

# Transcutaneous pO<sub>2</sub> measurement on plantar foot surface: establishing the reference range

OV Udovichenko, EG Chernova, LV Dadova, AV Belyaeva, EM Nosenko, DO Ladygina, MN Alekhin

**Dorsal foot is a gold standard for transcutaneous pO<sub>2</sub> (tcpO<sub>2</sub>) measurements with a validated reference range. Nevertheless, it reflects arterial blood flow in only one of the foot angiosomes. Plantar tcpO<sub>2</sub> measurement is an attractive idea, but its implementation is limited by the lack of established reference range and some technical problems relating to the probe attachment. The authors established a technique for probe fixation and established the reference range for plantar tcpO<sub>2</sub> in people with diabetes with spared arterial blood flow. In these patients, plantar tcpO<sub>2</sub> values appeared to be higher than dorsal ones.**

Transcutaneous partial oxygen pressure (tcpO<sub>2</sub>) measurement is widely used in quantitative assessment of the lower-extremity arterial blood flow reduction for diagnosis of critical limb ischaemia, in decision-making concerning revascularisation and amputation, and also for control of treatment results (including surgical and endovascular interventions).

This method is used in practice along with ankle-brachial pressure index (ABPI) and toe pressure assessment. Nevertheless, usage of these methods have some limitations. Medial arterial calcification in patients with diabetic neuropathy can falsely elevate ankle and even toe pressure (Hinchliffe et al, 2016). Due to this effect and the possible presence of toe ulcers or gangrene in some people with diabetes, ABPI and toe pressure cannot be evaluated in almost 50% of people with diabetes with critical limb ischaemia and foot ulcers (Faglia et al, 2007).

Several studies were devoted to the establishment of tcpO<sub>2</sub> cut-off levels for impaired wound healing in patients with peripheral artery disease and diabetes; their comprehensive analysis was made by Wang et al (2016) in a recent systematic review. The authors of this review compared eight tests to predict wound healing based on non-invasive assessment of lower-limb blood flow (including ABPI, ankle peak systolic velocity, tcpO<sub>2</sub>, toe-brachial index, toe systolic blood

pressure, microvascular oxygen saturation, skin perfusion pressure and hyperspectral imaging). The authors found that “most of the available evidence evaluates only tcpO<sub>2</sub> and ABPI”, and the degree of risk (DOR) of both poor wound healing and amputation was much higher for tcpO<sub>2</sub> than for ABPI.

As the influence of blood flow reduction on wound healing is more gradual than binominal (‘yes or no’), recent guidance documents (Setacci et al, 2011; Hinchliffe et al, 2016) and classification systems, such as PEDIS (Schaper, 2004) and WIFI (Mills et al, 2014), suggest several grades of foot ischaemia: none, mild, moderate and severe ischaemia. These grades are based on tcpO<sub>2</sub>, ABPI or ankle systolic pressure value. In all these documents, tcpO<sub>2</sub> level of 60 mmHg or higher is considered a sign of absence of ischaemia and level <30 mmHg a sign of severe ischaemia.

Not all the studies on the prognostic value of tcpO<sub>2</sub> measurement describe the location of the testing area in detail. However, where described, the testing area was dorsum of the foot (Scheffler and Rieger, 1992; Kalani et al, 1999; Zimny et al, 2001; Ladurner et al, 2010; Tara et al, 2011; Pedrini et al, 2014). This method is considered a standard technique by Faglia et al (2007).

According to the angiosome conception (Taylor and Palmer, 1987; Attinger et al, 2006; Alexandrescu

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## Article points

1. Plantar tcpO<sub>2</sub> measurement may enable accurate assessment of blood flow reduction in patients with below-the-knee arterial lesions, predominantly in posterior tibial artery.
2. This study in people with diabetes with spared arterial blood flow established the reference range for this parameter as 45–87 mmHg; it was slightly higher than that for dorsal foot surface.
3. Estimation of cut-off value of plantar pO<sub>2</sub> for adequate for healing blood flow in system of posterior tibial artery needs further prospective study.

## Key words

- Angiosomes
- Plantar foot
- Transcutaneous pO<sub>2</sub>

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Figure 1. The technique of the probe attachment to the plantar foot skin, shown in (a) and (b).



et al, 2008), the foot consists of six angiosomes, which are supplied by blood from different sources (Table 1). One of these angiosomes is supplied by the anterior tibial/dorsalis pedis artery (ATA), three others (representing together most of the plantar surface and medial calcaneal area) — by posterior tibial artery (PTA), and two more (placed in lateral malleolar and lateral heel areas) — by peroneal artery. Despite significant variability of angiosome borders (Kelikian, 2011), in patients with below-the-knee arterial stenoses, predominant ischaemia in the PTA supply area (and poor collateral blood supply), tcpO<sub>2</sub> assessment on dorsal foot surface may not provide relevant information on the degree of ischaemia.

The diagnostic and prognostic values of plantar tcpO<sub>2</sub> measurement results are not known. The establishment of a reference range for this parameter in extremities with normal arterial blood flow should be the first step. The second step should be a prospective study to reveal prognostic value of this parameter in patients with critical limb ischaemia. The aim of this study was to establish the reference range for plantar tcpO<sub>2</sub> assessment.

### Study object and methods

The participants in this study were 36 consecutive patients with diabetes mellitus (DM) from an endocrinology department in a large teaching hospital in an urban area. All patients were in a stable health condition (i.e. without recent surgery, disease progression, acute diseases, etc) and without symptoms

of lower-limb ischaemia or history of foot ulcers. Status of arterial blood flow was assessed with duplex ultrasound scan (DUS). Eleven patients appeared to have asymptomatic, but hemodynamically significant, arterial occlusions or stenoses (of more than 60% of artery diameter with reduction of ankle-brachial pressure index [ABPI] below 0.9) and were excluded.

The remaining 25 patients (50 legs) with good arterial blood supply of lower extremities (no arterial lesions or stenoses less than 60% and ABPI >0.9) were enrolled into the further tcpO<sub>2</sub> study. In these patients, simultaneous dorsal and plantar foot tcpO<sub>2</sub> measurements were conducted on both feet. Simultaneously, the authors placed one electrode in left subclavian region (as a reference) and then calculated the ratio of extremity to chest tcpO<sub>2</sub>, or transcutaneous regional perfusion index (RPI), according to Hauser and Shoemaker (1983). A 6-channel TCM-400 device (Radiometer, Denmark) was used for the measurement. All the probes were placed by the same experienced operator.

The areas selected were not directly over any veins and foot probes were placed in the midfoot area. The probe fixation on the plantar foot surface was not technically difficult for the clinicians (Figure 1). Immediately after calibration of the probes, they were attached to the skin by means of adhesive fixation rings, according to the manufacturers instructions. The time of testing was counted from the probe attachment. During the measurement procedure, the patient was lying in the supine position. Taking into

account possible small fluctuations of the pO<sub>2</sub> with time (even in the 'stable' phase of the measurement), the authors used the maximum value from 16–20 minutes as the measurement result.

Clinical examination of the patients included detection of diabetic peripheral neuropathy based on combination of symptoms (i.e. painful sensation in feet at rest, paresthesias, burning or ice-cold sensation and numbness) and sensory tests results. The latter included vibration perception threshold measured by a Rydel-Seiffer graduated tuning fork and touch sensation measured by a 10-g Semmes-Weinstein monofilament. The authors also hypothesised that plantar skin dryness can influence measurement results affecting attachment of the probe with the standard fixation ring. Therefore, dryness of plantar skin was semi-quantitatively assessed in the studied patients. Dryness was assessed by one person in all patients on the basis of visual appearance (no dryness/mild dryness/prominent dryness).

Statistical analysis of study results was performed with statistical tools (Microsoft Excel 2007, Microsoft Company and Statistica version 8.0. for Windows, StatSoft Inc). Due to lack of normal distribution in some parameters the results were presented as median values, within a minimum-maximum range. Correlation analysis was used to reveal dependency of numeric values. A Mann-Whitney U test was used for the evaluation of statistical significance of difference between the two groups, and analysis of variance was implemented for comparison of three subgroups. A *P* level lower than 0.05 was considered as statistically significant. The reference range for non-normal distributed data was estimated with method of percentiles (2.5th to 97.5th), according to Bland (2000).

## Results

Among the patients included in the study, 4% had type 1 and 96% type 2 DM. The male:female ratio was 42:58%, while the median age was 62 (49–81) years and the median DM duration was 13 (1–31) years. None of the patients had symptoms of lower-limb ischaemia or a history of foot ulcers. Eighteen (72%) had diabetic peripheral sensory neuropathy, while only four (16%) were smokers. TcpO<sub>2</sub> measurement results are presented in Figures 2 and 3.

The difference between plantar and dorsal tcpO<sub>2</sub> results was statistically significant both for absolute

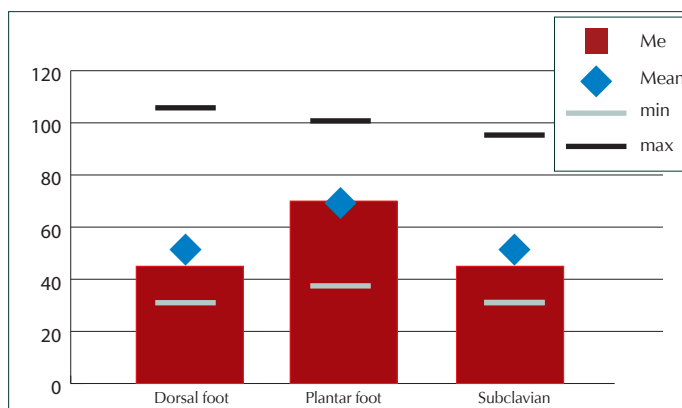


Figure 2. Measurement results for tcpO<sub>2</sub> in several skin areas, mmHg.

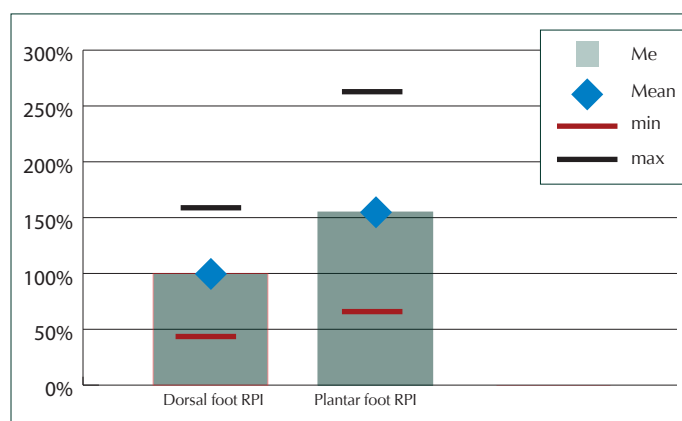


Figure 3. Results for RPI (ratio of foot to subclavian tcpO<sub>2</sub>) in several skin areas. *p*<0.0001 (dorsal vs. plantar foot).

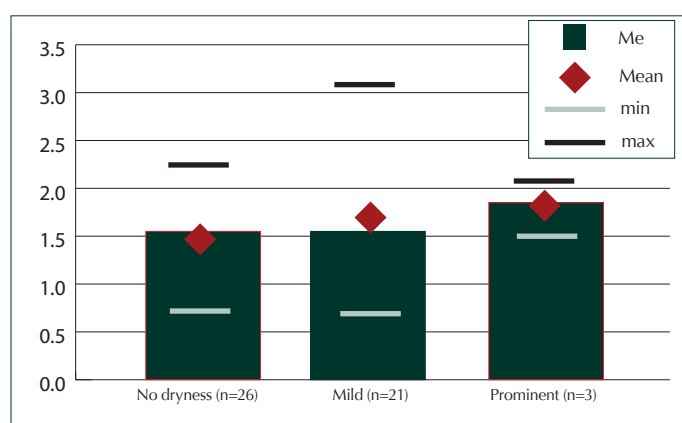


Figure 4. Median plantar to dorsal pO<sub>2</sub> ratio in patients with different skin dryness. *P*=0.47 (ANOVA for 3 groups); *P*=0.46 (Mann-Whitney test for groups 1 and 2 only).

(*P*<0.01) and RPI (*P*<0.01) values. The authors found no sufficient correlation between dorsal and plantar pO<sub>2</sub> values (*r* = 0.12, *P* = 0.43), but found correlation for RPI values (*r* = 0.5, *P*<0.05).

**Table 1. Angiosomes of the foot and their sources of arterial blood supply (Taylor and Palmer, 1987; Attinger et al, 2006; Alexandrescu et al, 2008).**

Artery	Angiosomes (according to arterial branches)	Regions of blood supply
Anterior tibial (dorsalis pedis)	Dorsal	Dorsal foot
Posterior tibial	Calcaneal	Medial and plantar heel
	Medial plantar	Medial plantar instep
	Lateral plantar	Lateral forefoot, plantar midfoot and entire plantar forefoot
Peroneal	Calcaneal	Lateral heel
	Lateral ankle	Lateral ankle

**Table 2. Reference ranges for plantar absolute pO<sub>2</sub> value and RPI calculated from our sample by percentile method.**

Artery	Absolute pO <sub>2</sub> value	Regional perfusion index
Dorsal foot	32-65 mmHg	0.55-1.45
Plantar foot	46-87 mmHg	0.87-2.41

No difference was found in pO<sub>2</sub> or RPI values between smokers and non-smokers, and neuropathic and non-neuropathic patients ( $p > 0.05$  in all testing areas), perhaps due to the small sizes of these subgroups.

For analysis of possible influence of plantar skin dryness on measurement results, the authors compared the ratio of plantar and dorsal pO<sub>2</sub> values in subgroups of patients with no skin dryness, mild dryness and prominent dryness. The difference between groups was not statistically significant as presented in *Figure 4*. Nevertheless, only three of 50 feet had prominent skin dryness, and one can speculate that in patients with severe skin dryness, plantar pO<sub>2</sub> may be influenced by this factor.

### Discussion

This study enabled the characterisation of plantar pO<sub>2</sub> values in a group of patients with normal lower-limb arterial blood flow. Some clinicians have conducted tcpO<sub>2</sub> measurement in several parts of lower extremity (i.e. at upper and lower calf, thigh (Burgess et al, 1982; Hauser and Shoemaker 1983; Naoki et al, 2007) and in the periwound area in

chronic leg ulcers (Barnikol and Pötzschke, 2011). Nevertheless, the diagnostic and prognostic value of this parameter in diabetic foot and critical limb ischaemia patients is well established and validated only for dorsal foot (forefoot pO<sub>2</sub>) (Scheffler and Rieger, 1992; Kalani et al, 1999; Zimny et al, 2001; Ladurner et al, 2010; Tara et al, 2011; Pedrini et al, 2014), and it is possible that normal pO<sub>2</sub> values differ between various skin areas. Štalc and Poredos (2002) showed that dorsal foot pO<sub>2</sub> is more reliable in the assessment of PTA effects than pO<sub>2</sub> value obtained 10 cm below the knee.

A search of available in PubMed publications revealed only few studies comparing tcpO<sub>2</sub> measurement results on plantar and dorsal foot surfaces (Smith et al, 1995; Boyko et al, 2001). These publications were devoted to skin blood flow response to cutaneous warming from 37°C to 44°C in individuals with or without diabetes. These studies showed that cutaneous warming leads to a paradoxical fall in pO<sub>2</sub> on the plantar foot surface, while warming increases pO<sub>2</sub> value in dorsal foot skin. This phenomenon did not depend on the presence of autonomic neuropathy or diabetes.

Concerning the absence of correlation between dorsal and plantar pO<sub>2</sub> values, it can be hypothesised that in this study (with the absence of foot ischaemia), pO<sub>2</sub> reflects local rather than whole-extremity blood flow and may vary due to this reason. Assessing RPI instead of absolute pO<sub>2</sub> values may reflect status of blood flow more accurately and may be less prone to variations due to skin blood flow peculiarities. However, one should remember that intra-group variability of measurement results in this study (in patients with spared lower extremity blood flow) is not clinically significant.

Establishing a reference range for plantar pO<sub>2</sub> measurement is important for clinical practice. It enables skin pO<sub>2</sub> values assessment, not only in anterior tibial angiosomes, as well as the ability to make evidence-based clinical decisions based on obtained results.

The reference ranges for plantar absolute pO<sub>2</sub> value and RPI calculated from the sample by percentile method for our sample are presented in *Table 2*. Similarly calculated reference ranges for dorsal pO<sub>2</sub> are presented only for comparison as the more important prognostic value of several dorsal pO<sub>2</sub> cut-off points



was also analysed in many prospective studies (White et al, 1982; Scheffler and Rieger, 1992; Ballard et al, 1995; Kalani et al, 1999; Naoki et al, 2007; Ladurner et al, 2010; Tara et al, 2011).

### Limitations of the study

The first limitation is concerned with the possible influence of autonomic neuropathy on cutaneous blood shunting. In this study, standards of clinical examination included only screening for peripheral sensory neuropathy, but not autonomic dysfunction tests. Due to this and the relatively small size of the group, the authors could not study this possible influence.

The second limitation appears to be more crucial. One can assume that following blood flow reduction to the extremity, the pO<sub>2</sub> value on plantar foot surface may be changed in different way than that on dorsal one. So our initial findings need a further step — estimation of a plantar pO<sub>2</sub> cut-off values for adequate for healing blood inflow in a prospective study. The authors plan to conduct a longitudinal (perhaps collaborative) study in future, to assess the pattern of non-dorsal pO<sub>2</sub> changes in ischaemic limbs and the prognostic value of several degrees of its reduction for healing of wounds in different foot angiosomes.

### Conclusion

This study demonstrated that the reference range for plantar pO<sub>2</sub> measurement may be different from the dorsal foot one. Further studies should assess cut-off points, i.e. prognostic value of several degrees of plantar pO<sub>2</sub> reduction in critical limb ischaemia. Patients with severe skin dryness may need elaboration of special fixation rings for more durable probe fixation in order to prevent contact fluid leakage from the chamber under the probe. ■

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