

# Critical limb ischemia: current challenges and future prospects

Luigi Uccioli<sup>1</sup>  
Marco Meloni<sup>1</sup>  
Valentina Izzo<sup>1</sup>  
Laura Giurato<sup>1</sup>  
Stefano Merolla<sup>2</sup>  
Roberto Gandini<sup>2</sup>

<sup>1</sup>Department of Systems Medicine,

<sup>2</sup>Department of Interventional Radiology, Università di Tor Vergata Roma, Rome, Italy

**Abstract:** Critical limb ischemia (CLI) is considered the most severe pattern of peripheral artery disease. It is defined by the presence of chronic ischemic rest pain, ulceration or gangrene attributable to the occlusion of peripheral arterial vessels. It is associated with a high risk of major amputation, cardiovascular events and death. In this review, we presented a complete overview about physiopathology, diagnosis and holistic management of CLI. Revascularization is the first-line treatment, but several challenging cases are not treatable by conventional techniques. Unconventional techniques for the treatment of complex below-the-knee arterial disease are described. Furthermore, the state-of-the-art on gene and cell therapy for the treatment of no-option patients is reported.

**Keywords:** peripheral arterial disease, critical limb ischemia, medical therapy, revascularization, cell therapy

## Introduction

Critical limb ischemia (CLI) may be considered the most severe pattern of peripheral artery disease (PAD), being associated with a high risk of major amputation, cardiovascular events and death.<sup>1</sup> A mortality rate of 20% within 6 months after the diagnosis and 50% at 5 years has been reported.<sup>2,3</sup> This excessive mortality may be related to the systemic cardiovascular diseases, including coronary artery disease and cerebrovascular arterial disease.<sup>4,5</sup> Furthermore, CLI is associated with peripheral complications such as ulceration, gangrene, infection and a high risk of lower limb amputation estimated in 10%–40% of patients at 6 months, especially in non-treatable patients.<sup>6,7</sup>

## Definition

According to the Inter-Society Consensus for the Management of Peripheral Arterial Disease (TASC II), CLI is defined by the presence of chronic ischemic rest pain, ulceration or gangrene attributable to arterial occlusive disease.<sup>7</sup> Usually, the impairment of peripheral perfusion is a long chronic process that occurs along months or years in relation to age, predisposing factors and cardiovascular risk factors such as smoke, diabetes, hypertension, dyslipidemia, chronic kidney disease, hypercoagulable states and hyperhomocysteinemia.<sup>8</sup>

The diagnosis of CLI is defined by clinical findings associated with objective peripheral examination such as ankle–brachial index (ABI), toe systolic pressure and transcutaneous oxygen pressure (TcPO<sub>2</sub>). CLI is considered in case of ischemic rest pain with ankle pressure <50 mmHg or a toe pressure <30 mmHg and in patients affected by

Correspondence: Luigi Uccioli  
Department of System Medicine,  
Università di Tor Vergata Roma, Viale  
Oxford 81, 00133 Rome, Italy  
Tel +39 34 8371 0745  
Email luccioli@yahoo.com

foot ulcers or gangrene by an ankle pressure  $<70$  mmHg, a toe systolic pressure  $<50$  mmHg or  $\text{TcPO}_2 <30$  mmHg.<sup>7</sup> Among CLI subjects, a subgroup of asymptomatic patients should be considered. They usually are sedentary or diabetic patients with peripheral neuropathy with reduced pain perception. In these patients, CLI is defined in case of ulceration or non-healing ulcers in the presence of arterial occlusive disease.

## Pathophysiology

CLI is usually the result of multi-segmental PAD with impaired blood flow in peripheral tissues. In some cases, the simultaneous presence of impaired cardiac output may worsen the peripheral perfusion in CLI patients. The reduced oxygenation and nutrition of peripheral tissues may cause claudication or rest pain, even if this typical symptom of PAD may be reduced or absent in diabetic patients with neuropathy. Furthermore, diabetic CLI patients show usually distal arterial lesions characterized by the involvement of the vessel below the knee (BTK), and often the first signs of PAD are ulceration, necrosis or gangrene.

## Diagnosis of PAD and CLI

The detection of PAD/CLI is characterized by different steps. The holistic approach requires the identification of cardiovascular risk factors and the evaluation of peripheral pulses (femoral, popliteal, dorsalis pedis and posterior tibial artery) even if their presence cannot exclude completely a potential condition of ischemia.<sup>9</sup> The diagnosis of PAD is usually the result of clinical evaluation associated with one or more instrumental examinations. Among the first-level examinations, we find ABI, TBI,  $\text{TcPO}_2$  and ultrasound (US) color duplex. The second-level examinations included are magnetic resonance imaging (MRI) and computed tomography (CT). ABI defines a condition of reduced peripheral blood flow if  $<0.9$ . A value  $<0.4$  identifies a severe ischemia.  $\text{ABI} >1.3$  may be related to peripheral calcification and PAD cannot be excluded. Normal values are between 0.9 and 1.3.<sup>10,11</sup> TBI  $<0.50$  associated with abovementioned clinical findings identifies a condition of CLI.<sup>12</sup>  $\text{TcPO}_2$  is usually used to identify the chance of healing in diabetic patients with foot ulceration (FU). Furthermore, revascularization is often indicated in patients with foot ulcers and  $\text{TcPO}_2 <30$  mmHg to allow wound healing (Box 1).<sup>13</sup>

US color duplex is a sensitive and specific examination that allows to obtain several data about peripheral flow even if it is related to personal skills and patient's compliance determined by the operator dependence and the patient collaboration.<sup>14,15</sup> MRI and CT are the gold-standard to detect

### Box 1 Definition of CLI

Presence of chronic ischemic rest pain plus

- ankle pressure  $<50$  mmHg or
- toe pressure  $<30$  mmHg

Presence of foot ulcers or gangrene plus

- ankle pressure  $<70$  mmHg
- toe systolic pressure  $<50$  mmHg or
- $\text{TcPO}_2 <30$  mmHg

**Abbreviations:** CLI, critical limb ischemia;  $\text{TcPO}_2$ , transcutaneous oxygen pressure.

the arterial lesions. They provide an accurate description of stenosis or obstructions and could help the vascular surgeons or the interventional radiologist performing the revascularization.<sup>16</sup> MRI is not indicated in patients with pacemaker, sutures and metal implants and claustrophobic patients. Furthermore, it cannot be performed in patients with glomerular filtration rate  $<30$  mL/min due to the high risk of nephrogenic systemic fibrosis.<sup>17–19</sup> In addition, CT allows a clear evaluation of peripheral arterial district. Its limitation may be related to the use of iodinated contrast organ and increased risk of contrast-induced nephropathy in patients with severe chronic kidney disease.<sup>20</sup> In high-risk patients with impaired renal function, some data support the use of carbon dioxide ( $\text{CO}_2$ ) as an alternative supplemental contrast agent that can be applied safely preventing kidney dysfunction.<sup>21</sup>

## Holistic management of CLI patients

The goal of CLI treatment is to relieve pain, allow wound healing, improve patient's function, prevent limb amputation and reduce mortality. Lower limb revascularization is the first-line treatment in CLI patients that can tolerate this procedure. In few cases, CLI patients with multiple comorbidities or low chance of successful revascularization may require a primary amputation. A simultaneous medical intervention is required for pain management, control of cardiovascular risk factors and optimization of glycemic control.

## Medical treatment

### Pain

Pain management is essential to improve quality of life and function. Commonly, in the majority of cases, adequate peripheral revascularization relieves peripheral pain. In no option-CLI patients, identified as subjects not treatable by revascularization, medical therapy is mandatory. Paracetamol and nonsteroidal anti-inflammatory drugs are usually the first-line treatment even if opioids are often required. Usually, a

regular administration of analgesic therapy is more effective than that on demand. Owing to the presence of peripheral neuropathy, in some cases, pain may be neuropathic. A careful differential diagnosis should be performed because neuropathic pain may require a different therapeutic approach.

## Smoking

Smoking cessation is strongly required to reduce the worsening of PAD and the risk of major amputation and any cardiovascular events. Furthermore, smoke increases the risk of revascularization failure.<sup>22</sup> Furthermore, smoking cessation reduces mortality and improves amputation-free survival in patients in comparison with those who continue smoking.<sup>23</sup>

## Dyslipidemia

Total cholesterol, low-density lipoprotein cholesterol (LDL-C), triglycerides and lipoprotein(s) are risk factors for development and progression of PAD.<sup>24</sup> The use of statins in PAD patients is recommended. It is well documented that low levels of LDL-C reduce cardiovascular events (myocardial infarction, cerebrovascular events), and the goal in all patients with PAD is LDL-C <70 mg/dL.<sup>25,26</sup>

## Hypertension

Guidelines suggest a close control of blood pressure with values <140/90 mmHg in all patients and <130/80 mmHg in diabetic patients or patients with proteinuria.<sup>27</sup> All drugs that are effective in lowering blood pressure can be used: thiazide diuretics, angiotensin-converting enzymes (ACEs), angiotensin receptor blockers (ARBs), calcium channel blockers (CCBs) and beta-adrenergic blockers. In diabetic patients, ACE and ARB are considered as the first-line treatment.

## Diabetes

Diabetes is recognized as a strong risk factor of PAD. A close control of glycemia should be considered to reduce the progression of micro- and macrovascular complications even if PAD is usually related to different cardiovascular risk factors.<sup>28,29</sup>

Diabetes increases the risk of PAD approximately three- to fourfold and the risk of claudication to twofold. Most patients with diabetes have other cardiovascular risk factors (smoking, hypertension and dyslipidemia) that contribute to the development of PAD. Diabetes is also associated with peripheral neuropathy and decreased resistance to infection, which leads to an increased risk of foot ulcers and foot infections. Furthermore, there is a common thought that impaired glycemic control may increase the risk of nonhealing of diabetic foot ulcers even if there are no studies that

evaluated the impact of HbA1c on the outcomes of diabetic foot ulcers. However, HbA1c is considered as a predictor of major amputation,<sup>30,31</sup> and hyperglycemia is an independent risk factor for mortality in hospital patients with diabetic foot.<sup>32</sup> HbA1c <7.0% is the goal to reduce the risk of macrovascular complication and progression of PAD.<sup>30</sup>

## Antiplatelet therapy

Aspirin/acetylsalicylic acid (ASA) or clopidogrel is indicated for secondary prevention in patients with PAD and/or other cardiovascular diseases. Low dose of aspirin/ASA (75–160 mg) is effective and safe during related complications such as gastrointestinal bleeding.<sup>33</sup> In diabetic patients who undergo lower limb revascularization, dual antiplatelet therapy (ASA+clopidogrel or ticlopidine) is recommended for at least 1 month after endovascular procedure; after 1 month, ASA or clopidogrel should be lifelong continued.<sup>34</sup>

## Treatment of CLI

Revascularization is the first-line treatment for CLI. Revascularization may be surgical through bypass or endovascular technique. There is an open debate whether open surgery is preferable or not to angioplasty. Nowadays, the decision is related to many factors: anatomical lesions, distribution of arterial disease, patient's health status, comorbidities, presence of foot ulcer and foot infection and local expertise.

The Bypass versus Angioplasty in Severe Ischemia of the Leg (BASIL) study was a multicenter, randomized controlled trial that compared bypass surgery first vs angioplasty first in patients presenting with CLI due to infrainguinal disease.<sup>35</sup> In the middle term, the rates of amputation-free survival, all-cause mortality and health-related QOL were similar in both groups, while morbidity and hospital costs were higher in the surgery group in comparison with the endovascular group. In relation to long-term outcomes, the surgical patients who achieved limb salvage >2 years reported a longer survival than the angioplasty patients.

Two meta-analysis reviewed infrapopliteal angioplasty in CLI patients in comparison to popliteal–distal vein bypass grafts in a homogeneous cohort of patients. The rate of limb salvage was similar comparing open surgery and endovascular approach.<sup>36,37</sup> Therefore, the authors support percutaneous transluminal angioplasty (PTA) as a useful option to treat CLI.

## CLI in diabetic patients with FU

The treatment of CLI in diabetic patients with FUs is a topic of discussion in the last few years, and the majority of guidelines referred to general consensus or native experience.

In case of FUs in diabetic patient with PAD, it is mandatory to evaluate the usefulness of revascularization and then the method of revascularization according to several parameters: the chance of healing, the foot aspect and its potential mechanical function after local surgical procedures, the arterial lesions and the patient's general conditions.

The chance of healing is related of foot perfusion, and this aspect is directly related to successful revascularization. In this context, TcPO<sub>2</sub> may be helpful to detect the chance of healing and the indication to revascularize or not. Faglia et al have identified TcPO<sub>2</sub> levels <34 mmHg as indication for revascularization due to the rate of 85% of amputation in the case of no revascularization; in patients with TcPO<sub>2</sub> between 34 and 40 mmHg, the probability of amputation was ~20% and the need of revascularization should be established according to physician's evaluation, while TcPO<sub>2</sub> values of >40 mmHg revascularization should be considered in case of extended tissue loss, osteomyelitis treated by conservative approach or slow healing (ie, absence of signs of healing after 4–6 weeks of gold standard therapy).<sup>38</sup>

The residual foot function should be always considered in the limb salvage procedures. In case of severe impairment, primary amputation may be considered. However, also in this case, it is useful to evaluate the chance of revascularization to allow a more distal amputation (BTK), achieve the healing of amputation stump and improve the next rehabilitation.

In order to choose the best revascularization technique, it is mandatory to have an adequate knowledge of vascular tree (mainly the involvement of common iliac and femoral arteries) and to evaluate the distal runoff. Regardless of the revascularization approach, the procedure should ensure direct flow to dorsal pedal or plantar arch.<sup>39</sup>

Patient's general health needs to be considered, mainly life expectancy and comorbidities. Bypass approach usually requires at least 2 years of life expectancy, while in case of life expectancy <6 months, there is no indication to any revascularization procedures.<sup>40</sup> However, this is the general indication, but any situation should be analyzed case by case, considering the impaired quality of life related to peripheral ischemia.

According to comorbidities, the presence of dialysis complication should be considered in the evaluation of potential outcomes after limb salvage protocol. In fact, literature reports that between 22% and 44% of diabetic-dialyzed patients with CLI are candidates for primary amputation. They are very difficult to treat, and they show high short-term (3%–17%) and long-term mortality rate (55%) that may influence the chance to revascularize these patients.<sup>41–43</sup>

In a recent paper, our group confirmed that diabetic patients with CLI and FUs on dialysis have reduced chances of healing and higher risk of major amputation and death if compared to non-dialyzed patients.<sup>44</sup> We reported 65% of limb salvage, 21% of mortality and 14% of major amputation after endovascular revascularization in dialyzed patients during a mean follow-up of 15 months, while non-dialyzed patients had 78.2% of limb salvage, 10.8% of major amputation and 11% of death. In comparison to non-dialysis group, patients on dialysis had more steno-obstructions, higher risk of unsuccessful revascularization and needed more procedures to get limb salvage. However, it is hard to find a specific factor predictive of outcome in dialyzed subjects; therefore, we retain that all diabetic-dialyzed patients with ischemic FUs have to be considered as high-risk patients as a whole.

Our results obtained in diabetic-dialyzed patients are similar to those reported in literature in terms of limb salvage.<sup>45</sup> However, it must be highlighted that in these studies, the outcomes are referred only to patients revascularized after a careful selection, while the outcomes reported in our study refer to unselected consecutive patients.

## Revascularization technique

There is still an open debate on the first-line strategy between open surgery and endovascular revascularization in diabetic patients. PTA has shown good results in term of limb salvage, feasibility and complications,<sup>45–47</sup> especially for infrainguinal lesions.

Even if bypass is characterized by a long-term patency, angioplasty can be performed in patients not suitable for bypass due to the presence of several comorbidities, reduced life expectancy, unavailability of veins, absence of landing zone for distal bypass and foot infection in the site of potential anastomosis.<sup>36,48–51</sup> Angioplasty does not require general anesthesia and usually shows few contraindications in patients with active comorbidities. Furthermore, in fragile patients with impaired renal function and in case of complex procedure, angioplasty can be performed in various steps to reduce physical stress and the amount of contrast medium administered. However, it has been shown that through an adequate prophylaxis, the risk of contrast-induced nephropathy is very low also in patients with advanced renal failure.<sup>52</sup>

Angioplasty can also be easily repeated in case of restenosis or can be proposed after bypass failure.<sup>53–55</sup>

The choice of revascularization technique should be examined case by case according to vascular disease and local expertise. Obstruction of the common femoral artery and its bifurcation is usually suitable for surgical approach. In case

of long occlusion of femoral–popliteal and infrapopliteal vessels, bypass is usually more effective and ensures long patency; however, there is a real consensus and this pattern of PAD may be treated by endovascular approach in centers with long experience with angioplasty.<sup>50,56–58</sup> Atherectomy is considered as an alternative technique in the treatment of PAD to excise the atheroma by a rotating cutting blade. However, there is poor evidence to support atherectomy as an alternative to balloon angioplasty in maintaining primary patency. There was no evidence for superiority of atherectomy over angioplasty on any outcome.<sup>59,60</sup>

## Current challenges and future perspectives

### Unconventional techniques for treatment of complex BTK CLI

The ipsilateral antegrade approach, allowing optimal pushability and trackability of guidewires and balloon catheters through infrapopliteal lesions, can ameliorate rates of complex BTK procedures compared to the contralateral common femoral approach.

Nevertheless, failure rates of conventional antegrade revascularization in intraluminal or subintimal manner for occlusive lesions still range from 10% to 40% in the BTK district, despite the use of innovative technologies and the development of dedicated devices.<sup>61–63</sup>

In the last few years, there has been a great evolution of endovascular strategies conceived to recanalize some complex patterns of CLI, thus enabling the treatment of a larger number of patients. Several alternative techniques have been proposed to increase the chance of success for tibioperoneal occlusions: pedal–plantar loop technique for the revascularization of foot arteries (Figure 1), trans-collateral angioplasty for chronic total occlusion of the tibial vessels (Figure 2) and combining intraluminal or subintimal recanalization with a double antegrade–retrograde approach puncturing either the pedal or the posterior tibial artery (PTa) performed in cases of femoropopliteal occlusions extending to the popliteal trifurcation or in order to preserve blood flow to the foot sustained by collaterals (Figure 3).<sup>64–67</sup>

Another unconventional revascularization technique has been described as a rescue strategy by Palena and Manzi<sup>68</sup> who performed in cases of failure of antegrade approaches when tibial and pedal arteries are occluded or are not amenable for direct retrograde puncture, a retrograde direct puncture of the transmetatarsal arteries or the plantar arch with the encouraging result of 71% of amputation-free survival at 6 months of follow-up.

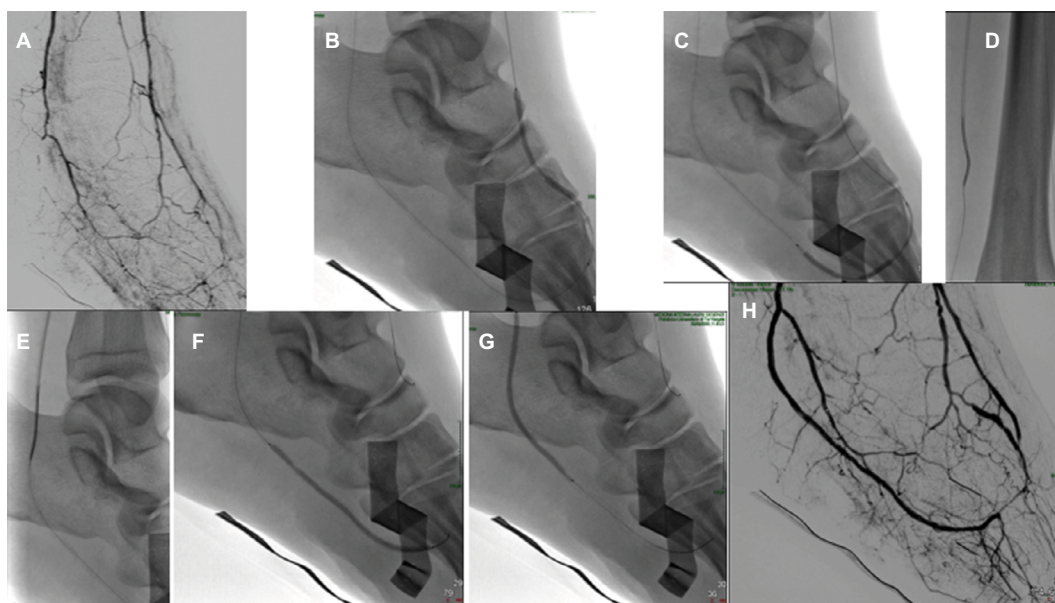
The increasingly widespread use of these alternative, albeit demanding, endovascular techniques has allowed a good rate of limb salvage in the treatment of complex occlusions in case of failed antegrade BTK revascularization attempts. In a recent study, our group reported a limb salvage rate of 83% at 6 months of follow-up using alternative techniques; furthermore, we had a reduction in major amputation (16% vs 39%) in comparison to a previous study where conventional techniques were exclusively used.<sup>68</sup>

### Target revascularization

Although Taylor and Palmer<sup>70</sup> provided for the first time in 1987 with reconstructive plastic surgery purposes precious anatomical information about arteriovenous bundles called angiosomes,<sup>69</sup> their clinical implications for limb salvage have been demonstrated only 10 years ago by Attinger et al who reported in a series of 52 distal bypasses higher unsuccessful wound healing rates (38%) when ulcers were revascularized indirectly compared to lower unsuccessful wound healing rates (9%) when ulcers were revascularized by their angiosomes. Since 2007, many prospective and retrospective studies<sup>71–76</sup> have showed better outcomes for patients undergoing lower limb revascularization according to the angiosome theory; thus currently, the main aim of limb salvage procedures is to restore a direct straight-line inflow to the target wound area in agreement with these principles. According to the concept of wound-related artery and the abovementioned angiosome-directed revascularization, the usefulness of TcPO<sub>2</sub> in the diagnosis of CLI in relation to wound site and corresponding angiosome has been also showed. Particularly, Izzo et al<sup>78</sup> showed that in case of heel ulcer, TcPO<sub>2</sub> recorded on the dorsum of the foot does not confirm the presence of CLI (not <30 mmHg); a second oximetry recorded on the rearfoot may be useful to point out ischemia of the peroneal artery and/or of the posterior tibial artery.

### Venous arterialization

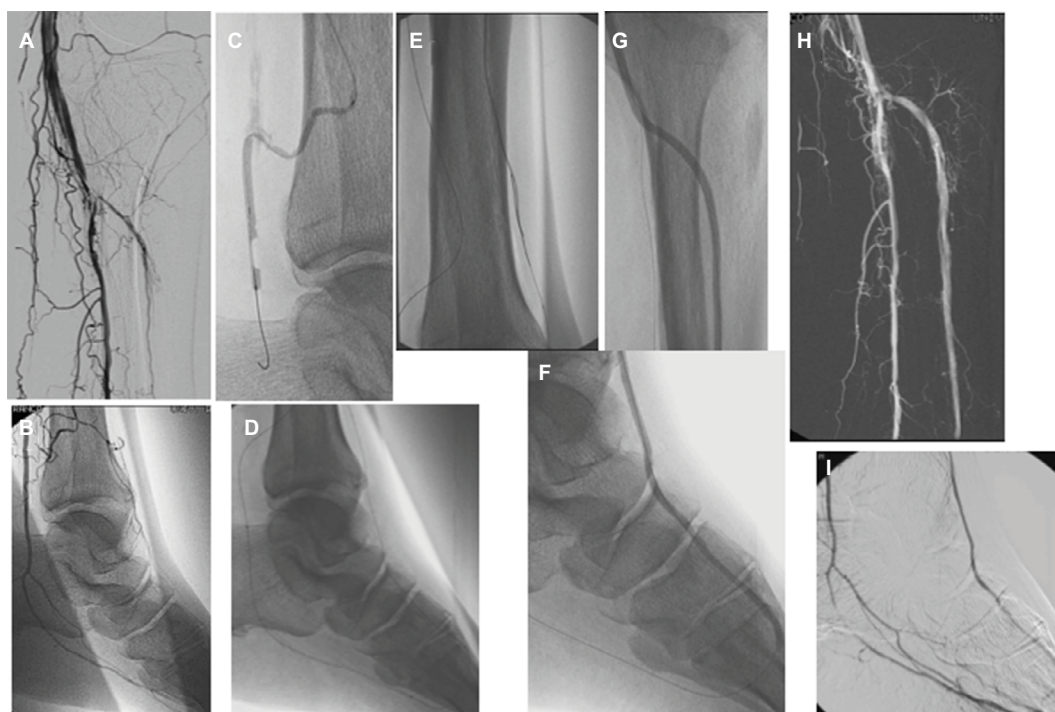
Clinical effectiveness of BTK revascularization, performed either by traditional or unconventional techniques, is often poor in diabetic-dialyzed patients with CLI due to the severity of foot arteries disease. Improvement in peripheral perfusion is obtained approximately in only half of this peculiar subset of patients<sup>77</sup> due to the more severe pattern of arterial disease, often characterized by long calcified occlusions that are extremely difficult to recanalize, especially in patients with heel ulcers and with involvement of posterior tibial artery. Moreover, a BTK amputation is mandatory in case of nonhealing heel ulcers, leading to worse prognosis.<sup>78</sup> Long



**Figure 1** Pedal to plantar technique.

**Notes:** Preprocedural angiography (A). Multiple balloon dilations performed in a pedal to plantar loop manner (B and C). After the rendezvous in the PTa of the antegrade catheter and the retrograde guidewire advanced from the ATA (D and E), further balloon dilations have been performed in an antegrade manner from the posterior tibial artery (F and G). Final angiography (H).

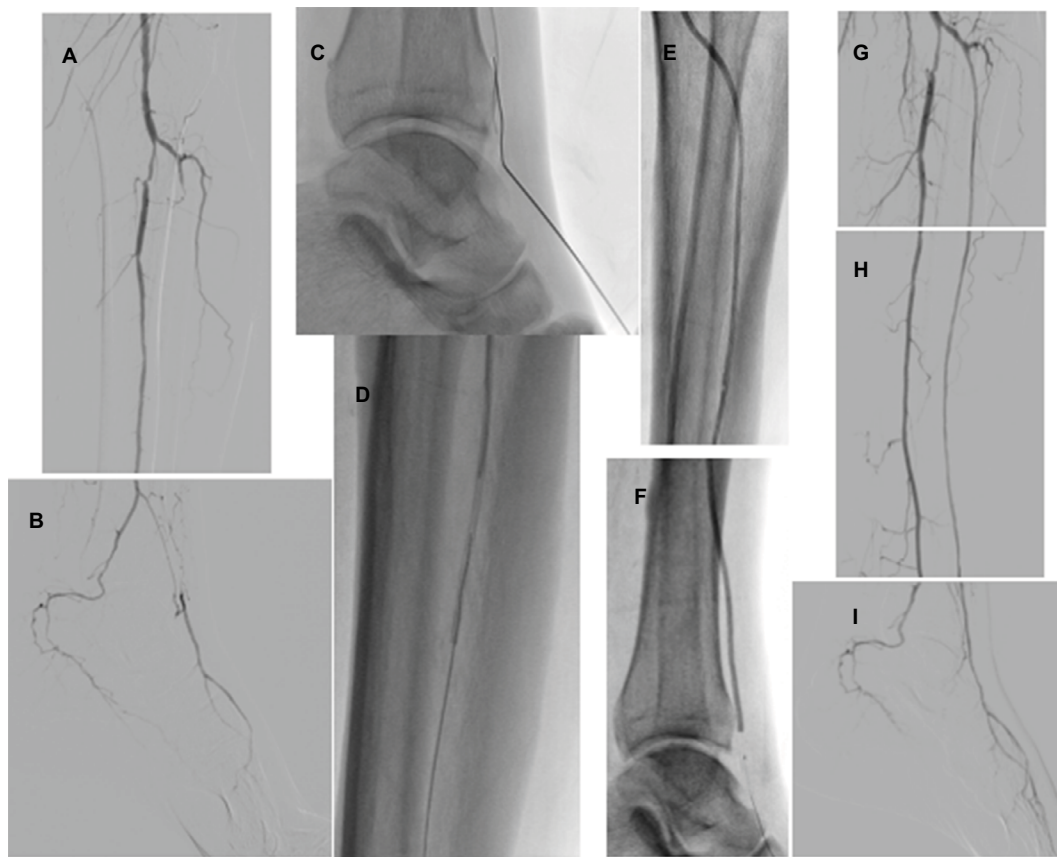
**Abbreviation:** PTa, posterior tibial artery.



**Figure 2** Trans-collateral technique.

**Notes:** Owing to the chronic occlusion of the ATA, in order to avoid damage to the anterior perforator branch of the peroneal artery, which sustained blood flow to the pedal artery (A and B), a retrograde recanalization of the plantar arch and the ATA through the lateral calcaneal branch of the peroneal artery was performed (C–E). After the rendezvous of the antegrade and retrograde guidewires in the ATA, multiple balloon dilations were done in an antegrade manner (F and G). Patency of the ATA lumen was reestablished at the final angiographic control (H and I).

**Abbreviation:** ATA, anterior tibial artery.



**Figure 3** Double approach technique.

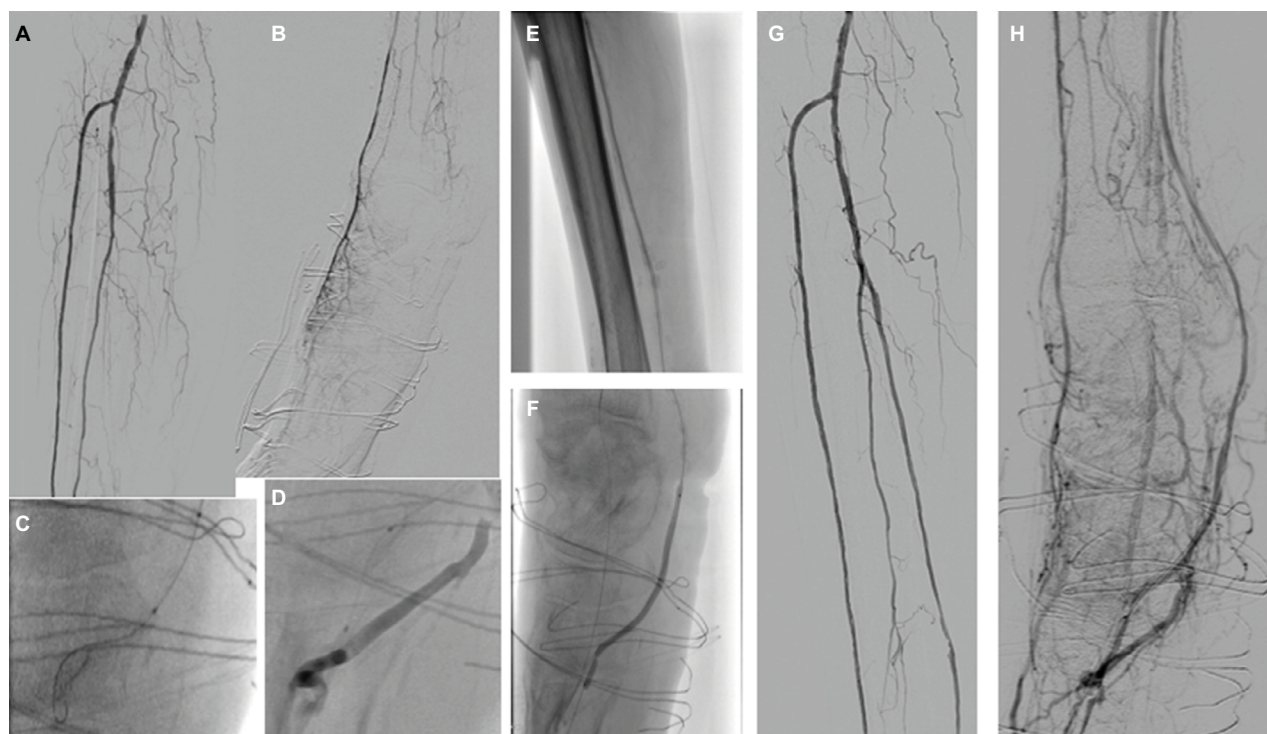
**Notes:** Preprocedural angiography showed occlusion of the ATA with patency of the pedal artery via the anterior perforator branch of the peroneal artery (**A** and **B**). In order to avoid the dissection of this precious collateral, the subintimal recanalization of the ATA was not extended beyond this level; therefore, a retrograde puncture of the plantar artery was performed (**C**). After the rendezvous (**D**) of the guidewires advanced in opposite directions, balloon dilatation (**E** and **F**) from the antegrade approach was performed obtaining a direct straight flow to the forefoot (**G–I**).

**Abbreviation:** ATA, anterior tibial artery.

calcifications can hinder not only the intraluminal or subintimal progress of guidewires but also a potential intraluminal reentry from a subintimal space. In these cases, it might be very challenging to ensure an adequate flow in the wound area, especially in patients with poor or absent runoff.

A new technique has been recently proposed to cross the patchy calcifications of posterior tibial arteries and plantar arteries allowing the creation of an arteriovenous fistula with the surrounding plantar veins.<sup>79</sup> The deep plantar venous arch runs from the proximal end of the first interosseous space to the base of the fifth metatarsal and accompanies the deep plantar arterial arch, which receives the deep metatarsal veins and surrounding muscular veins. In the deep plantar system, doubled veins have been constantly observed with the corresponding arteries. The vessels are surrounded by connective tissue, and this arrangement facilitates venous compression by the artery, serving as a localized pumping action. In this very recent paper, Gandini et al showed the potential role of this technique achieving direct blood flow to

the lesion through the distal venous circulation by means of a completely percutaneous arterialization of the venous bed (Figure 4) in patients not treatable by conventional or alternative endovascular techniques due to long calcific occlusions of PTa and poor or absent runoff. In these case series, 33% of patients underwent BTK amputation at 6 months after the procedure, while 66% had limb salvage. Although further investigations enrolling larger patient populations are needed, these data should be considered very encouraging in dialyzed patients affected by CLI in relation to the high risk of major amputation historically recorded in this complex subset of patients. Even if the earliest theories about the arterialization of the peripheral venous bed were developed more than one century ago,<sup>80</sup> the mechanisms that may justify the benefits of venous arterialization for improving wound healing are still poorly understood, but reversed perfusion of arterioles through the arterial network of the foot and neovascularization stimulated by angiogenic factors seem to be the most likely explanations.<sup>81</sup>



**Figure 4** Distal venous arterialization.

**Notes:** Preprocedural angiography showed patency of the ATA and the peroneal artery with absence of the PTa, medial plantar artery and lateral plantar artery (A and B). After a failed intraluminal attempt, a subintimal recanalization of the PTa was performed, but a reentry in the true lumen of the medial plantar artery was not achieved. Therefore, an entry in the distal plantar vein was obtained (C) and then confirmed by a gentle injection of a contrast medium through the balloon catheter (D). After balloon catheter dilatations of the arteriovenous fistula and the occluded arterial segment (E–F), postprocedural angiography showed patency of the PTa (G) and a good retrograde filling of the small distal venous channels toward the nonhealing wound area of the heel (H).

**Abbreviations:** ATA, anterior tibial artery; PTa, posterior tibial artery.

## Gene and cell therapy

There is a large amount of CLI not eligible for revascularization procedure due to several comorbidities, high operative risk, multiple failures of revascularization, high rate of restenosis or reocclusion after angioplasty and/or bypass. These patients are suitable for medical management, but the outcomes are poor in comparison to patients treated by successful revascularization, and in many circumstances, they are amputee due to the worsening of FU, infection and risk of sepsis, not tolerable pain. However, amputation can confer often a worse prognosis, being an independent predictor of death.<sup>82,83</sup> In these non-revascularizable patients, currently, the new goal is to increase the local angiogenesis. Gene therapy offers a potential efficacious therapy with an acceptable rate of adverse events as documented in Phases I and II of different clinical trials.<sup>84–86</sup> Various types of gene therapies have been studied (ie, fibroblast growth factor 1, vascular endothelial growth factor [*VEGF*] and hepatocyte growth factor), of which the latter currently seems the most promising.<sup>87,88</sup> Meta-analysis of randomized trials of gene therapy on *VEGFs* did not show significant differences

between active group and placebo.<sup>86</sup> Otherwise, cell therapy seems to be effective in the treatment of CLI and reduction in major amputation is documented in diabetic and non-diabetic patients.<sup>86,89–91</sup>

Endothelial progenitor cells (EPCs) derived from bone marrow or peripheral blood are new emerging therapies to treat CLI in this subset of patients, promoting the regeneration of impaired endothelium and neoangiogenesis in ischemic tissues.<sup>92</sup>

The effects of several types of cell therapy (eg, bone marrow-derived mononuclear cells, CD34+ bone marrow cells and mesenchymal stromal cells as well peripheral blood mononuclear cells) have been studied in CLI patients, and the rate of major amputation was significantly decreased after cell therapy in several trials, while other studies did not show any difference between treatment and placebo.<sup>93,94</sup> This discrepancy between the preclinical and the clinical results of cell therapy in CLI may be explained by the potential role of disease-mediated stem cell dysfunction, which may limit the effects of these autologous cell therapies. However, mesenchymal stem cells appear less sensitive to this

disease-mediated dysfunction and can be considered as a promising target for next future cell therapy in CLI patients.<sup>95</sup>

Different studies about autologous cell therapy in CLI subjects included diabetic patients in whom the healing process may be influenced by different parameters such as hyperglycemia and peripheral neuropathy that can interfere with the outcomes of clinical trials.

In CLI patients, angiogenesis is reduced, mainly in diabetic patients with hyperglycemia, due to the reduction in hypoxia-dependent protection of hypoxia-inducible factor 1- $\alpha$  against proteasomal degradation.<sup>96</sup> Furthermore, the increased plasma levels of nitric oxide inhibit angiogenesis and proangiogenic growth factors. Hyperglycemia can also inhibit hypoxia-induced expression of *VEGFs*.<sup>97</sup> The mechanism of therapeutic angiogenesis is not already completely clear; the arterial neoformation is usually reduced by local inflammation that affects microcirculation, and the neoformation of collateral vessels is not allowed. Cell therapy allows therapeutic angiogenesis also in these circumstances, promoting the formation of new vessels from preexisting smaller vessels that can take days or weeks to develop. This principle appears to be a long and complex biologic process related to the release of hypoxia-inducible factor 1- $\alpha$  and *VEGFs* in the environment of ischemic tissues.<sup>98–100</sup>

Although both gene- and cell-based therapies in CLI seem to be encouraging in the potential treatment in a subset of patients, all of these studies need more double-blinded control studies and the evaluation of longer outcomes in terms of wound healing, amputation, safety and quality of life to reinforce the initial promising results of these novel therapies.

## Author contributions

All the authors give a substantial contribution to conception and design. They revised the manuscript critically for intellectual content and approved the final version to be published.

## Disclosure

The authors report no conflicts of interest in this work.

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