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The impact of arterial pedal arch quality and angiosome revascularization on foot tissue loss healing and infrapopliteal bypass outcome

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Objective: **This study evaluated the effect of pedal arch quality on the amputation-free survival and patency rates of distal bypass grafts and its direct impact on the rate of healing and time to healing of tissue loss after direct angiosome revascularization in patients with critical limb ischemia (CLI).**

Methods: **Between 2004 and 2011, patients undergoing distal bypass for CLI (Rutherford 4-6) were divided in groups taking into consideration the state of the pedal arch and direct angiosome revascularization (DAR) and non-DAR. Angiography was used to divide the pedal arch into three groups: complete pedal arch (CPA), incomplete pedal arch (IPA), and no pedal arch (NPA). The primary end points were patency rates at 12 months, amputation-free survival at 48 months, and the rate of healing and time to healing of foot tissue loss.**

Results: **A total of 154 patients (75% men) with CLI underwent 167 infrapopliteal bypasses. Patients were a median age of 75 years (range, 46-96 years). Diabetic mellitus was present in 76%, chronic renal failure in 28%, and ischemic heart disease in 44%. The primary patency rates at 1 year in the CPA, IPA, and NPA groups were 58.4%, 54.6%, and 63.8%, respectively ($P = .5168$), the secondary patency rates were 86.0%, 84.7%, and 88.8%, respectively ($P = .8940$), and the amputation-free survival at 48 months was 67.2%, 69.7%, and 45.9%, respectively ($P = .3883$). Tissue loss was present in 141 of the 167 bypasses. In the CPA group, 83% of tissue loss with DAR healed compared with 92% in the non-DAR (median time to healing, 66 vs 74 days). Similarly in the IPA group, 90% with DAR healed compared with 81% in the non-DAR (median time to healing, 96 vs 86 days). In the NPA group, only 75% with DAR healed compared with 73% in the non-DAR (median time to healing, 90 vs 135 days). There was a significant difference in healing and time to healing between the CPA/IPA and NPA groups ($P = .0264$).**

Conclusions: **The quality of the pedal arch did not influence the patency or the amputation-free survival rates. However, the rates for healing and time to healing were directly influenced by the quality of the pedal arch rather than the angiosome revascularized. (J Vasc Surg 2013;57:1219-26.)**

An angiosome is a "block of tissue supplied by a named artery whose territories in the integument and the underlying deep tissue correspond," as described by Taylor and Palmer[1] in an elaborate publication in 1987. Five distinctive angiosomes were described in the leg and foot territory and are supplied by the anterior tibial, peroneal, and posterior tibial arteries, with its terminal branches, the medial and lateral planter arteries.

This angiosome concept has generated great interest, with studies extrapolating this model on the treatment of patients with critical leg ischemia (CLI) and tissue healing. In 2006, Attinger et al[2] published their study looking into the clinical implications of foot and ankle angiosomes on revascularization and limb salvage. Since then, several reports have been published supporting the angiosome concept on healing patients with CLI by open bypass surgery[3] or endovascular intervention.[4,5]

Infrapopliteal and pedal arterial bypass are now firmly established techniques in the treatment of patients with CLI. However, there is still scarce evidence concerning the effect of the quality of the pedal arch on the outcome of distal bypass grafts in these patients. Although studies addressing the concept of foot angiosome revascularization have been published,[2-5] we are not aware of any studies looking at the effect of direct angiosome revascularization (DAR) in the presence of a complete or incomplete pedal arch (IPA) after crural or pedal bypass. The aim of this study was to evaluate the effect of pedal arch quality on the amputation-free survival and patency rates of infrapopliteal bypass grafts and its direct effect on the rate of healing and time to healing of tissue loss after DAR in patients with CLI.

METHODS

This was a retrospective analysis of prospectively collected data. All patients undergoing infrapopliteal bypass between 2004 and 2011 at a single tertiary vascular

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referral center were included. The inclusion criteria for all patients was CLI, (Rutherford category 4, 5, and 6) secondary to long occlusive femoropopliteal disease or trifurcation disease (TransAtlantic Inter-Society Consensus [TASC] type C and D classification for femoropopliteal disease) or both,[6] requiring infrapopliteal bypass surgery as determined by digital subtraction angiography (DSA).

Patient risk factors, including diabetes mellitus, chronic renal failure (defined as serum creatinine baseline ≥120 μmol/L), hypertension, history of symptomatic ischemic heart disease and smoking were documented. Data of clinical presentation, operative details, and follow-up were recorded and entered prospectively into an Excel database (Microsoft Corp, Redmond, Wash) and were analyzed retrospectively for this study.

Patients presenting with CLI were assessed according to an established protocol at our center. The protocol includes clinical assessment of the foot tissue loss and the vascular status of the leg. All patients underwent a detailed arterial duplex scan with distal waveforms analysis. A dedicated foot duplex assessment was also performed in selected patients to look specifically into the pedal arteries and arch size and amount of calcification. Because a large proportion of these patients with CLI are diabetic with chronic renal failure, we did not routinely use ankle-brachial pressure index in the ischemia assessment due to unreliable readings in these patients.

Our policy is to operate on patients on clinical presentation and presence of damped waveforms in the crural and pedal vessels. The target runoff vessel for the bypass is selected on the basis of anatomic and clinical factors to restore a straight-line flow to the area of ischemia following the angiosome principle.

Conventional DSA was obtained to delineate the anatomy of the infrapopliteal arterial system with dedicated pedal arch images taken in two planes to fully delineate the state of the arch. Planned inflow angioplasty was performed before surgical intervention should there be a stenotic lesion of >50% proximal to the site of the proposed proximal anastomosis.

The preoperative DSA was used to classify the pedal arch into three groups: the complete pedal arch (CPA; Fig 1), when both the dorsalis pedis artery and at least one of the plantar arteries are present and joined by the deep plantar artery or the first dorsal metatarsal artery; the IPA (Fig 2), when the dorsalis pedis artery or one of the plantar arteries are present; and no pedal arch (NPA; Fig 3), when neither the dorsalis pedis nor the plantar arteries are present but the foot flow is through collateral circulation. Five patients underwent on-table exploration of pedal vessels of which two could not be bypassed and were excluded from any further analysis. The remaining three patients were included in the NPA group.

Patients only undergoing distal bypass for foot tissue loss were divided into two groups: the DAR group, where the perfused angiosome artery matched that of the foot tissue loss; and the non-DAR group, when the artery perfused did not match the tissue loss angiosome.

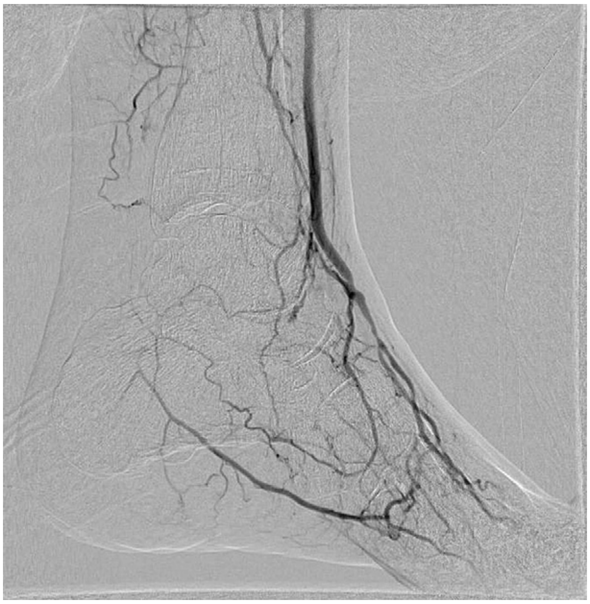


Fig 1. Complete pedal arch (CPA).

We divided the foot angiosomes into three groups based on Neville et al.[3] DAR bypasses were to the anterior tibial artery for a dorsal foot ulcer, bypass to the peroneal artery for a lateral ankle ulcer, and bypass to the posterior tibial artery for an ulcer at the medial plantar instep. An ulcer on the plantar heel was considered in the DAR group if the bypass was to the peroneal artery or posterior tibial artery.

Each ulcer was graded using the Wagner wound classification system.[7,8] Wounds were debrided urgently before revascularization if there was a clinical need such as wet gangrene, pus collection, or extensive infected necrosis. Otherwise, wound debridement or minor amputations were performed during bypass surgery. Wounds were treated with appropriate topical wound care. Large wounds (>7 cm in diameter) underwent split-thickness skin grafts (SSG) to achieve faster wound coverage. Vacuum-assisted closure (VAC; Kinetic Concepts Inc, San Antonio, Tex) was liberally used in postdebridement wounds as well as after SSGs.

The great saphenous vein was used as the preferred conduit of choice. Polytetrafluoroethylene grafts were used when no suitable superficial vein could be detected. Preoperative duplex imaging for superficial vein assessment and mapping was performed in all patients according to a standard protocol. The smallest vein conduit used was 2 mm in internal diameter. This has been shown to have good patency rate in infrainguinal bypasses.[9]

All distal bypass grafts followed a standard surgical procedure as well as graft surveillance protocol.[10]

Postoperative anticoagulation was maintained using a therapeutic dose of low-molecular-weight heparin (Clexane; Sanofi Winthrop Industrie S.A., Ambarès-et-Lagrave,

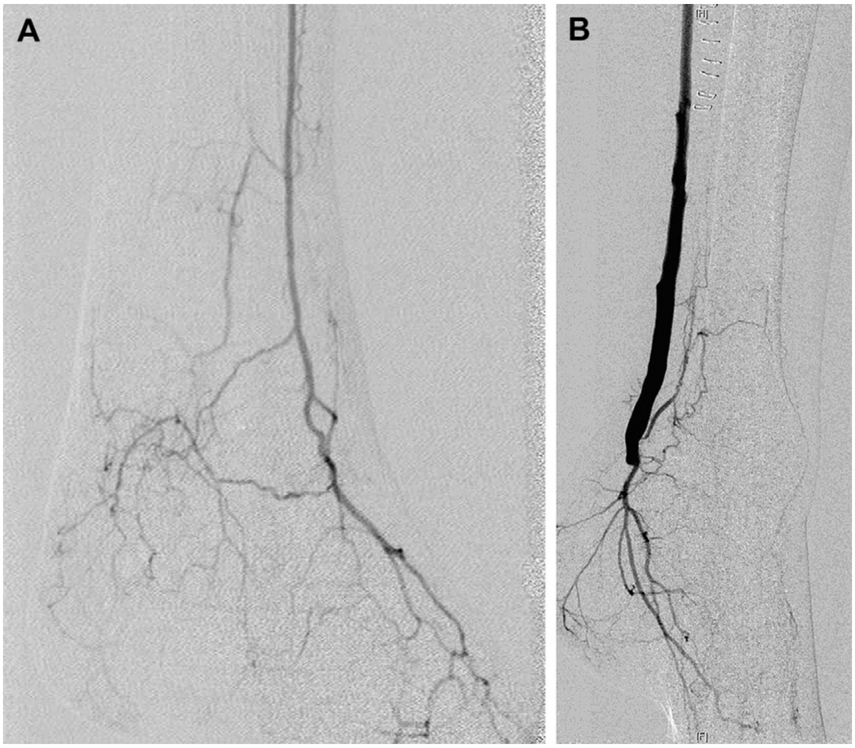


Fig 2. A, Incomplete pedal arch (IPA) with dorsalis pedis arch only. **B,** IPA with plantar arch only.

France) adjusted according to body weight (1.5 mg/kg once daily) in all bypass patients and maintained throughout the in-hospital period.

Antiplatelet and statin therapy were initiated preoperatively and maintained postoperatively. Patients undergoing ultradistal bypasses received dual antiplatelet therapy. Such regimen was the same for prosthetic as well as autogenous grafts.

Bypasses were divided into CPA, IPA, or NPA groups according to the state of the pedal arch. Each group was analyzed separately, and the outcomes were compared. The primary end points were amputation-free survival at 48 months and primary, assisted-primary, and secondary patency rates of the bypass leg at 12 months for all patients. The clinical outcome for each foot wound was also assessed and divided into healed, when full skin closure was achieved, or nonhealed, which included patients who died with active wounds. The effect of DAR and non-DAR in the three pedal arch groups on the rate of healing and time to healing in patients with foot tissue loss (only Rutherford 5 and 6) was also analyzed.

Amputation-free survival, defined as the first major amputation above the ankle (ie, transfemoral or transtibial) in the limb on which bypass was performed (ie, ipsilateral limb), or death from any cause—whichever occurred first—was chosen as an end point for its clear clinical significance. Similarly, amputation-free survival was chosen as an end point in the Bypass Versus Angioplasty in Severe Ischaemia of the Leg (BASIL) trial.[11]

Patency rates were defined according to the Rutherford reporting standards,[12] and were reported for 1 year only because the graft duplex surveillance program was only performed for 1 year.

Kaplan-Meier life-table analysis with the Mantel-Cox log-rank test was used to analyze patency, amputation-free survival, and healing rates for the pedal arch groups. The Fisher exact test was used where appropriate. Values of $P < .05$ were considered significant. Statistical analysis was performed using Prism 5.0 software (GraphPad Software, Inc, La Jolla, Calif).

RESULTS

A total of 154 patients with CLI underwent 167 infrapopliteal bypasses. Patients median age was 75 years (range, 46-96 years), and 116 (75%) were men. Diabetes mellitus was present in 127 (76%), chronic renal failure in 47 (28%), and ischemic heart disease in 74 (44%).

All patients included presented with CLI (Rutherford 4, 5, and 6). Tissue loss was present in 91 legs (54%), toe gangrene requiring minor amputation in 50 (30%), and rest pain in 26 (16%). Autogenous great saphenous vein was used in 152 of 167 bypasses (91%), arm veins in four (2%), and polytetrafluoroethylene with Miller's cuff in 11 (7%).

Fifty-three of the 167 legs had inflow disease on duplex scan and underwent successful preoperative angioplasty. Target arteries were two common iliac (4%), one external iliac (2%), one common femoral (2%), 22 superficial

Fig 3. No pedal arch (NPA).

femoral (41%), 16 popliteal (30%), and 11 (21%) combined superficial femoral artery/popliteal artery.

The site of the proximal anastomosis was the external iliac artery in one (0.5%), common femoral artery in 33 (20%), deep femoral in one (0.5%), superficial femoral in 54 (32%), above-knee popliteal artery in 18 (11%), below-knee popliteal artery in 58 (35%), and the posterior tibial artery in two (1%).

The site of the distal anastomosis was the tibioperoneal trunk in 14 (9%), the anterior tibial artery in 45 (27%), the peroneal artery in 30 (18%), the posterior tibial artery in 47 (28%), the dorsalis pedis in 24 (14%), and the plantar arteries in seven (4%).

The overall mortality rates were 1% (2 of 167) at 30 days and 11% (19 of 167) at 1 year. Of the 167 bypasses, DSA showed that 31 (19%) had CPA, 104 (62%) had IPA, and 32 (19%) had NPA. The demographic characteristics and risk factors (defined and graded according to the Society for Vascular Surgery/International Society for Cardiovascular Surgery recommended criteria[13]) for the CPA, IPA, and NPA groups are summarized in Table I.

Of the 167 grafts, 55 (33%) threatened grafts were detected on the duplex scan surveillance program and required 85 salvage angioplasties. Details of salvage angioplasty site in the CPA, IPA, and NPA groups are summarized in Table II.

There was no statistically significant difference between the groups in the patency rate at 1-year and amputation-free survival at 48 months (Table III). Details of the primary patency, assisted primary patency, secondary patency, and amputation-free survival rates are presented in Table III and Figs 4-7.

Of the 167 bypasses, 141 performed for ischemic foot tissue loss or gangrene (Rutherford 5 and 6) were analyzed separately, taking into consideration the angiosome revascularization theory. Patients presenting with rest pain only (26 limbs of 167 limbs) were excluded from this analysis. Of the 141 in this cohort analysis, 78 underwent minor amputation, 63 had ulcer debridement, and 18 patients underwent SSG in the foot for large tissue loss. Full wound healing was achieved in 116 of the 141 patients (82%), 10 wounds (7%) failed to heal, and 12 patients (9%) died with nonhealed ulcers within 1 year after bypass. Three patients (2%) were lost during follow-up. The major

Table I. Patient demographics and risk factors in the pedal arch groups

Variables[a]	*CPA (n = 31)*	*IPA (n = 104)*	*NPA (n = 32)*
Age, years	71 (51-86)	75 (46-90)	79 (55-96)
Men	27 (87)	73 (70)	28 (88)
Diabetes mellitus	24 (77)	78 (75)	23 (72)
Renal insufficiency	10 (32)	27 (26)	10 (31)
Hypertension	24 (77)	85 (82)	29 (91)
Ischemic heart disease	14 (45)	42 (40)	16 (50)
Smokers/former smokers	25 (81)	64 (62)	14 (44)

CPA, Complete pedal arch; *IPA*, incomplete pedal arch; *NPA*, no pedal arch.
[a]Continuous data are given as median (range) and categoric data as number (%).

Table II. Site of salvage angioplasty in the pedal arch groups

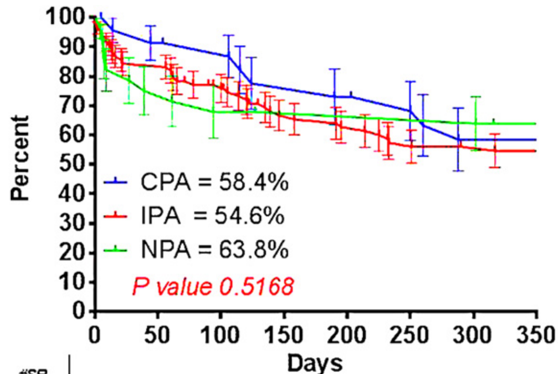
Salvage angioplasty (N = 85)	*CPA (n = 16), No. (%)*	*IPA (n = 52), No. (%)*	*NPA (n = 17), No. (%)*
Inflow	5 (31)	8 (15)	6 (35)
Graft	11 (69)	38 (73)	9 (53)
Outflow	0 (0)	6 (12)	2 (12)

CPA, Complete pedal arch; *IPA*, incomplete pedal arch; *NPA*, no pedal arch.

Table III. Patency rates at 12 months and amputation-free survival at 48 months in the pedal arch groups

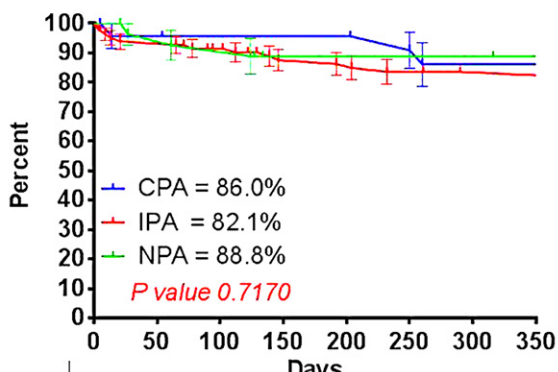
Variable	*CPA (n = 31), %*	*IPA (n = 104), %*	*NPA (n = 32), %*	P
Primary patency	58.4	54.6	63.8	.5168
Assisted primary patency	86.0	82.0	88.8	.7170
Secondary patency	86.0	84.7	88.8	.8940
Amputation-free survival	67.2	69.7	45.9	.3883

CPA, Complete pedal arch; *IPA*, incomplete pedal arch; *NPA*, no pedal arch.



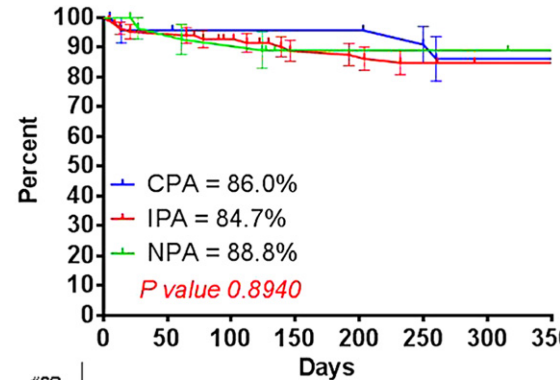
#SR								
CPA	24	21	20	17	16	15	13	11
IPA	83	70	62	50	48	43	42	40
NPA	28	22	20	19	19	17	17	15

Fig 4. Kaplan-Meier analysis of the primary patency rate with standard error bars and number of subjects at risk (*#SR*) is shown for those with complete pedal arch (*CPA*), incomplete pedal arch (*IPA*), and no pedal arch (*NPA*).



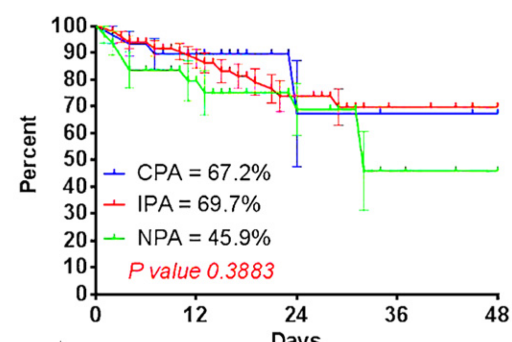
#SR								
CPA	24	22	22	21	21	20	19	17
IPA	81	78	72	67	66	64	62	60
NPA	28	26	25	22	22	21	21	20

Fig 5. Kaplan-Meier analysis of the assisted primary patency rate with standard error bars and number of subjects at risk (*#SR*) is shown for those with a complete pedal arch (*CPA*), incomplete pedal arch (*IPA*), and no pedal arch (*NPA*).



#SR								
CPA	24	22	22	21	21	20	19	17
IPA	83	77	73	68	67	64	63	62
NPA	28	27	27	22	22	21	21	20

Fig 6. Kaplan-Meier analysis of the secondary patency rate with standard error bars and number of subjects at risk (*#SR*) is shown for those with a complete pedal arch (*CPA*), incomplete pedal arch (*IPA*), and no pedal arch (*NPA*).



#SR					
CPA	30	20	4	3	1
IPA	100	66	23	10	5
NPA	31	20	12	4	1

Fig 7. Kaplan-Meier analysis of the amputation-free survival rate with standard error bars and number of subjects at risk (*#SR*) is shown for those with a complete pedal arch (*CPA*), incomplete pedal arch (*IPA*), and no pedal arch (*NPA*).

amputation rate for patients presenting with foot tissue loss was 3% (4 of 141).

The site of tissue loss in the foot in the 141 patients was 122 (86%) in the posterior tibial artery angiosome territory compared to 14 (10%) in the ATA angiosome territory and five (4%) in the peroneal artery angiosome territory. CPA was present in 31 of 141 patients (22%) compared with 88 (62%) with IPA and 22 (16%) with NPA. Because of the distribution of the disease, direct revascularization of the specific angiosome was only feasible in 66 of 141 patients (47%) compared with the nonspecific angiosome in 75 (53%). Complete foot wound healing was achieved in 57 out of the 66 cases (86%) in the DAR group compared to 59 out of the 75 cases (79%) in the non-DAR group ($P = .2736$).

Details of healed wounds, time to healing, minor and major amputation, graft occlusion at 1 year, patients dying with nonhealed wounds at 1 year, SSG, and grade of wounds according to Wagner wound classification in the three groups are summarized in Table IV and Table V. SSGs were used liberally for wounds sized >7 cm in diameter (15% in DAR vs 11% in non-DAR groups; $P = .4582$).

There was significant difference in the healing and the time to healing between the CPA/IPA and the NPA groups ($P = .0264$; Fig 8).

Of 167 bypass grafts in the CPA group, two occluded but no patients required major amputations. In the IPA group, 19 grafts occluded and six patients underwent

Table IV. Details of direct angiosome revascularization (*DAR*) and non-DAR in the pedal arch groups

		Healed					*Amputation*	
Pedal arch groups	*No.*	*No. (%)*	*Median days (range)*	*Died non-H, No.*	*SSG, No.*	*1-year GO, No.*	*Minor, No.*	*Major, No.*
CPA								
DAR	18	15 (83)	66 (7-235)	3	2	1	9	0
Non-DAR	13	12 (92)	74 (7-541)	1	2	1	10	0
IPA								
DAR	40	36 (90)	96 (7-647)	2	5	5	22	1
Non-DAR	48	39 (81)	86 (10-538)	3	5	7	24	3
NPA								
DAR	8	6 (75)	90 (22-377)	0	3	1	5	0
Non-DAR	14[a]	8 (73)	135 (56-582)	3	1	0	8	0
Total bypasses	141							

Died non-H, Patients died with non-healed ulcer; *GO*, graft occlusion; *SSG*, split-thickness skin graft.
[a]Three patients were lost to follow-up.

Table V. Wagner wound classification grades in all groups

		Wagner wound classification			
Variable	*No.*	*Grade 2, No. (%)*	*Grade 3, No. (%)*	*Grade 4, No. (%)*	*Grade 5, No. (%)*
CPA					
DAR	18	7 (39)	6 (33)	5 (28)	0
Non-DAR	13	3 (23)	2 (15)	5 (38)	3 (23)
IPA					
DAR	40	15 (38)	12 (30)	10 (25)	3 (8)
Non-DAR	48	20 (42)	13 (27)	13 (27)	2 (4)
NPA					
DAR	8	2 (25)	4 (50)	2 (25)	0
Non-DAR	14	3 (21)	3 (21)	6 (43)	2 (14)

CPA, Complete pedal arch; *DAR*, direct angiosome revascularization; *IPA*, incomplete pedal arch; *NPA*, no pedal arch.

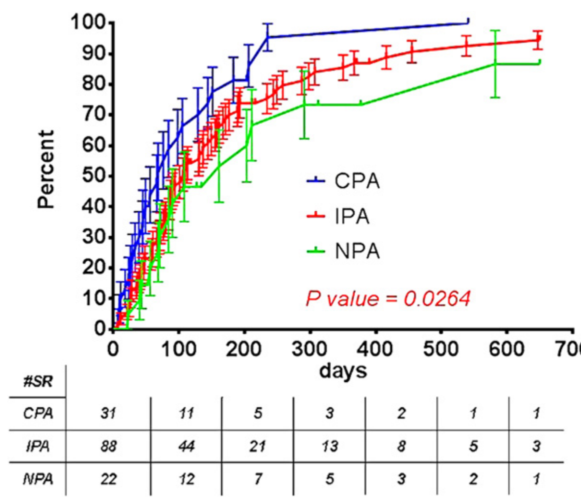


Fig 8. Kaplan-Meier analysis of the healing rate and time to healing with standard error bars and number of subjects at risk (*#SR*) in complete pedal arch (*CPA*), incomplete pedal arch (*IPA*), and no pedal arch (*NPA*) groups.

major amputations. Thirteen of these 19 grafts occluded between 10 and 223 days after the procedure; however, by the time the grafts occluded, the ulcers had healed and did not result in limb loss in these patients. Eight grafts in the NPA group occluded, and one patient required major amputation. Three of the eight grafts occluded between 27 and 124 days after the bypass, with healed ulcers.

DISCUSSION

The angiosome concept is an anatomic rather than a physiologic study, as stated by Taylor and Palmer[14] in a letter published in 1992. The authors even stated that they were careful not to make this extrapolation. Thus, applying this concept wholly to patients with CLI may not be as rewarding as hoped because these patients do have generalized peripheral arterial disease spreading down to the pedal arch.

We believe that direct revascularization as a concept is acceptable, and all effort should be made when selecting the target artery to consider the specific angiosome vessel. However, direct revascularization was only feasible in 47% in this series, reflecting the severity of the crural arteries disease in this group of patients. Similarly, a CPA was only present in 19% of the cases, whereas 62% had IPA, and the foot in 19% was perfused only through collateral circulation rather than a named pedal artery. In our institution, a dedicated high-quality pedal arteries and foot arch DSA is always obtained to help select the target vessel. This is also supported by routine pedal arch duplex scan when no runoff artery could be visualized on angiography. On-table exploration of pedal vessels is also performed in selected patients, as recommended by Pompeselli et al.[15] This protocol has helped reduce the number of cases deemed nonreconstructible on preoperative imaging.

The results of this study show that DAR did not influence the outcome of distal bypass surgery in patients with CLI. The time to healing did not differ between the DAR and non-DAR groups except in the NPA group, where the time to healing was significantly longer. These results are similar to the study recently published by Azuma et al.[16] They concluded that the location and extent of the ischemic wounds as well as comorbidities are more relevant than the angiosome revascularized.

In this series, the quality of the pedal arch did not affect the primary, assisted-primary, and secondary patency rates. Similarly, the amputation-free survival between all pedal arch groups did not show a statistically significant difference. Previous studies have shown that the quality of the runoff vessels can affect graft patency rates[17,18]; however, in this series, this was not the case.

In their study published in 2006, Attinger et al[2] stated that the blood flow to the foot and ankle is redundant because the three major arteries feeding the foot have multiple arterial–arterial connections. The "choke vessels" described by Taylor and Palmer[1] illustrate a type of connection between different angiosomes; however, they also stated that some connections are true anastomoses without a change in arterial caliber, using the example of the connection between the dorsalis pedis and the posterior tibial arteries to demonstrate this type of anastomosis. We fully agree with these conclusions and believe that in cases where the arterial pedal arch is completely intact, the crural artery perfused is irrelevant to the healing of tissue loss due to these arterial–arterial connections between the three main arteries of the leg, rendering the angiosome principle irrelevant, too.

We are fully aware of the effect of other important factors in wound healing, as highlighted by Azuma et al.[16] Different wound care techniques will also influence the time to healing in these patients. In this series, SSG were used liberally in patients with residual wounds >7 cm in diameter (15% in DAR vs 11% in non-DAR). This, however, did not influence the outcome between the groups.

Azuma et al[16] demonstrated that the angiosome perfused did not influence healing or amputation-free survival in patients undergoing distal bypass surgery for CLI. They, however, found that the degree of renal disease in these patients had a direct effect on outcome, where patients with end-stage renal disease had significantly lower healing and limb salvage rates compared with non-end-stage renal disease patients. These results are similar to data published by Pomposelli et al,[19] and others,[20-22] where outcomes in these patients were less favorable than non-end-stage renal disease patients. This could be explained by the poor quality of the arterial pedal arch in these patients.[23]

There are several reports supporting DAR using endovascular techniques.[4,5] The "pedal-planter loop angioplasty" technique has also been described to reconstruct the pedal arch in patients with CLI, with an 85% success rate and a significant improvement of transcutaneous oxygen tension after the procedure.[24] On the basis of the results of the current series, where healing was significantly lower in patients with an IPA, we believe that the endovascular reconstruction of the arterial pedal arch could reduce the time to healing in patients with foot tissue loss.

CONCLUSIONS

The quality of the pedal arch did not influence rates of patency or amputation-free survival in patients undergoing infrapopliteal bypass for CLI. However, the healing and time to healing rates were directly influenced by the quality of the pedal arch rather than the angiosome revascularized.

AUTHOR CONTRIBUTIONS

Conception and design: HR, HS
Analysis and interpretation: HR, HS, DH, CW, DE, PS
Data collection: HS
Writing the article: HR, HS
Critical revision of the article: HR, HS, HZ, DH, CW, DE, PS, ME
Final approval of the article: HR, HS
Statistical analysis: HR, HS
Obtained funding: Not applicable
Overall responsibility: HR
HR and HS participated equally and share first authorship.

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