exposed the FDMA and the RB of the FDIA and their branches to the TM's periosteum. Along their respective courses, cutaneous and muscular branches of the FDMA and the RB of the FDIA were ligated, and the vessels then followed into the metacarpal head. At this location, and in accordance with the measures of the slot created in the scaphoid, a rectangular periosteal graft was designed that was centered on the FDMA. The lateral border of the flap overlying the APB was then incised and the pedicle within the periosteal dissected from the dorsal side of the TM, in a rectangular shape, to the level of the first metacarpal neck. The periosteal flap was elevated from distal to proximal using a periosteal elevator. Finally, proximal release of the periosteum at the level of the metacarpal midshaft was performed. The proximal vascular pedicle was then released from the base of the TM to the trapeziometacarpal joint capsule. Then an intraoperative assessment to ensure the blood supply of the periosteal flap was performed. A tunnel down to the tendons of the first dorsal compartment was created. The VTMPF then was pushed in a palmar direction toward the scaphoid nonunion. The vascular pedicle lay radial, while the VTMPF was placed transversally over the nonunion and sutured to adjacent soft tissues. The vascular pedicle then was inspected to detect any kinking, compression, or tension. The capsular flaps were approximated loosely and the subcutaneous layer and skin sutured. The length and width of the flap before detachment were 2.5 cm and 1.8 cm, respectively, and 2 cm and 1.4 cm after harvesting. A below the elbow plaster cast was applied, but removed three weeks postoperatively, after which the patient underwent daily physiotherapy to enhance his wrist and thumb range of motion.

Periosteal callus ossification was initially observed four weeks after surgery. A nonunion junction was achieved at three months, completely filling the volar defect. The patient developed volar and radial scaphoid exophytic ossification that did not impinge upon either the radial styloid or radiocarpal joint (Figure 5).

Fourteen months postoperatively, the nonunion had united both clinically and radiologically. The patient's VAS pain rating was 0, and his quick DASH score was 5. The patient also had painless range of motion that was 95% that of the contralateral limb. The limits of active wrist range of motion were 80° flexion, 70° extension, 15° radial deviation, and 30° ulnar deviation. The patient's pinch and grip strength were 6.5 kg and 28 kg, respectively, which equaled 95% of the strength of unaffected hand. The patient had resumed all his usual daily activities.

5 | DISCUSSION

In this paper, we have described the anatomy of dorsal TM periosteal branches of the RA, allowing to designed a novel pedicled periosteal flap, harvested from the dorsum of the TM using the first dorsal metacarpal vessels' axis. The VTMPF was successful at achieving bone consolidation in a patient with recalcitrant scaphoid nonunion.

The vascular blood supply of the dorsal side of the thumb was constant in all our dissections, in agreement with previous anatomic studies (Bertelli, Pagliei, & Lassau, 1992; Brunelli, Brunelli, & Nanfito, 1991; Pistre, Pelissier, Martin, & Baudet, 2001). However, limited information exists regarding the dorsal TM periosteal branches. The FDMA

FIGURE 5 Radiographic evolution after the VTMPF. (A) Anteroposterior, (B) contralateral wrist and (C) lateral radiographs; and (D) coronal and (E) sagittal computed tomography (CT) images at at 6-months of follow-up, revealing a nonunion junction and volar and radial scaphoid exophytic ossification (white arrows)

axis has been described as a means by which to obtain TM bone flaps (Bertelli et al., 1992; Brunelli et al., 1991; Pistre et al., 2001). Our procedure is similar to what has been described previously for adult patients in whom scaphoid nonunion was treated with vascularized TM bone flaps supplied by the FDMA (Bertelli et al., 1992; Yuceturk, Isiklar, Tuncay, & Tandogan, 1997). Our technique might be considered a modification of the previous one that has been adapted for the pediatric population, focusing solely on periosteum rather than bone. The rationale for this change is that a vascularized periosteal flap yields faster consolidation than a vascularized bone flap (Yuceturk et al., 1997). This can be explained by the abundance of osteogenic stem cells located within the cambium layer (Finley, Wood, & Acland, 1979; Soldado et al., 2012a,b). The cambium layer, in intimate contact with both the nonunion focus and the poorly-vascularized surrounding tissues, may induce healing more efficiently than a vascularized bone graft (Soldado et al., 2012c,2015,2017).

Contrary to Bertelli et al. (1992) and Pistre et al. (2001) who reported that small osteoperiosteal branches of the FDMA were present only at the levels of the proximal and distal thirds of the TM, we found a vascular network formed between the periosteal branches from the FDTA and the RB of the FDIA, which supplied the complete dorsal aspect of the TM. This finding increases the versatility of the VTMPF, as it facilitates custom sizing and location harvesting. Another important consideration concerning vascularized bone grafts raised in and around the wrist, is their fragility and susceptibility to trauma during tailoring and manipulation (Steinmann & Bishop, 2001; Straw, Davis, & Dias, 2002). However, this may be avoided because the VTMPF allows for the inclusion of a different vascular axis (FDMA and RB of the FDIA), increasing the reliability of the periosteal flap. Furthermore, because of its versatility, the VTMPF can be transferred in either a palmar or dorsal direction, whichever is required by the surgeon (Bertelli et al., 2004). In addition, according to results reported previously (Pistre et al., 2001), with regard to the number and distribution of cutaneous branches arising from the FMDA, a composite periosteocutaneous flap could be used in the same way. The skin paddle should be located either on the proximal or the distal part of the TM, because cutaneous branches are present at this level. Finally, as with any FDMA axis flap (Bertelli et al., 2004; Yuceturk et al., 1997), the VTMPF can be raised in either an anterograde or retrograde fashion (Pistre et al., 2001).

Using a FDMA pedicle graft requires separate incisions to accomplish periosteal harvesting and scaphoid treating. This is inconvenient, relative to a 1,2 intercompartmental supraretinacular artery pedicle graft (Straw et al., 2002), but is of great advantage in multi-surgery cases like the one reported here. Like our own patient, none of the patients in the Bertelli et al.series expressed any donor site complaints (Bertelli et al., 2004).

Several vascularized periosteal graft techniques have been reported recently as reliable techniques to enhance bone union in particularly-unfavorable scenarios in children (Diaz-Gallardo et al., 2017; Finley et al., 1979; Qi et al., 2008; Soldado et al., 2012a,b, c2012c,2015,2017), with excellent results treating bone nonunion (Diaz-Gallardo et al., 2017; Finley et al., 1979; Qi et al., 2008; Soldado et al., 2012a,b,c,2015,2017; Yuceturk et al., 1997). Vascularized periosteal grafts are easy and quick to harvest at this young age, and the flap's elasticity permits it to readily conform to the recipient's bed configuration (Finley et al., 1979; Soldado et al., 2012a,b,2017). Previous vascularized periosteal grafts reported for the treatment of recalcitrant nonunion did not require nonunion-focused bone grafting, as was true in our case (Finley et al., 1979; Qi et al., 2008; Soldado et al., 2012a, b2012b,2015,2017). With stable internal screw fixation, scaphoid waist nonunion with collapse and bone loss can be treated successfully using only a cancellous bone graft (Cohen, Jupiter, Fallahi, & Shukla, 2013). One potential disadvantage of a VTMPF without a corticocancellous bone graft for scaphoid nonunion might be the risk of scaphoid collapse. To decrease this risk and provide superior biomechanical stability of the construct, we performed the fixation with two headless compression screws (Garcia, Leversedge, Aldridge, Richard, & Ruch, 2014). This rigid fixation allowed the patient to initiate rehabilitation after only three weeks of immobilization, so that the patient attained 90% of the contralateral wrist's range of movement within two months of surgery. Advantages include the marked simplification of surgical carpentry and the rapid periosteal callus than can fill the bone gap that eventually evolves into a cortical union without compromising scaphoid reduction or carpal alignment.

We disregarded nonbiological surgical techniques (Reigstad et al., 2013) and opted for a vascularized procedure, owing to our patient's grave clinical scenario (nonunion D4[12]), which was characterized by both avascular necrosis of the proximal pole and nonunion that had persisted beyond four years, both significant predictors of a poor functional outcome (Bae, Gholson, Zurakowski, & Waters, 2016; Moon, Dy, Derman, Vance, & Carlson, 2013. This condition required both angiogenic and vascular resources (Bae et al., 2016; Moon et al., 2013; Sunagawa, Bishop, & Muramatsu, 2000).

Alternative biological procedures might include a free vascularized periosteal or bone graft (Bürger, Windhofer, Gaggl, & Higgins, 2013). However, a local pedicled vascularized periosteal flap offers several advantages over a free flap for complex scaphoid nonunion. These advantages include less donor-site morbidity; an operative field that is limited to one upper extremity; there being no need to sacrifice either of the main vascular axes (Bertelli et al., 2004; Brunelli et al., 1991; Pistre et al., 2001; Straw et al., 2002; Steinmann & Bishop, 2001; Yuceturk et al., 1997); and, finally, being a technically less demanding and shorter procedure. Other local reconstructive options include a pedicled dorsal distal radius bone graft supplied by the dorsal vasculature of the wrist, which in turn include the 1,2 inter-compartmental supraretinacular artery (1,2 ICSRA), the 2,3 ICSRA, the fourth extensor compartment artery (fourth ECA), the fifth ECA, and the 4–5 ECA combination (Derby et al., 2013; Steinmann & Bishop, 2001; Straw et al., 2002); but these options all were disregarded for the present case because we needed to correct the scaphoid humpback deformity in a palmar direction, and because the distal radius growth plate was adjacent. We also disregarded the option of a vascularized bone graft pedicled on the transverse volar carpal artery, because the patient had previously had an autograft, with the volar aspect of the distal radius used as the donor site.

Regardless of the limitations inherent in a single case report, we feel that the technique we have just described can be used successfully to manage selected cases of scaphoid nonunion with a bone gap. The VTMPF we have described is an attractive alternative to conventional nonvascularized and free vascularized bone/periosteal grafting procedures to treat this difficult condition in children and adolescents.

CONFLICT OF INTEREST

Neither the authors, their immediate family, nor any research foundation with which they are affiliated have received any financial payments or other benefits from any commercial entity related to the subject of this article.

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How to cite this article: Barrera-Ochoa S, Mendez-Sanchez G, Rodriguez-Baeza A, Knörr J, Bertelli JA, Soldado F. Vascularized thumb metacarpal periosteal pedicled flap for scaphoid nonunion: An anatomical study and pediatric case report. *Microsurgery*. 2017;00:000–000. https://doi.org/10.1002/micr.30233