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CLINICAL INVESTIGATION ARTERIAL INTERVENTIONS

Endovascular Extra-Anatomic Femoro-Popliteal Bypass for Limb Salvage in Chronic Critical Limb Ischemia

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Abstract

Purpose To report the initial clinical experience with fully endovascular extra-anatomic femoro-popliteal bypass (FPB) for limb salvage in patients with critical limb ischemia (CLI) and no traditional endovascular or surgical revascularization options.

Methods Between June 2013 and May 2018, endovascular procedure was proposed for limb salvage during multidisciplinary team meeting in fifteen hospitalized patients (median age 67 years; 73% men) with CLI and a high risk of major amputation. Primary outcome was amputation-free survival at 1 year. Secondary outcomes included mortality, cardiovascular (CV) events and major limb amputation at 1 year, primary/secondary bypass patency and wound healing at the last follow-up visit. Procedure-related complications (deaths, CV events, hemorrhages) were recorded through 30 days.

Results Technical procedure success rate was 100%. Major peri-procedural outcomes occurred in two patients (13%): One patient died secondary to cardiogenic shock; one patient suffered acute coronary syndrome associated with iliopsoas bleeding. No major amputation occurred through 30 days. Median follow-up period was 21.5 (18.25–45.5) months (last follow-up visits on April 2019). Amputation-free survival at 1-year and at the last follow-up visit was 80% and 53%, respectively. Cumulative mortality at 1-year and at the last follow-up visit was 13% and 33%, respectively. Primary and secondary bypass patency was 27% and 60%, respectively. Complete wound healing was achieved in 11 patients (73%).

Conclusion Endovascular extra-anatomic FPB represents an innovative approach for limb salvage in CLI with no traditional endovascular or surgical revascularization options. Our clinical experience highlights that this technique remains challenging because of frequent comorbidities and fragility of this patient population.

Level of Evidence Level 4, Case series.

Keywords Critical limb ischemia · Endovascular revascularization · Femoro-popliteal bypass · Limb salvage

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Introduction

Critical limb ischemia (CLI) is defined as ischemic foot pain at rest, non-healing foot wounds or gangrene that is attributable to hemodynamically severe arterial occlusive disease [1]. Revascularization is the cornerstone of therapy to relieve ischemic pain, heal ischemic ulcers, prevent limb loss and preserve patient autonomy. If no revascularization can be achieved, CLI has a predictive value for very poor outcome with a 1-year all-cause mortality and major amputation rate of 22%, respectively [2].

The complexity of the disease process and the development of surgical, catheter-based or hybrid interventions to achieve tissue perfusion encourage multidisciplinary team approach and revascularization techniques on a case-by-case basis [3]. In the absence of feasible revascularization due to comorbidities or anatomic considerations, limb salvage can be achieved in a subset of patients with CLI following a program of wound management with directed healing [4]. However, nearly one-third of patients with an ankle-brachial pressure index (ABI) < 0.5 experienced major amputation at 6 months of initial wound management program compared with 10% of patients with an ABI > 0.5. Recommend major amputation is an ethical issue in patients with CLI presenting with severe ischemia associated with an extensive tissue loss [5]. In patients with an independent living status, this decision is difficult to support without exhausting all chances to attain limb salvage and preserve functional autonomy [6].

Over the last two decades, advancements in endovascular techniques offer the possibility to manage multi-vessel disease during the same procedure and to perform distal revascularization of the plantar arch and the pedal artery [7, 8]. The present study reports the results of a revascularization procedure consisting in a totally extra-anatomic percutaneous femoro-popliteal bypass for the treatment of limb-threatening CLI in patients with previous failure of conventional surgical and/or endovascular revascularization procedures. The objectives of the present cohort study are to describe this revascularization technique and to report patients' outcomes.

Methods

Study Design

Between June 2013 and May 2018, 15 patients with limb-threatening CLI, hospitalized in our vascular medicine department, underwent endovascular femoro-popliteal bypass for limb salvage procedure. Clinical data, with follow-up details until April 2019, were retrospectively collected in a dedicated report form. This study is registered according to local reglementary procedures. All patients gave informed consent regarding the use of their medical data for the study.

Participants and Eligibility Criteria

All patients had an independent living status. Eligibility criteria were limb-threatening CLI and no option for traditional surgical or endovascular revascularization procedure. Active life-threatening condition including life-threatening foot sepsis, patient with knee flexion contracture or contraindication to antithrombotic therapy precluded attempting this procedure.

The patients had experienced failure of multiple previous surgical and/or catheter-based revascularization procedures. Critical limb ischemia was objectively assessed with hemodynamic measurements: ABI < 0.40, ankle pressure < 50 mmHg and toe pressure < 30 mmHg [3]. Patients presented with rest pain associated with extensive non-healing ulcers with a short-term risk of major amputation (WIFI classification ≥ 4) [9]. Hemodynamic evaluation consisted of ABI and great toe laser Doppler flowmetry (LDF) measurement. In addition to duplex ultrasonography, computed tomography angiography or magnetic resonance angiography was performed to evaluate the treatment options. All patients presented with extensive infra-inguinal arterial lesions involving femoro-popliteal and infra-popliteal arteries, classified as type D according to the TransAtlantic Inter-Society Consensus (TASC) criteria [10]. During a multidisciplinary team meeting consisting of vascular medicine doctors, vascular surgeons and interventional radiologists, a percutaneous bypass procedure was proposed for limb salvage, in the absence of conventional surgical or endovascular revascularization option.

Follow-Up and Outcomes

Technical success was defined by the endovascular extra-anatomic bypass patency at the end of the procedure. Clinical success was defined by resolution of rest pain, formation of tissue granulation on the wound and statistically significant increase in ankle pressure index and great toe pressure index after the procedure. Bypass patency was proved by imaging (Doppler ultrasound or computed tomography angiography in the follow-up).

Ankle pressure index and great toe LDF were monitored in the postoperative period during the index hospitalization, and bypass patency was assessed with Doppler ultrasonography. After patient discharge, a personalized wound care management was planned. Follow-up was performed monthly with clinical and ultrasound Doppler evaluation until wound healing was achieved, and then, patients' follow-up was performed tri-annually.

Primary outcome measurement was amputation-free survival at 1 year. Secondary outcome measurement included mortality, cardiovascular events, major limb amputation, bypass patency (proved by imaging) and wound healing. Mortality, cardiovascular events and major limb amputation were obtained at 1 year and at the last follow-up visit. Secondary bypass patency was obtained at the last follow-up visit. Procedure-related complications (deaths, cardiovascular events, hemorrhages) were recorded through 30 days.

Statistical Analysis

Continuous variables were presented as median and interquartile range (IQR). Categorical variables were expressed as percentage. To compare ABI, great toe LDF and great toe LDF index values in the pre- and postoperative period, the Wilcoxon signed-rank test was used. A $p \leq 0.05$ was considered as statistically significant. Kaplan–Meier curves are presented for survival, limb salvage and primary and secondary bypass patency. Kaplan–Meier survival curves are presented as an estimator of the true survival functions. Study period starts from June 12, 2013, to April 1, 2019, which is the right-censoring date. Risk tables are also presented with numbers and percentages of the cohort still not affected by the event at *t* days. The statistical software used is R with the "survival" and "survminer" packages.

Results

Patients Characteristics

Clinical characteristics and hemodynamic parameters of the 15 patients are presented in Table 1. Median age of the patients was 67 (62–73.5) years. Smoking and hypertension were highly prevalent (80% and 67%, respectively), and 33% of the patients were current smokers. Diabetes was present in 27% of the patients. Median creatinine clearance was 83 mL/min; one patient presented with moderate renal insufficiency (creatinine clearance of 40 mL/min).

Angio-anatomical situation precluding traditional revascularization procedure was surgical femoro-popliteal bypass thrombosis with no more vein available in 13 patients (87%), ligation of femoral or popliteal artery secondary to previous operative site infection in 4 patients (27%) and failure of endovascular recanalization procedures with the sub-intimal approach due to important arterial calcifications in 4 patients (27%). All patients presented with extensive infra-inguinal arterial lesions involving femoro-popliteal and infra-popliteal arteries. Arterial anatomy and revascularization procedure are described in Table 2.

Table 1 Clinical characteristics of the patients and hemodynamic parameters

Variables	Patients, *n* = 15
Clinical and biological parameters	
Gender, men (%)	11 (73%)
Age, years	67 (62–73.5)
Diabetes, *n* (%)	4 (27%)
Hypertension, *n* (%)	10 (67%)
Tobacco, *n* (%)*	12 (80%)
Creatinine clearance, mL/min	83 (76–98)
History of ischemic heart disease, *n* (%)	6 (40%)
Nutritional deficiency, *n* (%)	8 (53%)
Hemodynamic parameters before procedure	
ABI	0.13 (0–0.43)
Great toe LDF, mmHg	30 (6.25–34)
Great toe LDF index	0.23 (0.04–0.25)
Hemodynamic parameters after procedure	
ABI	0.73 (0.59–0.79)
Great toe LDF, mmHg	51 (45–62.5)
Great toe LDF index	0.39 (0.34–0.51)

Continuous variables were presented as median (IQR)

ABI Ankle-brachial pressure index; *LDF* laser Doppler flowmetry of the great toe

*Seven patients were former smokers and 5 patients were current smokers

Endovascular Procedure Description

In the angiography suite, revascularization procedures were performed under local anesthesia.

Preoperative dual antiplatelet therapy with 75 mg/day of acetylsalicylic acid and 75 mg/day of clopidogrel was started at least 72 h before the procedure. Low-molecular-weight heparin (LMWH) with enoxaparin 100 IU/kg administered twice daily was maintained for 10 days in the postoperative period. Intravenous cefazolin 2 g was used as antibiotic prophylaxis at anesthesia induction.

To describe the technique, three revascularization procedures are presented: angio-anatomical situation included femoro-popliteal bypass thrombosis, proximal femoral artery ligation and no vein available (Patient 1, Fig. 1); recurrent femoro-popliteal bypass graft thrombosis, and popliteal artery ligation (Patient 2, Fig. 2); bilateral limb-threatening CLI with long femoro-popliteal calcified occlusion and no vein available (Patient 3, Fig. 3).

Table 2 Arterial anatomy and revascularization procedures

Patients	Previous failed revascularization procedures	Endovascular bypass anatomy, landing zones (run-off vessel)	Arterial approach	Bypass patency*
Woman, 68 years	Femoro-popliteal prosthetic bypass graft thrombosis, proximal SFA ligation	DF–supra-articular popliteal artery (AT)	Antegrade CFA	Yes
Man, 65 years	Femoro-popliteal prosthetic bypass graft thrombosis, popliteal artery ligation	Proximal popliteal–infra-articular popliteal artery (posterior tibial and peroneal artery)	Double approach (CFA + AT)	Yes
Woman, 81 years	Femoro-popliteal venous bypass graft thrombosis, highly calcified femoro-popliteal occlusion	SFA–supra-articular popliteal artery (peroneal artery)	Antegrade CFA	Yes
Man, 77 years	Femoro-popliteal prosthetic bypass graft thrombosis, highly calcified femoro-popliteal occlusion	SFA–supra-articular popliteal artery (peroneal artery)	Double approach (CFA + AT)	Yes
Man, 41 years	Femoro-tibial venous bypass graft thrombosis, popliteal artery ligation	Sub-intimal recanalization of the SFA and SFA–infra-articular popliteal artery bypass (AT)	Double approach (CFA + AT)	No
Woman, 83 years	Femoro-femoral crossover graft thrombosis, occlusion of external iliac artery	Recanalization + stenting of external iliac artery + iliac artery-CFA bypass	Crossover CFA + retrograde ipsilateral femoral	Yes
Man, 66 years	Femoro-tibial venous bypass graft thrombosis, proximal SFA ligation	DF—supra-articular popliteal artery (posterior tibial artery)	Antegrade CFA	Yes
Man, 69 years	Ilio-femoral and femoro-popliteal prosthetic bypass grafts thrombosis	DF–infra-articular popliteal artery (posterior tibial artery)	Double approach (CFA + AT)	No
Man, 70 years	Highly calcified femoro-popliteal occlusion, no vein available	DF—supra-articular popliteal artery (posterior tibial and peroneal artery)	Double approach (CFA + AT)	Yes
Woman, 61 years	Highly calcified femoro-popliteal occlusion, no vein available	DF—supra-articular popliteal artery (AT and peroneal artery)	Antegrade CFA	Yes
Man, 63 years	Ilio-femoral and femoro-tibial bypass graft thrombosis	DF—supra-articular popliteal artery (AT and posterior tibial artery)	Double approach (CFA + AT)	No
Man, 67 years	Recurrent occlusions of femoro-popliteal bypass grafts	SFA recanalization + SFA–supra-articular popliteal artery (peroneal artery)	Antegrade CFA	Yes
Man, 79 years	Femoro-popliteal bypass graft thrombosis, long superficial femoral artery occlusion	DF—supra-articular popliteal artery (AT)	Antegrade CFA	yes
Man, 60 years	Multiple occlusions of femoro-popliteal bypass grafts	SFA–supra-articular popliteal artery (AT)	Double approach (CFA + AT)	No
Man, 51 years	Multiple occlusions of femoro-popliteal bypass grafts, failure of endovascular recanalization	SFA–supra-articular popliteal artery (posterior tibial artery)	Antegrade CFA	No

CFA Common femoral artery; *SFA* superficial femoral artery; *DF* deep femoral artery; *AT* anterior tibial artery

*Bypass patency at the last follow-up visit, proved by imaging

In the first revascularization procedure, an endovascular extra-anatomic femoro-femoral (from the deep femoral artery to distal femoral artery) bypass (Fig. 1) was performed in June 2013. Popliteal artery and anterior tibial artery were recanalized in the same operative procedure. An antegrade approach was performed with an 8-Fr introducer sheath inserted in the common femoral artery. There were two well-developed branches of the deep femoral artery. After catheter placement in the medial branch, an angulated Colapinto needle (Transjugular intrahepatic access set, COOK, Bloomington) was used for an intentional puncture of the deep femoral artery that was performed putting the tip of the needle into the extravascular space (Fig. 1D). An angled hydrophilic 0.035″ stiff guidewire (Terumo Radifocus, Europe) was advanced, and the needle was withdrawn. The advance of the guidewire into the extravascular space was supported by an angulated catheter Bern tip 5 Fr (Boston Scientific, USA). The objective was to navigate through the muscles toward the knee to the distal landing zone. The progression of the guidewire and catheter was achieved under two orthogonal projections; this was mandatory in order to get a precise control of the catheter position in the extravascular space. Simultaneously, injection of 20 cc of xylocaine 1% was performed from the catheter tip inside extravascular space.

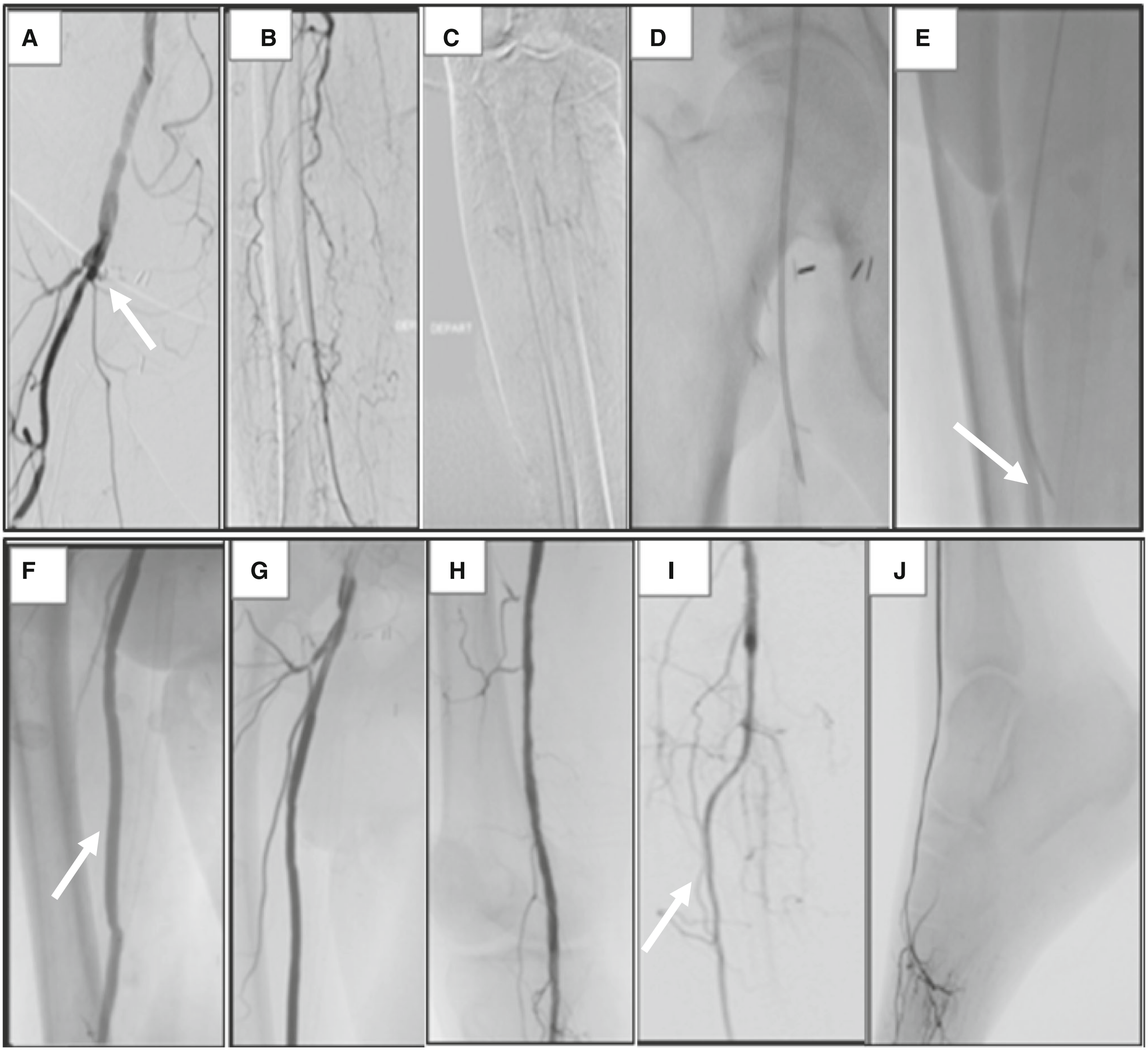


Fig. 1 Revascularization procedure (Patient 1). **A–C** Angio-anatomical situation precluding traditional revascularization procedure: femoro-popliteal bypass thrombosis, proximal femoral artery disconnection (arrow), popliteal artery thrombosis, no vein available, poor outflow vessel. **D** Antegrade ipsilateral femoral artery access with an 8-Fr 10-cm-long introducer (Radifocus, Terumo, Japan), using the Seldinger technique. A puncture of the medial branch of the deep femoral artery was performed by pushing the Colapinto needle (Transjugular intrahepatic access set, COOK, Bloomington) until the tip has reached the extravascular space. **E** Re-entry into the lumen of the distal superficial femoral artery was performed by pushing the needle into the occluded stent (arrow). **F–H** Final angiographic result showing the good patency of the endovascular deep femoral—distal femoral bypass with covered stent grafts that have been deployed into the extravascular space in order to perform the bypass and "bridge" the medial branch of the deep femoral artery to the distal superficial femoral artery (arrow). **H–J** Final angiographic result showing good patency of the distal popliteal, anterior tibial artery (arrow) and the plantar arch of the foot after recanalization and angioplasty

Our objective was to come as close as possible to the distal femoral artery-P1 level (Fig. 1E). Distal landing zone was the supra-articular popliteal artery with previously implanted stent. Exchange of the hydrophilic guidewire with an Amplatz Super Stiff guidewire (Boston Scientific, USA) was performed in order to advance the needle used previously. The guidewire was retracted, and the needle advanced in order to puncture the occluded stent. Once the tip of the needle was inside the occluded stent, a 0.035 hydrophilic stiff guidewire was advanced distally inside the occluded popliteal artery. A 6-Fr 45-cm-long (COOK, Bloomington, USA) introducer was inserted inside the femoral 8-Fr introducer and advanced to the popliteal artery. Recanalization of the anterior tibial artery

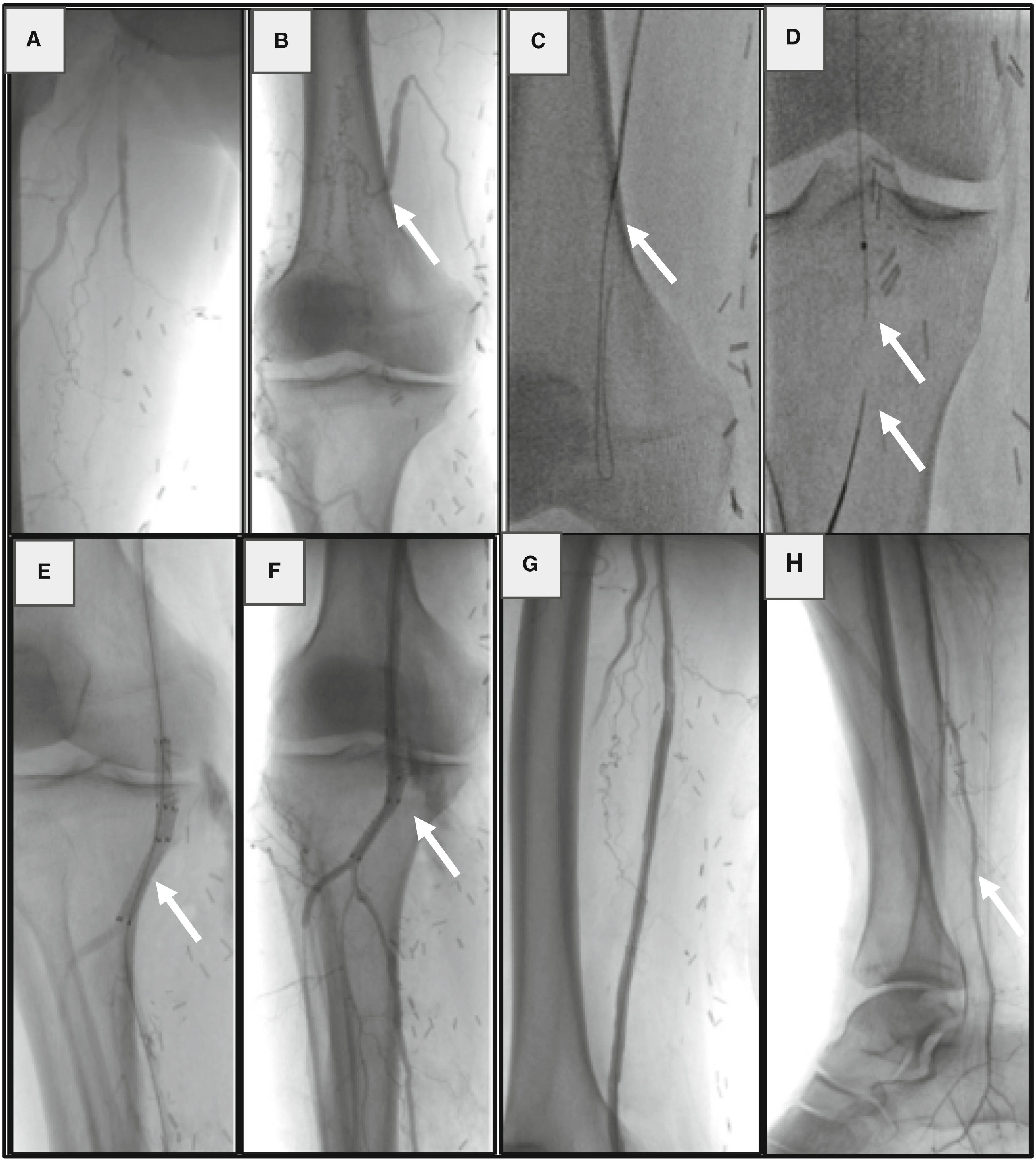
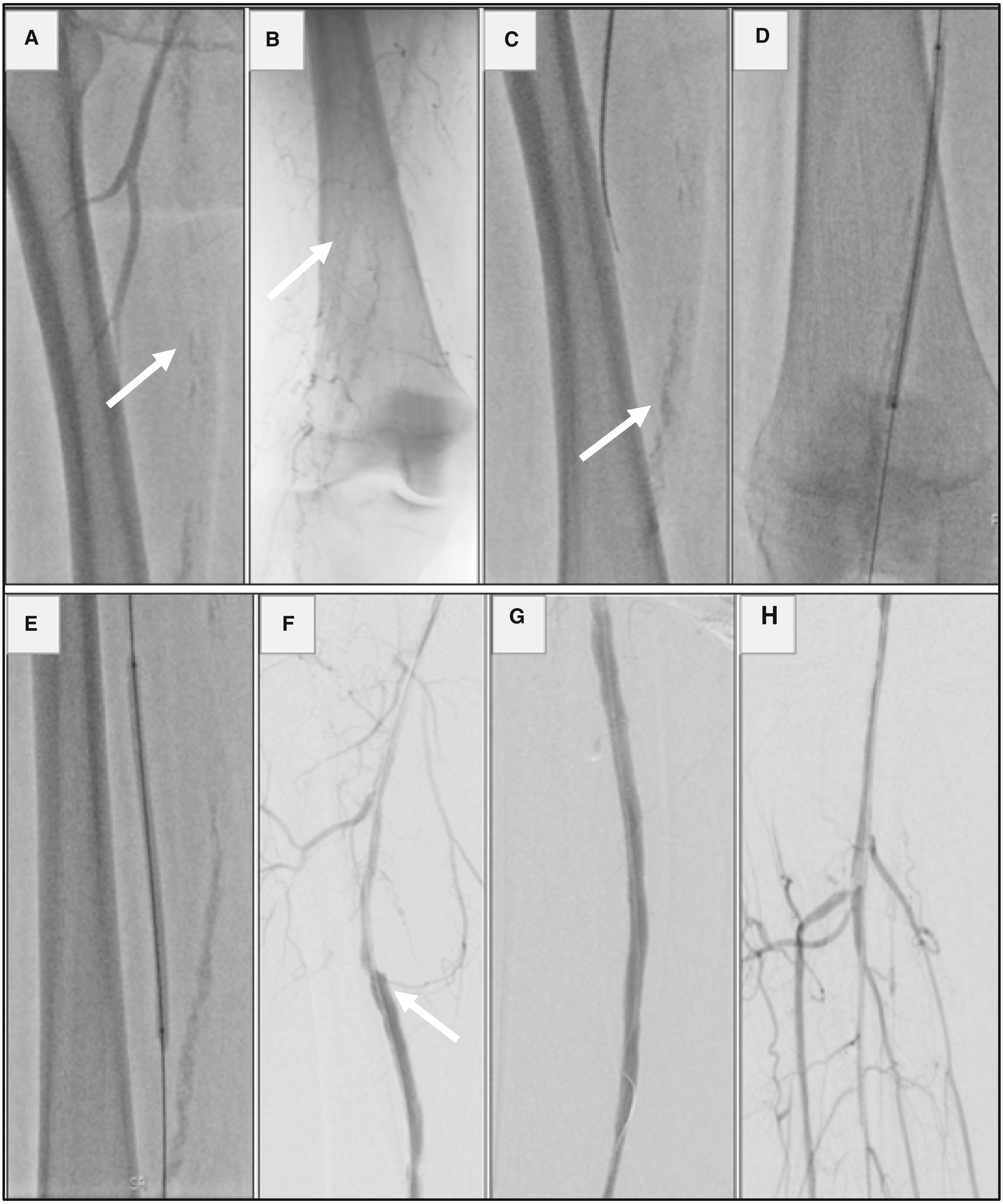


Fig. 2 Revascularization procedure (Patient 2). **A**, **B** Long occlusion of the femoral artery with segmental opacification at the distal third, and popliteal artery ligation (arrow). **C–E** Antegrade ipsilateral femoral artery access; a sub-intimal recanalization of femoral artery to proximal popliteal artery was performed (**C**, arrow). A double approach technique (**D**, arrows) with puncture of the anterior tibial artery was used with placement of covered stent grafts in the extravascular space (arrow) (distal third of the popliteal artery to its proximal third). **F–H** The final angiographic result showed good patency of the extra-anatomic popliteal bypass (**F**, arrow) and good opacification from the superficial femoral artery (**G**) to the distal posterior tibial artery (**H**, arrow)

was then performed, and the stiff guidewire was left in the distal anterior tibial artery. At this point, angioplasty was performed with a 5 × 80 mm balloon (0.035″ Armada, Abbott, USA) at the popliteal artery, the extravascular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◀**Fig. 3** Revascularization procedure (Patient 3). **A**, **B** Angio-anatomical situation precluding traditional revascularization procedure: long calcified occlusion of the femoral and popliteal artery (arrows), poor outflow vessel. **C** Antegrade ipsilateral femoral artery access; advance of the guidewire into the extravascular space, supported by an angulated catheter; supra-articular popliteal artery (the distal landing zone) was targeted with arterial calcifications (arrow) visible under fluoroscopy. **D–E** Angioplasty of the extravascular space, in order to facilitate the placement of covered stent grafts from distal to proximal level. **F–H** Final angiographic result showing good patency of the endovascular deep femoral (**F**, arrow)—supra-articular popliteal artery bypass, good patency of the distal popliteal and lower leg vessels (**H**)

space and the deep femoral artery. The 6-Fr 45-cm-long introducer was progressively retracted in order to facilitate the placement of covered stent grafts. The deployment of extravascular covered stent grafts was performed from distal to proximal landing zones. In Fig. 1, three covered stents of 7 × 150 mm, 8 × 150 mm and 8 × 100 mm (Viabahn, Gore, USA) were inserted, with an overlap over 3 cm in order to avoid any secondary stent graft disconnection.

Once the endovascular bypass was performed, the stiff wire in the anterior tibial artery was exchanged with a V 18 wire and an angioplasty with a 2.5 × 200 mm balloon (0.018″ Armada, Abbott, USA) of the anterior tibial and pedal artery was performed (loop technique).

The final angiographic result was excellent (Fig. 1F–J) with good patency of the bypass, the popliteal artery, the anterior tibial artery, pedal artery and pedal arch.

In the second revascularization procedure, landing zones were the supra-articular and infra-articular popliteal artery targeted during a double approach revascularization technique (Fig. 2). Arterial disease anatomy showed long occlusion of the femoral artery with segmental opacification at its distal third, and popliteal artery ligation, with opacification of the posterior tibial artery and the peroneal artery. Anterior tibial artery presented an occlusion in its middle third. Sub-intimal recanalization from the femoral artery to proximal popliteal artery was performed. Surgical popliteal artery ligation precluded sub-intimal recanalization at this level. The angulated Colapinto needle was used for an intentional puncture of the proximal popliteal artery into the extravascular space (Fig. 2D). A double approach technique was performed with retrograde proximal anterior tibial artery access, and retrograde sub-intimal infra-popliteal recanalization was carried out until popliteal ligation level. An intentional puncture of the popliteal artery was performed putting the tip of the needle into the extravascular space. Continuity was achieved between retrograde and antegrade guidewires into the extravascular space which provided an adequate support for the placement of covered stent grafts: Three stent grafts (6 mm in diameter) were inserted from the distal third of the popliteal artery to its proximal third. The final angiographic result showed opacification from the superficial femoral artery to the distal posterior tibial and peroneal artery.

In the third revascularization procedure, proximal landing zone was one of the branches of the deep femoral artery and the distal landing zone was the popliteal artery, targeted with arterial calcifications visible under fluoroscopy (Fig. 3). Arterial disease anatomy showed long bilateral highly calcified occlusion of the proximal femoral artery and popliteal artery with poor outflow vessel. Bilateral revascularization procedure with endovascular extra-anatomic bypass from the deep femoral artery to supra-articular popliteal artery was performed with 2 months between the two procedures, for limb-threatening ischemia. An antegrade common femoral artery approach was performed. After catheter placement in one of the branches of the deep femoral artery, a BRK Transseptal needle (St. Jude Medical Inc., St. Paul, MN, US) was used for an intentional puncture of the deep femoral artery into the extravascular space (Fig. 3C). Bypass landing zone was the supra-articular popliteal artery targeted with visible arterial calcifications under fluoroscopy. The final angiographic result showed opacification from the deep femoral artery to the supra-articular popliteal artery with two patent lower leg vessels, anterior tibial and peroneal arteries.

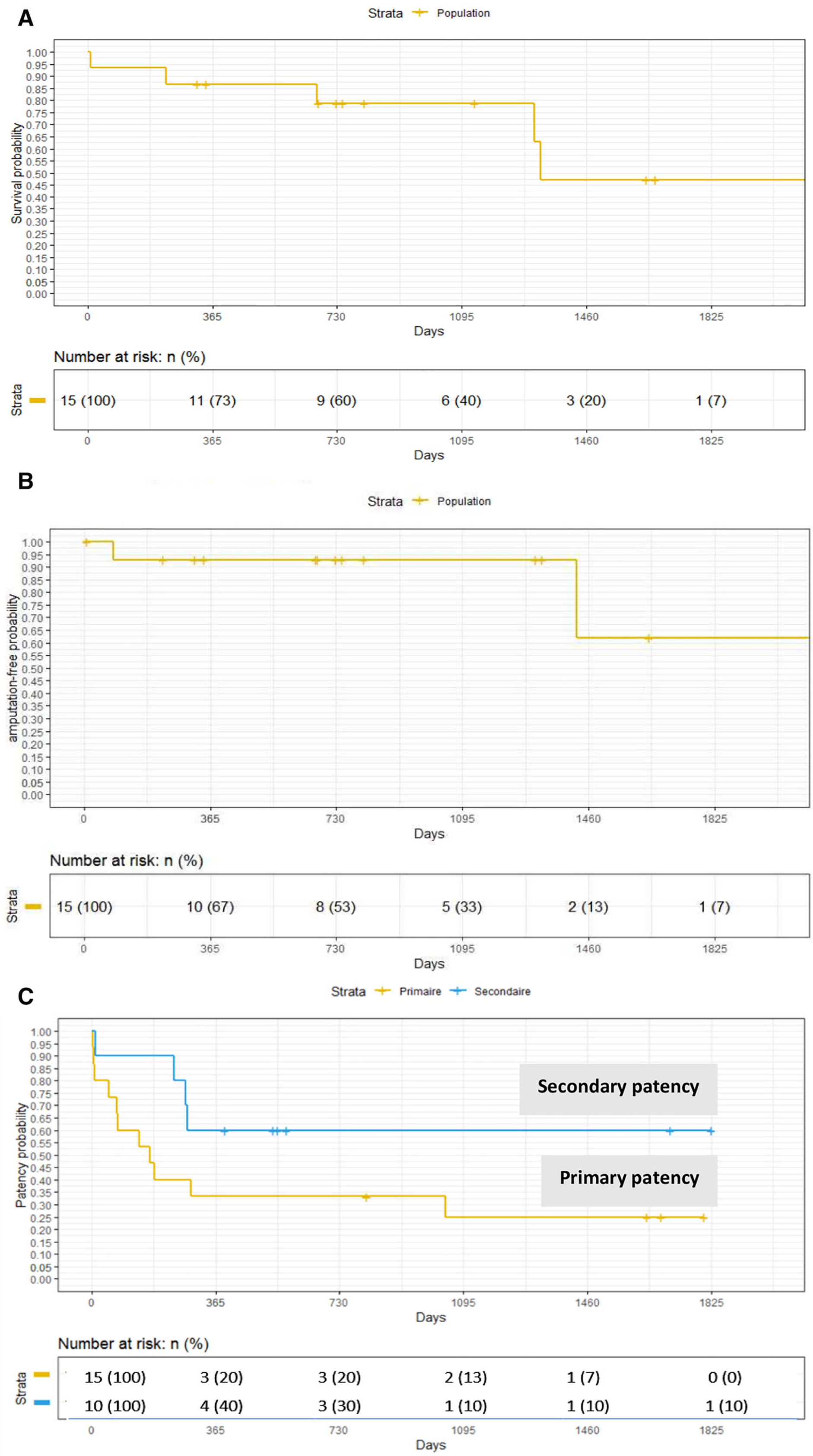
Outcome Data

Technical procedure success was obtained in all patients. Below-the-knee catheter-based revascularization was also performed in 10 patients (67%), in order to obtain at least one direct continuous artery to the distal vascular bed. Clinical improvement was demonstrated in all patients with resolution of rest pain and formation of tissue granulation on the wound. Median (IQR) post-procedural LDF and great toe pressure index were 51 (45–62.5) mmHg and 0.39 (0.34–0.51) mmHg compared to pre-procedural levels of 30 (6.25–34) mmHg and 0.23 (0.04–0.25) ($p = 0.002$ and $p = 0.008$, respectively). Ankle pressure index increased from 0.13 (0–0.43) before intervention to 0.73 (0.59–0.79) in the post-procedure period ($p = 0.017$).

Procedure-related complications through 30 days occurred in two patients (13%): One death occurred secondary to cardiogenic shock and one patient suffered acute coronary syndrome associated with iliopsoas intramuscular bleeding. Peri-procedural hemorrhages at the puncture site occurred in 2 patients (13%) requiring transfusion. There was no major amputation through 30 days.

No patient was lost to follow-up. Median follow-up period was 21.5 (18.25–45.5) months, with last patient visit follow-up on April 2019. Amputation-free survival at 1 year was 80% and 53% at the last follow-up visit.

Fig. 4 Kaplan–Meier curves for survival (A), amputation-free survival (B), primary and secondary bypass patency (C)



Kaplan–Meier curves (Fig. 4) are presented for survival (Fig. 4A), limb salvage (Fig. 4B) and primary and secondary bypass patency (Fig. 4C).

- Four patients died (27%) during the follow-up period. Cumulative mortality at 1 year was 13% and 33% at the last follow-up visit (Fig. 4A). Deaths were related to severe chronic pulmonary obstructive disease at 9 months (one patient), septic shock at 22 months (one patient), peritonitis at 42 months (one patient) and parotid cancer at 44 months (one patient). A known history of coronary artery disease was present in all patients who died during the follow-up period.
- Two patients experienced major limb amputation (13%) because of failure of secondary bypass patency and reoccurrence of limb-threatening ischemia: One patient had below-the-knee amputation 3 months after the revascularization procedure, and one patient had above-the-knee amputation 4 years after revascularization procedure. Both patients regain walking function with prosthetic walking aid and physiotherapy.
- Re-interventions were performed in 10 patients to maintain bypass patency because of recurrent limb-threatening ischemia (Fig. 4B): Early acute bypass thrombosis occurred in three patients within 1 week after the procedure and was managed with percutaneous mechanical thrombectomy; four patients underwent percutaneous mechanical thrombectomy because of bypass thrombosis in the follow-up; angioplasty of in-stent restenosis was performed in three patients in the follow-up. One patient lost bypass patency 3 months after the revascularization procedure, but no re-intervention was performed because of the absence of recurrent CLI.
- At the last follow-up visit, 4 patients (27%) maintained primary bypass patency. Among patients who were revascularized (10 patients), 6 patients (60%) maintained secondary bypass patency at the last follow-up visit (Fig. 4C). Bypass patency in computed tomography angiography is presented for the three revascularization procedures described hereabove (Fig. 5).

Survival, limb salvage and bypass patency outcomes are described in Tables 3 and 4. Complete wound healing was achieved in 11 (73%) patients, with a median healing time of 11 (7–20.5) months.

Discussion

We described here, a percutaneous revascularization technique consisting in an extra-anatomic femoro-popliteal bypass in the management of patients with CLI and no traditional endovascular or surgical revascularization options. It is a promising and innovative revascularization technique for limb salvage in a well-defined subset of patients. One-year amputation-free survival was achieved in 80% of this middle-aged patient population with an independent living status. Complete wound closure was achieved in 73% of patients. However, this endovascular technique remains a challenging procedure with regard to severe patient's comorbidities. The high prevalence of coronary artery disease could have accounted for the high mortality rate observed in this CLI population with end-stage arterial disease.

Due to the heterogeneity in patient's characteristics presenting with CLI, the choice for the initial revascularization strategy is not easily made [11]. In infra-inguinal disease, bypass surgery with an autologous saphenous vein is considered as the procedure of choice in terms of long-term patency and amputation-free survival [12]. Prosthetic bypass grafts compare poorly to vein bypass, with a low patency rate [12]. Surgical site infection is a common complication of prosthetic bypass surgery and is associated with more than twofold increased risk of early graft loss and reoperation [13]. In the present patient population, ligation of the femoral artery secondary to previous operative site infection was present in 4/15 patients (27%) and precluded traditional endovascular procedures. In the remaining patients, previous surgical bypass thrombosis and important arterial calcifications resulted in chronic limb-threatening ischemia with no traditional endovascular or surgical revascularization options.

From a technical point of view, during the revascularization procedure, the intentional arterial puncture at the proximal landing zone level can be performed with the Colapinto needle or with a BRK Transseptal needle (St. Jude Medical Inc., St. Paul, MN, US) (Patient 3, Fig. 3); the transseptal needle is longer but the penetration strength is lower and this can be a challenge for heavy calcified vessels. Femoral artery (SFA) is preferred as a proximal landing zone but should present at least 3 cm of vascular stump. If the vascular stump is insufficient, deep femoral artery is considered as a potential landing zone provided that there are at least two well-developed branches. Distal landing zone is preferentially the popliteal artery above the knee to ensure bypass patency. Landing zone with no previously implanted stent can be targeted as well with arterial calcifications visible under fluoroscopy (Patient 3, Fig. 3) or with a double approach technique (Patient 2, Fig. 2). The extravascular covered stent graft deployment was performed from distal to proximal landing zones in all revascularization procedures. Covered stent grafts Viabahn® (Gore, USA) or Covera™ (BD-Bard, USA) were used for extravascular bypass.

Below-knee amputation has been recommended to patients with CLI if no revascularization can be achieved

Fig. 5 Bypass patency in computed tomography angiography. Patient 1: patency of the right deep femoral—supra-articular popliteal artery bypass, patency of the distal popliteal and anterior tibial artery, in the follow-up, 54 months after revascularization procedure. Patient 2: patency of the sub-intimal recanalization of the left superficial femoral artery, patency of the extra-anatomic popliteal artery bypass (placement of covered stent grafts from the distal third of the popliteal artery to its proximal third) and of the posterior tibial artery, in the follow-up, 12 months after the revascularization procedure. Patient 3: patency of the bilateral endovascular deep femoral—supra-articular popliteal artery bypass, patency of the distal popliteal, and lower leg vessels, in the follow-up, 18 months after the revascularization procedure

[11]. Data on functional outcome in this specific patient population with the most extreme CLI are scarce. In the present study, percutaneous extra-anatomic femoro-popliteal bypass was proposed after discussion in a multidisciplinary consultation meeting. Initial technical success for endovascular bypass was achieved in all patients. However, early graft thrombosis occurred in 20% of procedures; primary and secondary patency rates were 27% and 60%, respectively.

Table 3 Survival, limb salvage and bypass patency

Patients	Revascularization procedure (dd/mm/yyyy)	Re-intervention date (dd/mm/yyyy)	Primary patency	Secondary patency	Limb salvage [yes/no (major amputation date)]	Survival [yes/no (date of death)]
Woman, 68 years	12/06/2013	01/04/2014	No	Yes	Yes	Yes
Man, 65 years	11/02/2014	01/08/2014	No	Yes	Yes	15/12/2015
Woman, 81 years	22/04/2014	0	Yes	–	Yes	19/11/2017
Man, 77 years	26/08/2014	0	Yes	–	Yes	04/09/2014
Man, 41 years	11/09/2014	18/09/2014	No	No	06/08/2018	Yes
Woman, 83 years	08/10/2014	0	Yes	–	Yes	Yes
Man, 66 years	30/10/2014	05/09/2017	No	Yes	Yes	18/06/2018
Man, 69 years	23/02/2016	06/05/2016	No	No	17/05/2016	Yes
Man, 70 years	10/01/2017	0	Yes	–	Yes	Yes
Woman, 61 years	01/04/2017	01/10/2017	No	Yes	Yes	Yes
Man, 63 years	14/03/2017	17/03/2017	No	No	Yes	Yes
Man, 67 years	26/05/2017	13/10/2017	No	Yes	Yes	Yes
Man, 79 years	16/01/2018	06/03/2018	No	Yes	Yes	01/09/2018
Man, 60 years	15/05/2018	19/05/2018	No	No	Yes	Yes
Man, 51 years	20/04/2018	0	No	No	Yes	Yes

Table 4 Perioperative and cumulative 1-year adverse outcomes

Variables	Patients, $n = 15$
Death, n (%)	
Perioperative	1(7%)
Cumulative 1-year mortality	2 (13%)
Non-fatal CV events, n (%)	
Perioperative	1 (7%)
Cumulative 1-year CV events	1 (7%)
Major amputation, n (%)	
Perioperative	0
At 1 year	1 (7%)

Continuous variables were presented as median (IQR); *CV* cardiovascular

Patients with CLI are more likely to have severe atherosclerosis and coronary artery disease accounting for the high morbidity and mortality rates. After peripheral arterial disease revascularization, reported risk of myocardial infarction, ischemic stroke or cardiovascular death through 12 months is about 16.8% among patients with CLI [14]. In patients with CLI, literature data underlined a 1-year mortality rate, amputation rate and amputation-free survival of 20%, 30% and 60%, respectively [15]. In our patient population, peri-procedural mortality and morbidity were mainly related to cardiovascular events (13%), spontaneous iliopsoas intramuscular bleeding (7%) and hemorrhages at the puncture site requiring transfusion (13%). Four patients died during follow-up from causes unrelated to CLI management. Cumulative mortality after 1 year and at the last follow-up visit was 13% and 33%, respectively. The high morbidity and mortality in this patient population must be taken into account while attempting limb salvage. Identification of predictors for poor outcomes in these patients would ultimately lead to adapted treatment strategies without prohibitive peri-procedural risk. Furthermore, management of antithrombotic therapy in the acute and chronic phase is challenging with regard to the risk of bleeding in the perioperative period. This revascularization procedure is expected to be more hemorrhagic than traditional endovascular technique because of difficult arterial puncture site due to previous femoral access and required antithrombotic therapy associating dual antiplatelet therapy and anticoagulation with LMWH maintained after the procedure.

Our patient population with severe CLI was relatively young, and preserving functional status was the primary objective of this revascularization procedure. A multidisciplinary setting is required for the treatment strategy in patients with CLI so that no patient should undergo a major amputation without taking into account all treatment alternatives. We describe here the percutaneous extra-anatomic femoro-popliteal bypass technique for limb salvage in patients with CLI in the absence of feasible revascularization with encouraging outcomes.

Limitation of our experience is that this technique is performed in a monocentric specialized center. The limited number of patients with inhomogeneous angio-anatomical situations is expected since this patient population presents with very variable anatomies, just as the underlying disease evolving since a long period of time with multiple previous invasive treatment attempts.

Conclusion

In conclusion, percutaneous extra-anatomic femoro-popliteal bypass is technically feasible and represents a promising revascularization strategy for limb salvage in patients with CLI and no option for traditional surgical or endovascular revascularization procedure. This is a technically demanding limb salvage procedure, requiring frequent re-interventions to maintain secondary patency. Indication and procedure-related major complications should be discussed in the multidisciplinary team meeting. Further studies are required to better define primary and secondary patency as well as limb salvage in this population.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

Consent for Publication Consent for publication was obtained for every individual person's data included in the study.

Disclosures The authors are solely responsible for the design and conduct of this study, all study analyses, the drafting and editing of this paper and its final contents.

Ethical Approval For this type of study, formal consent is not required.

Informed Consent Informed consent was obtained from all individual participants included in the study.

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