An Algorithm for Forefoot Reconstruction With the Innervated Free Medial Plantar Flap

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Background: Because of shearing forces, the forefoot is more prone to trophic ulcers than the heel. Reconstruction of trophic ulcers and other forefoot defects is a vexing challenge. We favor the innervated free medial plantar flap to replace like-with-like and confer protective sensation. We investigate the feasibility of this flap with the largest series to date and the first to describe ipsilateral flap transfer.

Methods: Between 2009 and 2013, 7 patients with forefoot defects were treated with innervated free medial plantar flaps. The average age of 4 men and 3 women was 35.1 years (range, 8–50 years). Indications were secondary reconstruction after trauma and coverage of oncologic defects. The mean defect was 5 × 7 cm (range, 4–6 cm × 6–10 cm). Four patients were treated with contralateral flaps and 3 with ipsilateral flaps using interposition vein graft.

Results: The mean flap size was 8.1 ± 1.6 cm × 5.9 ± 1.2 cm. There was no perioperative complication, venous congestion, or arterial insufficiency. Patients were followed clinically for 38.5 months (range, 6 months to 10 years). One patient died from complications of metastatic disease 7 months after plantar flap reconstruction. Two patients underwent sensory testing and gait analysis. The appearance was satisfactory, ambulation returned to normal, and there was protective sensation in every case. In 2 cases, hyperkeratotic tissue was excised in revision procedures.

Conclusions: The innervated free medial plantar flap is an attractive and feasible option for coverage of medium-to-large defects of the plantar forefoot in the hands of a skilled microsurgeon. It has a place in our algorithmic approach to forefoot reconstruction.

Key Words: foot reconstruction, free flap, instep flap, diabetic foot, limb salvage, diabetic neuropathy, forefoot reconstruction, microsurgery, extremity reconstruction

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There is no easy solution for management of defects of the weight-bearing forefoot. Pedicled reconstructive options are inherently scarce, and functional demands on the construct are great. In 1979, Woltering advocated the use of split-thickness skin grafts (STSG) for coverage of plantar skin defects of the foot, citing ease of harvest and excellent outcomes.[1] Banis[2] was not so supportive, citing hyperkeratosis, craters, and contractures in his preference for full-thickness glabrous skin grafts. Wu and Gottlieb[3] echoed Banis' sentiment, encouraging surgeons to replace like-with-like while minimizing donor site morbidity.

Plantar wounds that result from trauma, cancer, or illness often involve more than skin; durable reconstruction demands robust and hearty tissue. The choice of tissue has generated controversy, with authors supporting flaps that span the reconstructive ladder. Workhorse gracilis, latissimus, rectus abdominis, and anterolateral thigh flaps offer acceptable donor morbidity, but can be technically demanding, bulky, and inconvenient. Complex rehabilitation protocols, debulking procedures, and divergence from the ideal of replacing like-with-like are worthwhile criticisms of those methods. As a result, recent support for fasciocutaneous alternatives like the reverse sural,[4–7] abductor hallucis longus (sometimes paired with a medial plantar flap),[8,9] and distally based dorsalis pedis[10] flap has accumulated.

Though the medial plantar fasciocutaneous flap offers pliability, conformability, potential sensibility, and donor site proximity, its use in plantar reconstruction is infrequently reported.[11–15] Viscoelasticity of medial plantar skin is comparable to the forefoot; a specialized fat plane and fibrous septal attachments distribute shear forces in healthy patients.[16,17] Increased peak loading pressures and skin stiffness in the diabetic forefoot may predispose to trophic ulcers; relative pliability of medial forefoot skin may improve shear stress distribution.[18–20] Heel reconstruction with medial plantar flaps is supported by the literature, but comparatively increased shear forces in the forefoot promote callus formation and trophic ulceration of that region. This distinction warrants reevaluation of medial plantar flap feasibility and longevity in forefoot reconstruction.[21,22]

In 2010, Oh et al[14] reported a series of weight-bearing plantar defects reconstructed with pedicled and contralateral free medial plantar flaps. In that series, there were 4 forefoot defects; 2 were treated with innervated free flaps. The authors reported 4 free medial plantar flaps; it was the largest series at that time. We echo the authors' advocacy for sensate flaps in plantar reconstruction and present the largest series to date on innervated free plantar flaps for forefoot reconstruction. We emphasize that the contralateral foot must not be compromised, to aid with postoperative rehabilitation and mobility. When it was available, we reconstructed nononcologic defects with ipsilateral plantar free flaps; this is the first series to describe that technique. We provide a technical primer and algorithm for management of complex forefoot defects.

PATIENTS AND METHODS

Between August 2009 and September 2013, 7 patients with plantar forefoot defects were treated with innervated free medial plantar flaps at this institution. The average age was 35.1 years (range, 8–50 years) of 4 men and 3 women. Two primary reconstructions treated medial volar postextirpative oncologic defects for melanoma and squamous cell carcinoma (SCC) under the first metatarsophalangeal joint. Five patients had traumatic transmetarsal defects that spanned the width of the foot and were previously reconstructed with anterolateral thigh flaps (2 cases), skin grafted latissimus dorsi flaps (2 cases), and skin graft alone (1 case). In these cases, medial plantar flaps were used to secondarily reconstruct trophic ulceration and tissue breakdown. The mean trophic ulcer was 2 cm long × 3 cm wide (range, 1-3 cm long × 1–4 cm wide). Four patients were treated with contralateral innervated free medial plantar flaps because medial plantar tissue was lost in previous trauma (2 cases) and oncologic concerns (2 cases) (Fig. 1A). Three were treated with ipsilateral free innervated medial plantar flaps (Fig. 1B) by the senior author (Table 1).

Preoperative Evaluation

Plain radiographs were reviewed. Preoperative examination included perforator identification by Doppler of the donor instep, palpation of dorsalis pedis and posterior tibial artery and an Allen's test at

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FIGURE 1. A, Preoperative (left) and 3-year postoperative (Right) appearance of a contralateral medial plantar flap transfer. An ipsilateral flap was not an option as the tissue was affected by the original injury. B, Preoperative (left) and 3-month postoperative (right) appearance of an ipsilateral medial plantar flap transfer.

the level of the ankle. Although fluorescence and 3-dimensional computed tomography angiography were not routinely performed, imaging studies are encouraged when there is doubt. This is particularly relevant for patients with preexisting peripheral vascular disease, diabetes, and history of stroke; our algorithm assumes baseline patient health and dependable vasculature beyond the level of injury. Adequate inflow to the foot was ensured before surgery.

Surgical Technique

Reconstruction began with liberal debridement, osteotomy, or wide tumor resection with pathological evaluation at the recipient site; recipient neurovasculature was identified and prepared (Table 2). To reconstruct the plantar forefoot, we raised ipsilateral flaps when adequate glabrous tissue was available in noncancer cases (lest resection margins be involved with disease) (Fig. 2). In the other cases, the contralateral foot was used; careful planning avoided inclusion of weight-bearing tissue in the healthy foot, and suitable donor neurovasculature was explored intraoperatively in lieu of lengthy and costly preoperative imaging modalities (Fig. 3A).[23]

Cutaneous medial plantar artery perforators were identified by Doppler and marked. Flaps were tailored to defect shape and size, and centered over the perforator(s). Under tourniquet, the medial incision was made, and branches of the medial plantar nerve and artery

TABLE 1. Patients' Information

Age/Sex	Indications	Diagnosis	Site of Defect	Defect Size (cm)	Donor Site and Size (cm)	Recipient Artery	Recipient Vein	Recipient Nerve
8/F	Secondary: tropic ulcer over previous flap reconstruction	trauma	transmetatarsal	4 × 6	ipsi 5 × 8	first dorsal metatarsal	superficial dorsal (2)	medial and lateral plantar
32/M	Secondary: breakdown of 11-year-old ALT flap	trauma	transmetatarsal	5 × 7	ipsi 7 × 7	posterior tibial	posterior tibial	medial plantar
45/F	Secondary: tropic ulcer over previous flap reconstruction	trauma	transmetatarsal	5 × 7	ipsi 7 × 8	medial plantar	medial plantar	first common digital
30/F	Primary: oncologic defect	SCC	medial plantar	5 × 6	contra 5 × 8	medial plantar	greater saphenous	first common digital
39/F	Secondary: degeneration of 20-year-old LD muscle flap	trauma	distal plantar half of foot	6 × 10	contra 6 × 9	posterior tibial	posterior tibial	medial plantar
42/F	Secondary: 5-year-old ALT flap s/p multiple revisions for ulcer	trauma	transmetatarsal	5 × 8	contra 5 × 11	posterior tibial	posterior tibial	second common digital
50/F	Primary: oncologic defect	melanoma	medial plantar	5 × 5	contra 7 × 8	medial plantar	medial plantar	second common digital

were identified in the subfascial plane, then traced to the medial plantar nerve and artery proper and then as proximally as necessary to obtain desired pedicle length and vessel caliber. The lateral incision was made and the flap elevated. The abductor hallucis muscle was divided and repaired to facilitate dissection. Tourniquet was released and flap perfusion was evaluated. When ipsilateral flaps were used, at least twice the planned advancement length worth of saphenous vein graft (SVG) was harvested after the flap was divided and inset. The recipient artery was anastomosed to the reversed SVG segment, and venous outflow to the antegrade SVG.

Outcomes and Comparisons

Patient data collected from chart review included age, sex, etiology, wound location, donor-site laterality, defect size, flap size, pedicle length, donor vein, recipient vessels, recipient nerves, and outcomes. Our methods were in accord with the Helsinki Declaration of 1975. Patients who agreed to return for evaluation after more than one year were subject to static 2-point discrimination (2PD) testing and subjective gait analysis. For 2PD testing, flaps were divided in to longitudinal and transverse thirds similar to the technique described by Wan et al[24]; pain, pressure, and 2PD were evaluated in each ninth. In patients who did not consent to return to clinic for sensory and gait testing, a brief telephone interview subjectively assessed flap sensation and functional parameters.

RESULTS

The mean flap size was 8.1 ± 1.6 cm × 5.9 ± 1.2 cm. In 1 case, the area of the defect exceeded the area of the instep. Partial fifth metatarsal ostectomy was performed to facilitate closure. Medial plantar nerves from contralateral flaps were coapted end-to-end to a common digital nerve (3 cases) or a branch of the medial plantar nerve (1 case). Arteries were anastomosed to the medial plantar (2 cases) or posterior tibial artery (2 cases), and veins to the corresponding venae comitantes (3 cases); in 1 case, the greater saphenous vein was used because the vena comitantes were not reliable (Fig. 3B).

Nerves from ipsilateral flaps were coapted end-to-end to plantar nerve branches (2 cases) or a common digital nerve (1 case). Recipient arteries and their respective veins were the posterior tibial (1 case) and medial plantar (1 case). In 1 case, the recipient vessels were the first dorsal metatarsal artery and 2 superficial dorsal veins. The donor vein for interposition grafting was the greater saphenous vein in the 3 cases of ipsilateral transfer (Fig. 3C).

The donor site was managed with a full-thickness skin graft in 6 cases and STSG in 1 case. There were no perioperative complications, and no perioperative venous congestion or arterial insufficiency was reported. All patients were followed clinically for an average of 38.5 months (range, 6 months to 10 years). One patient died from complications of metastatic melanoma 7 months after plantar flap reconstruction; in that case, the flap survived but it was too soon to identify appreciable return of sensation. The patient with SCC was rehospitalized for diabetic renal failure, lumbosacral spondylolisthesis and gout, but this was unrelated to forefoot reconstruction. Eight patients who were examined at 6 months demonstrated return of protective sensation to their foot, though a formal sensory examination was not performed at that time. Two patients underwent 2PD testing and gait analysis at 22 months and 40 months postoperatively. Those patients were 32- and 45-year-old men, respectively, that walked with a normal gait wearing commercially available athletic shoes. One received ipsilateral flap and the other contralateral plantar flap transfer. The appearance of both reconstructions was satisfactory without fissure or recurrent wounding. Both flaps demonstrated protective sensation in greater than 80% of the flap, and 2PD ranged from 5 mm to greater than 30 mm (Fig. 4).

Four patients were interviewed by telephone because they were satisfied with their outcome and cited prohibitive distance from our clinic (3 cases) or hospitalized for SCC metastasis treatment at the time of writing (1 case). All four reported mobility without the need for a walking aid, comfort wearing sneakers, and sensation over most or all the flap. No additional information was obtained. Taking the surveys into account, the average adjusted follow-up for the 6 surviving patients was 53.5 months (range, 16 months to 12.5 years). No partial or total flap loss occurred, and there were no additional revisions at outside facilities. Five donor sites healed without incident when a full-thickness skin graft was used, but there was partial necrosis of the graft in 1 case leading to multiple revisions for subsequent scarring. In 1 case where a STSG was used, a 4 cm × 2 cm wound developed along the lateral aspect of the donor site that healed as a hypertrophic scar. In 2 cases, hyperkeratosis of the flap was addressed in subsequent revision procedures.

DISCUSSION

The innervated free medial plantar flap is a feasible method for reconstruction of soft tissue defects of the heel. The flap offers thin,

Pedicle Length	Donor Site Coverage	Clinical Follow-up	Phone Survey	Adjusted Follow-up	Revisions	Outcome	Reason for Phone Survey
ND	FTSG	4 y 11 mo	Yes	5 y 5 mo	1. debridement necrotic FTSG 2. revision of FTSG 3. revision of FTSG callus over metatarsal head 4. recurrent hyperkeratosis	sensate forefoot no hyperkeratosis normal gait	satisfied distance
20 cm	STSG	3 y 4 mo	No	3 y 4 mo	1. excision of hyperkeratosis at instep donor site	protective sensation normal gait	—
ND	FTSG	9 y 11 mo	Yes	12 y 5 mo	none	sensate forefoot no breakdown normal gait	satisfied distance
ND	FTSG	1 y 3 mo	Yes	1 y 4 mo	none	metastatic SCC sensate forefoot no breakdown	hospital inpatient
18 cm	FTSG	6 mo	Yes	2 y 2 mo	none	sensate forefoot no breakdown normal gait	satisfied distance
18 cm	FTSG	1 y 10 mo	No	1 y 10 mo	none	protective sensation normal gait	—
20 cm	FTSG	7 mo	No	7 mo	none	**EXPIRED** succumbed to metastatic disease	—

TABLE 2. Recipient Vessels Used for Each Type of Reconstruction

Ipsilateral			Contralateral		
Artery*	**Vein***	**Nerve**	**Artery**	**Vein**	**Nerve**
Posterior tibial	posterior tibial	medial plantar	posterior tibial	posterior tibial	common digital
Medial plantar	medial plantar	lateral plantar	medial plantar	medial plantar	medial plantar
FDM	superficial dorsal	common digital		greater saphenous	

*Via interposition vein graft.
FDM= first dorsal metatarsal.

pliable glabrous tissue with a forgiving donor site, reliable anatomy without considerable variation, and the potential for sensitization. Free muscle and other fasciocutaneous flaps are reliable but bulky, requiring secondary procedures in most cases, as we have shown.[25] However, the forefoot endures greater peak pressures and shear forces during midstance and propulsion phases of gait than the heel. This is conducive to callus formation and cutaneous stiffening.[18–20] Similar changes are seen in neuropathic diabetics; these changes promote skin breakdown and ulceration.

For these reasons, reconstructed forefeet are not expected to outlast native tissue or reconstructed heels, particularly if nonglabrous tissue is used. Despite the many benefits, few free plantar flap series are reported in the literature, and there are even fewer reported for forefoot reconstruction.[11–15,26] At the time of writing, no case of ipsilateral free plantar flap reconstruction has been reported for forefoot reconstruction, though one was recently described for great toe pulp reconstruction in a young boy.[27]

When the ipsilateral instep is available, it should be used to spare the healthy foot and facilitate postreconstructive mobility. Its use as a distally based island or rotation flap is supported in the literature.[28–34] However, an intact vascular pedicle imposes restrictions on flap mobilization and coverage of large distal wounds. It also depends on intact vascular collaterals linking the dorsal and plantar vascular channels that may have been injured in inciting trauma[35] or iatrogenically.[36] Challenges associated with retrograde flow flaps do not spare medial plantar flaps, and venous congestion has been reported;[29,30] physiologic inadequacies of retrograde flow flaps may necessitate delay procedures for

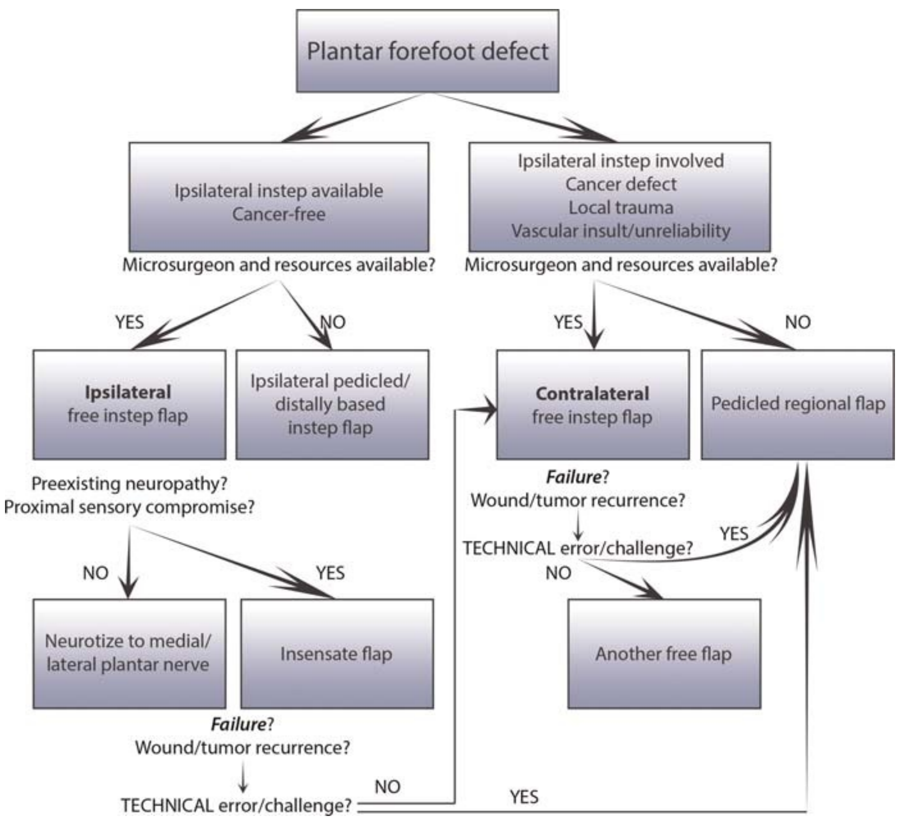

FIGURE 2. Algorithm for plantar forefoot reconstruction. In the hands of a skilled microsurgeon with appropriate resources, We prioritize ipsilateral free tissue transfer when there is adequate tissue. This facilitates postoperative ambulation and recovery. In certain cases, the contralateral medial plantar flap may be reserved for salvage.

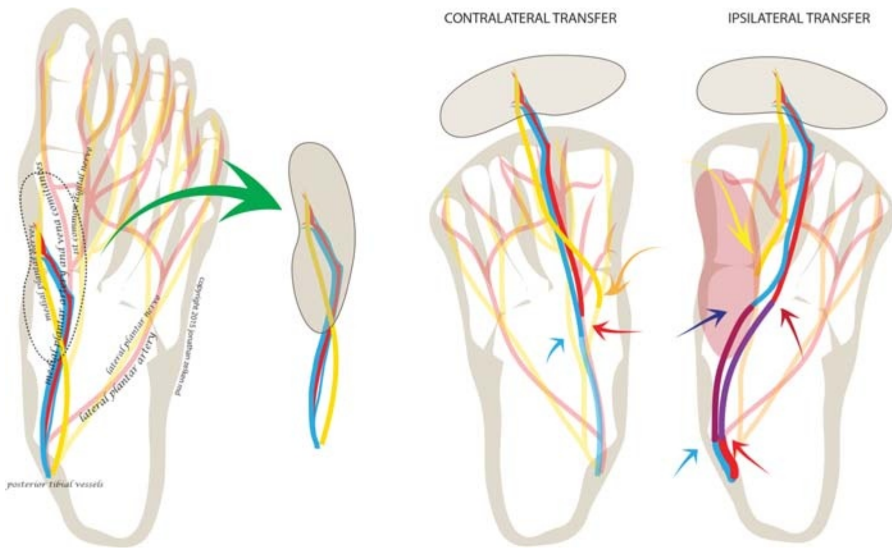

FIGURE 3. A, Anatomy of the free medial plantar flap the fasciocutaneous paddle is fueled by perforators of the medial plantar artery and sensitized by branch(es) of themedial plantar nerve. B, Contralateral transfer does not require interposition vein graft. The donor artery (red arrow) and vein (blue arrow) are anastomosed to the medial plantar artery or posterior tibial artery and vena(e) comitantes. The nerve is coapted to the medial or lateral plantar nerve. C, In ipsilateral transfer, vein grafts (purple structures) are required to advance the medial plantar flap distally. Nerve graft is generally not used as the donor nerve can be coapted to digital nerve(s) distally. The senior author prefers to anastomose the proximal artery (light red arrow), proximal vein (light blue arrow), distal vein (dark blue arrow), then distal artery (dark red arrow).

reliable results,[10] leading to increased treatment cost and downtime. We therefore prefer free ipsilateral plantar flap transfer when resources, expertise, and tissue are available. We support contralateral flap transfer when ipsilateral tissue is unreliable, unavailable, and for salvage procedures.

We did not document pedicle length and diameter in every case. If the medial plantar artery was the donor, the pedicle was about 3 cm long; vessel diameter at that level was 2 to 3 mm. During contralateral transfer, the greater saphenous vein became an important alternative with a diameter of up to 4 mm; it was preferred in 1 case in this series because the venae comitantes were not reliable. When vein graft interposition was at the level of the posterior tibial system, pedicle length was 18 to 20 cm. The diameter of the artery and venae at that level was as large as 5 mm. When they occurred, size discrepancies with the interposing saphenous vein were addressed with careful handsewn end-to-end anastomoses.

We advocate efforts to restore protective sensation during forefoot reconstruction. Although Wan et al[24] offers an elegant analysis of sensory recovery in heel reconstruction using pedicle medial plantar flaps, we are more concerned with whether or not the patient can react to painful stimuli than sensory discrimination itself. In that respect, the telephone survey was adequate. Moreover, it is yet to be determined whether sensate plantar flaps outperform anesthetic flaps for flap survival and ambulation. Ducic et al[37] approached this controversy with an extensive review and could not draw conclusions based on the existing literature. The authors advised using medial and lateral plantar donor nerves for forefoot reinnervation but warned that sensory dysesthesias might arise. Our results suggest sensory recovery in every case. In the 2 cases where 2PD was measured, it approached normal limits in over 80% of the flap area.

Accordingly, our algorithmic approach is designed to prioritize ipsilateral, homologous, sensate free tissue transfer for reconstruction of the plantar forefoot. Respecting the work of Ducic et al, we reserve innervation for patients with preexisting protective sensation and no identifiable proximal nerve injury. If the ipsilateral tissue fails, is unreliable, or

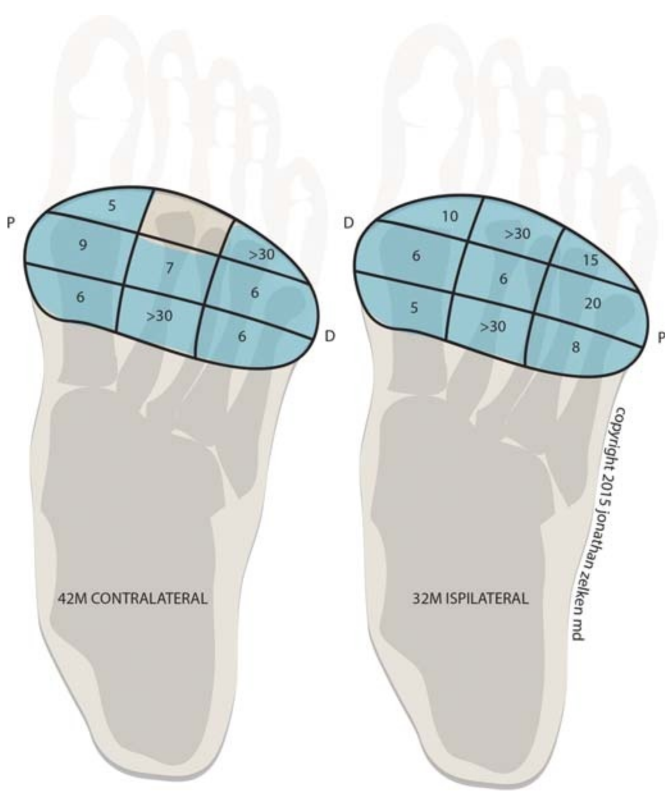

FIGURE 4. Sensory testing after contralateral (left) and ipsilateral (right) transfer had similar results in two men. Sensate tissue that responds to painful stimuli is shaded blue. 2-point discrimination values (mm) are listed. P indicates originally proximal; D, originally distal medial plantar tissue.

there is cancer, the contralateral foot may be approached, unless the cause of failure was iatrogenic. If failure was the result of a technical flaw or unfamiliarity with local anatomy, we advise distant free tissue transfer or local pedicled options.

We demonstrated adequate return of sensation over critical portions of the flap and satisfactory longevity without ambulatory compromise in every case followed beyond one year. The hesitation of patients to return to clinic should be interpreted positively. However, reliance on word-of-mouth in the majority of patients is a significant weakness of this study, especially in Asia where patients seem to withhold their dissatisfaction more than in other parts of the world. Although this is the largest series of free sensate plantar flaps, and the first to describe the free ipsilateral advancement flap with interposing SVG conduits, we did not compare the strategy to other techniques and therefore have no grounds to endorse our method as superior. We do demonstrate its feasibility and report universal patient satisfaction.

CONCLUSIONS

The innervated free medial plantar flap is an attractive and feasible option for coverage of medium-to-large defects of the plantar forefoot in the hands of a skilled microsurgeon. The medial plantar flap is sizeable, reliable, aesthetically favorable, and there is minimal donor site morbidity, particularly when harvested from the affected foot. The influence of innervation on ambulation and flap survival, and its superiority over pedicled flaps, is yet to be determined.

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