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Foot Skin Blood Flow Following Infrainguinal Revascularization for Critical Lower Limb Ischemia

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Introduction. *The aim of this study was to assess the blood flow in the feet before and after lower limb revascularization using laser Doppler imaging (LDI).*

Methods. *Ten patients with critical lower limb ischemia were prospectively enrolled from June to October 2004. All patients underwent successful unilateral surgical interventions including above-knee bypass, distal bypass and endarterectomy. Skin blood flow (SBF) over the plantar surface of both forefeet and heels was measured by LDI 24 h before and 10 days after revascularization, expressed in perfusion units (PU), and reported as mean ± SD.*

Results. *Measurements in the forefoot and heel were similar. Before revascularization mean SBF was significantly lower in the ischemic foot (130 ± 71 PU) compared to the contralateral foot (212 ± 68 PU),* $p<0.05$. *After revascularization a significant increase of the SBF in the forefoot (from 135 ± 67 to 202 ± 86 PU,* $p=0.001$*) and hindfoot (from 148 ± 58 to 203 ± 83,* $p=0.001$*) was observed on the treatment side. However, a large decrease of the SBF was seen in forefoot and hindfoot on the untreated side (from 250 ± 123 PU to 176 ± 83 and from 208 ± 116 to 133 ± 40,* $p=0.001$*, respectively).*

Conclusion. *This study confirms the benefits of revascularization in patients with nonhealing foot lesions due to critical limb ischemia. A significant increase of the SBF was observed on the treatment side. However, an unexpected decrease was observed on the untreated side.*

Keywords: Laser doppler imaging; Foot skin perfusion; Critical limb ischemia; Infrainguinal bypass.

Introduction

Current revascularization techniques have greatly improved limb salvage rates in patients with critical lower limb ischemia.[1] However, some authors have reported poor outcome with major amputation despite infrainguinal bypass.[2,3] Poor outcome have been particularly reported in patients with chronic renal failure or diabetes, with distal anastomosis sites or in the presence of infection.[4] In diabetic patients, the failure to improve functional ischemia following successful bypass grafting surgery is associated with an endothelial dysfunction and an ensuring impaired vasodilatation.[5]

One of the major aims of lower limb revascularization in patients with critical ischemia is to prevent or heal ulcer and gangrene by improving arterial pressure and flow. Healing of skin lesions on the foot depends on effective restoration of cutaneous microcirculation. Doppler and plethysmographic techniques used to assess the hemodynamic impact of vascular reconstructive surgery give little information about skin capillary hemodynamics.

The utility of laser Doppler flowmetry in assessing skin blood flow (SBF) has been proposed in previous studies.[6–9] However, standard laser Doppler flowmetry uses an optical fiber apposed in close contact to the skin. For this reason, it cannot be used for the global assessment of blood flow over a large surface (e.g. the whole foot sole as would be appropriate to evaluate results of revascularization surgery). More recently, a technique known as laser Doppler imaging (LDI) has been introduced.[10,11] The purpose of this study was to use LDI for bilateral assessment of SBF before and after infrainguinal revascularization in patients with critical limb ischemia.

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Table 1. Demographic data

Median age (range)	77 (94–64)
Sex ratio (M:F)	5:5
Risk factors	
Smoking	5
Hypertension	9
Diabetes	3
High cholesterol	4
Chronic renal failure	5
Mean preoperative plethysmography (mmHg)	21 (0–35)
Mean hospitalization time (days)	12 (4–35)

Table 2. Preoperative arteriography results

Number of patent distal vessels	
Three	1
Two	4
One	5
Patent pedal arch artery	1
Patent deep plantar arch artery	7
Patent anterior tibial artery	5
Patent posterior tibial artery	5
Patent peroneal artery	6

Material and Methods

Ten patients scheduled to undergo infrainguinal revascularization for critical lower limb ischemia were prospectively enrolled in this study between June and October 2004. Demographic data are summarized in Table 1. Plethysmography was performed to determine toe pressure before and 10 days after revascularization in all cases as well as ankle brachial index pressure. Preoperative angiography or MRI with gadolinium was performed in all patients with chronic renal failure. The patency of distal vessels and the pedal and deep plantar arch arteries (Table 2) was assessed by arteriography or MRI in all patients. The infrainguinal revascularization procedures were performed above the knee in five patients (by endarteriectomy in four patients and femoro-popliteal bypass in one patient). Distal bypass was performed in five additional patients. All patients underwent duplex scan to assess bypass patency 7 days after surgery.

The laser Doppler imager (Moor Instruments, Axminster, UK) used in this study is designed for noncontact visualization of blood perfusion. The predetermined area of interest (AOI) is scanned using a visible red helium–neon laser beam (wavelength, 632.8 nm) emitted at a distance and reflected onto the skin by a computer-controlled mobile mirror. Imaging is achieved by analyzing photon backscatter to determine flux values in each of several thousands points within the AOI. Flux values are proportional to SBF and expressed in perfusion units according to the principle of laser Doppler flowmetry. Flux data are converted into color-coded perfusion maps. In addition, analysis of the DC component of the backscattered light allows generation of a grey level photographic image of the named area (Fig. 1).

Assessment of SBF on both foot soles was carried out a few hours (less than 24) before surgical revascularization (day 1) and 10 days after revascularization (day 2). The same protocol was used on both days. Skin temperature was systematically monitored using a cutaneous sensor (G. Mettraux, Crissier, Switzerland). Temperature and relative humidity were maintained at 23 °C and 60%, respectively, by the hospital air conditioning system. Distance from laser source to skin was 70 ± 10 cm depending on foot size and conformation. Time for calculation of a single pixel was 4 ms allowing for an approximate distance of 2 mm between pixels. Although the Doppler imager used is reasonably insensitive to ambient lighting, measurements were

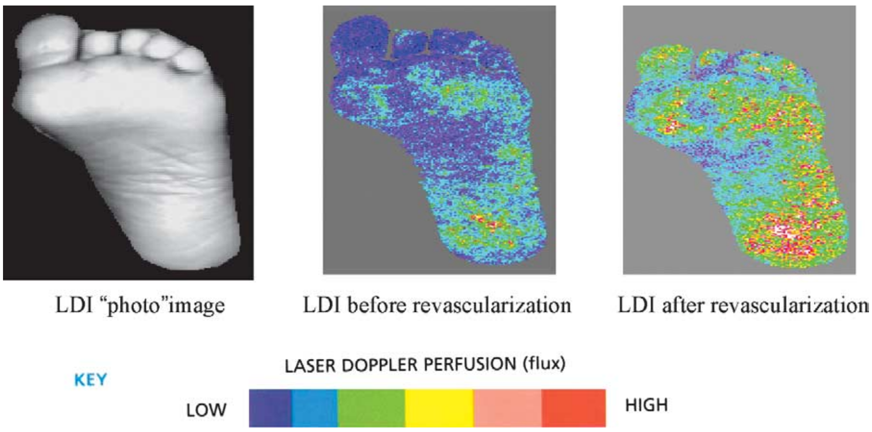

Fig. 1. LDI scanning.

performed with natural light provided through the window. Electric lighting was turned off and translucent shades were drawn if necessary to avoid direct sunlight.

The patient lay supine in a comfortable position on an adjustable hospital bed. Both legs were supported by a cushion and entirely uncovered below the knee. A bed sheet was hung vertically over the patient's abdomen to prevent the risk of laser-induced eye injury. During an initial rest period of 30 min, the LDI was installed so that the laser beam could scan the entire plantar skin surface following a horizontal path. Our aim was to obtain the greatest number of pixels in each image. Two areas of interest (AOI) were defined, i.e. the forefoot and hindfoot. The midfoot was excluded from analysis because the surface curvature in this particular area frequently resulted in the incidence of the laser beam being too oblique to obtain reliable results. Median flux was calculated in each AOI. Values retained for further analysis were means of three median fluxes from three consecutive scans.

Statistical analysis of LDI data was carried out with a mixed model analysis of variance. When the *F* value associated with an effect was significant, further comparisons were made with Fisher's least significant difference.[12] The alpha level of all tests was 0.05. Calculations were carried out using JMP version 3.2.2 (SAS Institute, Carry, NJ 27513, USA).

Results

Toe plethysmography (Figs. 2 and 3)

Preoperative toe plethysmography values on the treatment side confirmed that all patients presented with critical limb ischemia (mean, 21 mmHg). Comparison of preoperative and postoperative values showed a statistically significant increase ($p=0.001$) after revascularization. After revascularization toe plethysmography values were all above 40 mmHg. On the untreated side preoperative toe plethysmography excluded bilateral critical limb ischemia (mean, 66 mmHg) and did not significatively change following revascularization.

Ankle-brachial pressure index (ABPI)

Preoperative ABPI on the ischemic legs showed a high ABPI (greater than 1.5) in two patients with a long standing diabetes, which reflects most likely a falsely elevated value.[13] In the other patients, the mean ABPI averaged 0.4. The postoperative ABPI increased significatively on the treatment side (0.8, $p=0.002$). On the untreated side ABPI was always above 0.8 without any significant change after revascularization.

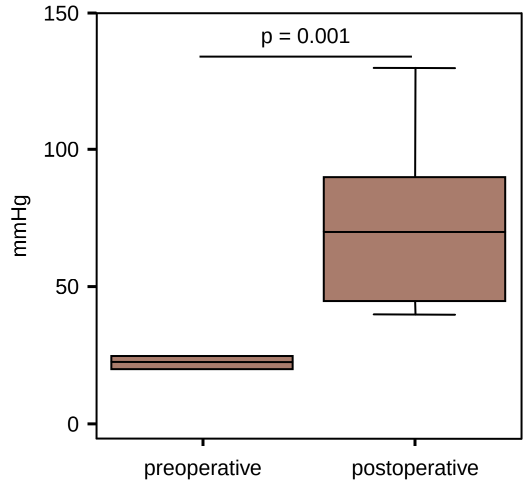

Fig. 2. Toe plethysmography on treated side.

Laser Doppler imaging (Figs. 4 and 5)

Comparison of preoperative and postoperative SBF on the treated side demonstrated a significant increase in skin perfusion on the hindfoot (from 148±58 to 203±83 PU, $p=0.001$) and forefoot (from 135±67 to 202±86 PU, $p=0.001$). The effect of revascularization was not different between the two locations. In contrast, SBF on the untreated side significantly decreased following surgery in both the hindfoot (from 208±116 to 133±40 PU, $p=0.001$) and the forefoot (from 250±123 to 176±83 PU, $p=0:001$). Preoperatively, SBF in both AOIs was

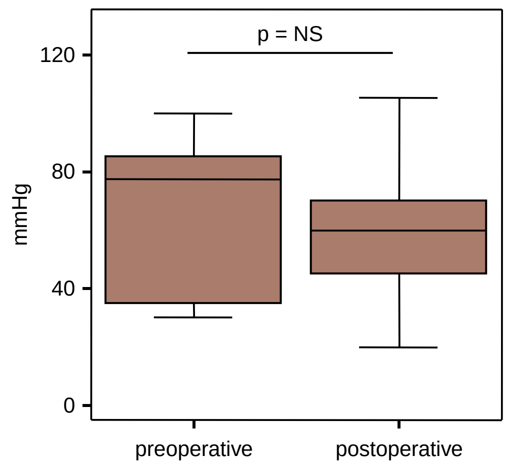

Fig. 3. Toe plethysmography on untreated side.

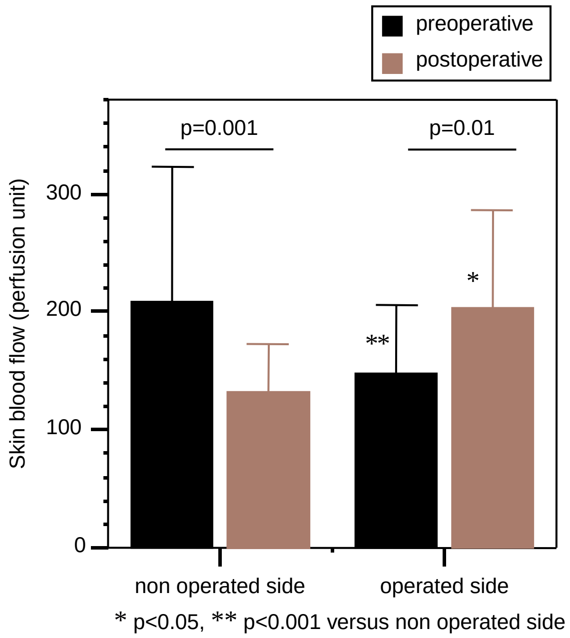

Fig. 4. Hindfoot LDI findings.

higher on the untreated than on the operated side. Postoperatively SBF the reverse was true in the hindfoot, although not in the forefoot.

Temperature monitoring

Mean skin temperatures before and after revascularization were not statistically different on either the

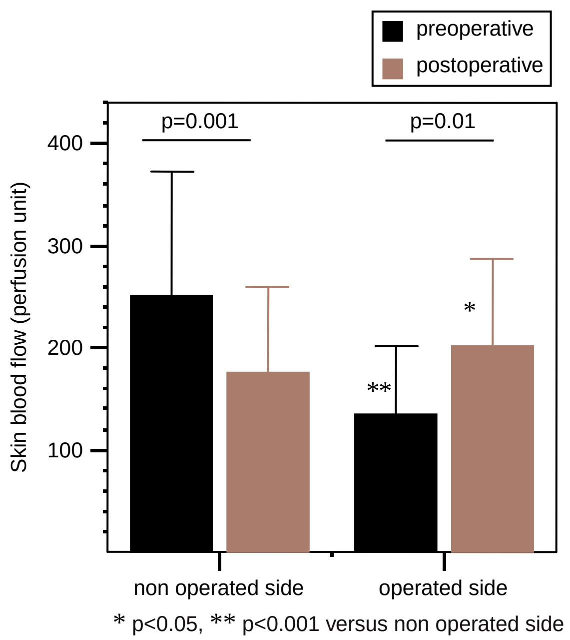

Fig. 5. Forefoot LDI findings.

treated side (30.9±1.1 °C and 31.5±1.1 °C, $p > 0.05$) or untreated side (31.5±1.3 °C and 31.8±1.4 °C, $p > 0.05$).

Follow-up

Clinical evaluation showed complete healing of skin lesion on the operated leg. No new lesions appeared on the nonoperated side.

Discussion

The findings of this study demonstrate that lower limb revascularization leads to an equal improvement in hindfoot and forefoot plantar skin blood flow. The opposite effect was observed on the untreated side. The improvement in microcirculation on the treated side led to healing of skin lesions on the operated side but the decrease on the untreated did not lead to necrosis on the untreated side during the study follow-up period. There was a good correlation between the significant increase in toe plethysmography values and SBF improvement on treated foot. This correlation is not found on the untreated foot.

Healing of ulcers due to critical ischemia depends on various factors. Tissue oxygenation necessary for development of granulation tissue[14] is only possible if perfusion is sufficient to support neovascularization. In this regard infrainguinal revascularization is essential to increase blood flow to the distal part of the limb. However, in some patients with distal bypass, reperfusion is insufficient to achieve healing or avoid major amputation. Reifsynder *et al.* reported that one third of patients requiring amputation after infrainguinal bypass had a patent bypass and concluded that this outcome was due to a paucity of branch vessels in the foot.[15] This conclusion suggests that small vessel quality is a critical factor for ischemic ulcer healing in the foot.

In our study, preoperative findings demonstrated that the deep plantar arch artery was generally patent on the treated side but that the pedal arch artery was often occluded. Despite the importance of the pedal arch artery in the forefoot perfusion, revascularization improved SBF in both the forefoot and hindfoot. This was probably due to the presence of an anastomotic network that allowed perfusion of the entire skin surface of the foot. However, a previous study reported failure to heal and ultimate amputation in some patients with patent bypass graft and palpable pedal pulse with an ankle-brachial index (ABI) greater than 0.70 or 0.80.[16] According to the authors this finding not only supports the concept of regional differences in pedal perfusion but also indicates that limb salvage depends on overall circulation in the foot that cannot be predicted by the ABI. The authors also concluded that patency of posterior tibial artery was an important predictor for successful revascularization.

In our study, the posterior tibial artery was patent in 50% of patients. This is important since hindfoot skin perfusion is critical for heel ulcer healing. However, it should be emphasized that revascularization achieved improvement in plantar SBF even if perfusion was not restored in posterior tibial artery. Heel perfusion is also dependent on patency of the deep plantar arch artery. In this regard, we noted that posterior tibial artery occlusion was always associated with deep plantar arch occlusion. Although this combination has a highly detrimental effect on heel perfusion, SBF to the hindfoot increased. These findings support the conclusion that foot skin perfusion involves an extensive anastomotic network.

The success of reconstructive vascular surgery is usually assessed based on evaluation of macrovascular circulation using ABI and plethysmography. However, the poor predictive value of these techniques for limb salvage, especially in uremic patients[4,17] or diabetic,[18] suggests that restoration of macrovascular circulation is not the only determinant factor for successful outcome of revascularization and that microvascular circulation should also be assessed.

In this study LDI was used to assess microvascular circulation. A major advantage of LDI is simplicity that allows use in the patient's room. However, precautions are necessary to reduce potential artifacts and enhance reproducibility especially for comparison of findings on two separate days. To reduce movement artifacts, we placed a cushion under the leg to minimize involuntary movement. To avoid the potential confounding influence of thermal conditions on SBF, measurements were carried out in a temperature-controlled environment. To ascertain reproducibility, a preliminary series of three consecutive measurements were performed on the same foot, with a difference of less than 10% between measurements. LDI is also used to test microcirculation reactivity by heating or cooling tests.[19] These tests can be performed several weeks after the operation, but probably not after a few days. In our study, we decided to scan the sole of the foot, which was divided in two parts: the forefoot and hindfoot. These regions are more sensitive to blood flow variations than the tissue necrosis, which is sometimes located in a hidden region (lateral part of the toe for example). We preferred, therefore, to scan a region of the foot and not a lesion. To our knowledge this report is the first to describe the impact of unilateral revascularization for critical limb ischemia on the SBF of the untreated foot, and an unexpected decrease was observed. The mechanism underlying this decrease is unclear. It was not due to a decrease in macrovascular perfusion since toe plethysmography showed no deterioration following revascularization. A possible explanation is a neuromediated vasoconstriction of microvascular networks. Further, investigation will be needed to clarify this point.

This study shows that LDI can be a useful tool to investigate the impact of revascularization on skin microcirculation of the foot. Our findings indicated that foot SBF increased in every part of the sole on the treated side even if the pedal or deep plantar arch was occluded. This increase was correlated with the healing of skin lesions. However, due to the small size of the population in this study, our results cannot be generalized to every situation and, in particular, to cases involving infected wounds. Moreover, since many patients with critical limb ischemia develop contralateral disease,[20] further investigations in a larger sample of patients followed up for a longer period are needed to assess the impact of revascularization on the contralateral microcirculation.

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