Transcutaneous Oxygen Tension: Principles and Applications

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Introduction

Beginning in the early 1970s, it became clear that empiric means of assessing foot perfusion were not adequate due to lack of sensitivity and specificity. Compelling research led to the discovery of a number of different objective tools that could be used to assess the degree of foot ischemia. Among the tested modalities, transcutaneous oxygen tension proved to be invaluable in the evaluation of lower extremity ischemia. Design of the transcutaneous sensor made it possible to obtain very accurate measurements of oxygen (pO₂) and carbon dioxide (pCO₂) tension on the surface of the skin. This chapter will discuss the physiology of transcutaneous oxygen (tcpO₂) measurements and demonstrate how these measurements can be used for the determination of amputation level. In addition, tcpO₂ measurements will be shown to be essential for the prospective management of diabetic patients with foot ischemia as well as nondiabetic patients with chronic lower extremity ischemia.

Physiology of the Measurement

Modern transcutaneous instrumentation has improved considerably from the viewpoint of maintenance, application and routine use. A small sensor is applied to the skin with an airtight self-adhesive fixation ring. The heating element of the transcutaneous sensor increases the temperature beneath the sensor to 44 °C. Heating the sensor creates local skin hyperemia, a decrease in flow resistance and compensatory arteriolarization of capillary blood. This effectively raises the pO₂ and decreases the pCO₂ values toward arterial levels. Contact liquid between the skin and sensor allows the underlying dermal tissue pO₂ to be in equilibrium with the sensor after 15–20 mins. In practice, stable tcpO₂ readings are generally achieved in 20–30 mins.

TcpO₂ monitoring is completely noninvasive and atraumatic if sensor placement at one skin site is limited to a maximum of 4 hours. The test can be accomplished with the patient comfortably supine at ambient room temperature in an outpatient setting. Oxygen inhalation, change in limb position and chest wall normalized tcpO₂ values are not part of our standard protocol. In our noninvasive vascular laboratory at Loma Linda University Medical Center, we use the Novametrix 800 monitor (Novametrix Medical Systems, Wallingford, CT), which has three modified Clark electrodes for simultaneous recording of skin oxygen tension at three sites (Fig. 30.1). As demonstrated in Fig. 30.2., the sensors are usually placed on the dorsal aspect of the forefoot between the great and second toe roughly 5 cm proximal to the second toe tip (forefoot measurement), on the medial aspect of the hindfoot in front of or behind the malleolus (hindfoot measurement) and 10 cm below the patella on the medial aspect of the calf (below-knee measurement). The sensor can also be
neous blood flow. Matsen et al.\textsuperscript{12} reported that tcpO\textsubscript{2} measurements are mostly dependent on arterial-venous gradients and cutaneous vascular resistance. In essence, there can be nutritive blood flow to the skin even with a tcpO\textsubscript{2} level of 0 mmHg.

One of the techniques used to improve the accuracy of tcpO\textsubscript{2} measurements is sensor probe heating (44 °C), which minimizes local vascular resistance. This makes tcpO\textsubscript{2} more linear with respect to cutaneous blood flow. Additional techniques used to improve tcpO\textsubscript{2} accuracy include measurements performed before and after oxygen inhalation or change in limb position, oxygen isobar extremity mapping and transcutaneous oxygen recovery half-time.

Wyss et al.\textsuperscript{13} evaluated the results of tcpO\textsubscript{2} measurements used as a predictor of success following amputation. The study analyzed 162 patients who had 206 lower extremity amputations. The authors concluded that tcpO\textsubscript{2} is one of the most reliable indicators of local tissue ischemia and is the best available method for predicting failure of amputation healing due to ischemia. However, there are two theoretical inadequacies that must be considered when using tcpO\textsubscript{2} measurements. First, the measurement is quite localized and one value may not be representative of the overall degree of limb ischemia. Second, as previously mentioned, there may still be some nutritive flow to the skin despite a tcpO\textsubscript{2} level of 0 mmHg.

Despite the fact that in theory a tcpO\textsubscript{2} value of 0 mmHg at a proposed site of amputation does not always indicate ischemia that precludes healing, a tcpO\textsubscript{2} level of 20 mmHg or less clearly indicates severe limb ischemia. In the Wyss study,\textsuperscript{13} a tcpO\textsubscript{2} measurement of 20 mmHg or less was associated with a rate of failure for amputations distal to the knee that was more than 10 times the 4% rate of failure in patients who had a tcpO\textsubscript{2} level of more than 20 mmHg.

**Clinical Applications in Peripheral Vascular Disease**

**Selecting The Appropriate Amputation Level**

Many authors have reported on the successful use of transcutaneous oxygen measurements to determine the appropriate lower extremity amputation
level. One of the initial reports on this topic was by Franzcek et al. Mean tcpO₂ levels in patients who experienced primary healing of a lower extremity amputation were compared with those of patients who failed to heal their amputation. The respective values for healing and non-healing were 36.5 ± 17.5 mmHg and less than 30 mmHg. However, three of nine patients whose tcpO₂ level was less than 10 mmHg healed primarily.

In a study of below-knee amputations, Burgess et al. noted that all 15 amputations that were associated with a tcpO₂ level greater than 40 mmHg healed. Primary healing was noted in 17 of 19 below-knee amputations with a tcpO₂ measurement between 1 and 40 mmHg, but none of the three patients with a tcpO₂ of 0 mmHg below the knee healed. Katsamouris et al. reported that lower extremity amputations healed in all 17 patients with a tcpO₂ level greater than 38 mmHg or a PO₂ index (chest wall control site) greater than 0.59. Ratliff et al. reported that below-knee amputations healed in 18 patients with a tcpO₂ measurement greater than 35 mmHg, whereas healing failed in 10 of 15 with a tcpO₂ value less than 35 mmHg. In a study of 42 lower extremity amputations (28 below-knee and 14 above-knee), Christensen and Klarke found that 27 of 31 patients with a tcpO₂ level greater than 30 mmHg healed primarily. Seven patients with tcpO₂ values between 20 and 30 mmHg healed although four patients had delayed healing. The amputation stumps of all four patients with a tcpO₂ value below 20 mmHg failed to heal because of skin necrosis.

Data from Wyss et al. are comparable to those yielded by a prospective study evaluating multiple tests used for amputation level selection. In this study, tcpO₂ measurements were prospectively compared with transcutaneous carbon dioxide tension, transcutaneous oxygen-to-carbon dioxide tension, foot-to-chest transcutaneous oxygen tension, intradermal xenon-133 clearance level, ankle/brachial index and the absolute popliteal artery pressure for accuracy in amputation level selection. All metabolic variables exhibited a high degree of statistical accuracy in predicting amputation healing, but none of the other tests showed statistical reliability. All amputations in this study (transmetatarsal, below-knee, and above-knee) healed primarily when the tcpO₂ measurement was greater than 20 mmHg and there were no false-positive or false-negative results. It was also noted that successful prediction of amputation healing for any of the metabolic parameters was not affected by the presence of diabetes mellitus. This finding is similar to the observation of Wyss et al.

In contrast to lower extremity amputations in nondiabetics, which usually result from severe peripheral vascular disease, most amputations in diabetic patients result from various combinations of contributing causes including neuropathy, ischemia, alterations of white cell function, infection, or gangrene, faulty wound-healing, cutaneous ulceration and minor trauma. Malone et al. and Christensen and Klarke concluded that a tcpO₂ of 20 mmHg or more accurately predicted amputation site healing, and they found no difference in the healing rate between diabetics and nondiabetics. Computerized analysis of various transcutaneous metabolic parameters by Malone et al. demonstrated a high association with primary amputation site healing with the following values: tcpO₂ greater than 20 mmHg, transcutaneous carbon dioxide tension less than 40.5 mmHg, transcutaneous oxygen to transcutaneous carbon dioxide index greater than 0.472 and foot-to-chest transcutaneous oxygen index greater than 0.442.

Thus, elective lower extremity amputation should not be performed without objective testing to insure selection of the most distal amputation site that will heal primarily yet allow removal of infected, painful or ischemic tissue. A variety of techniques are available to achieve this, depending on available equipment, the amputation level under consideration and the accuracy of the chosen modality. TcpO₂ measurements currently appear to be the most reliable technique; however, the technique is not suitable for whole limb mapping. Fiberoptic fluorometry may have some advantages due to its ability to measure multiple sites simultaneously, although the risk associated with intravenous administration of fluorescein must be considered.

The ultimate role of any method used for determination of amputation level is to inform the surgeon of the quantitative risk of nonhealing at the proposed site of surgery. The level of amputation can then be decided on the basis of this objective finding in conjunction with the surgeon's clinical judgment and the patient's physical findings. For example, a surgeon might perform an amputation distal to the knee through a site with a very low tcpO₂ level in a patient who is well motivated, relatively young and healthy. Such an amputation would almost certainly be contraindicated in a fragile
elderly person who faces a limited prospect for successful rehabilitation.

**Prospective Treatment of Diabetic Foot Problems**

Successful treatment of the patient with diabetes and limb-threatening ischemia requires an accurate assessment of limb perfusion. Presenting clinical symptoms may be misleading. Physical examination of pedal pulses or ankle/brachial index (ABI) may not be accurate due to the noncompressible nature of a diabetic patient's peripheral arteries. Often, the cause of the presenting foot problem is multifactorial. Commonly used noninvasive lower extremity hemodynamic studies lack discriminative accuracy. Arteriography is ultimately accurate. However, it is invasive, expensive and carries a small but well-defined set of associated complications. In this setting, tcpO₂ measurements can be extremely useful as they are noninvasive, inexpensive and reproducible.

In a clinical experience reported by Ballard et al., tcpO₂ measurements were prospectively demonstrated to predict severity of foot ischemia accurately in patients with diabetes. Based on clinical experience and previously published data on the determination of amputation level, an absolute transmetatarsal tcpO₂ measurement of 30 mmHg was used as the critical value to select a treatment option. If the level was 30 mmHg or greater, the patient's foot problem was managed conservatively with local wound care, wound debridement or a minor foot amputation. If the level was less than 30 mmHg, arteriography of the involved limb was performed to plan arterial reconstruction to improve foot perfusion.

There were 34 (62%) men and 21 (38%) women with diabetes with a mean age of 67 years (range 34–87 years) entered into this study. This presented 66 threatened feet for evaluation. Treatment indications included nonhealing ulcer (35 feet, 53%), gangrene (25 feet, 38%) and rest pain (6 feet, 9%). Thirty-three (60%) patients had insulin-dependent diabetes, and the others (22 patients, 40%) had non-insulin-dependent diabetes. TcpO₂ measurements were obtained at the forefoot (TM), below the knee (BK) and above the knee (AK) for this study protocol as described earlier. All patients were examined at weekly or biweekly intervals. Follow-up tcpO₂ mapping, repeat pedal pulse examination, and recalculation of the ABI was performed in all patients who had a procedure designed to improve foot perfusion. Dressing changes were performed by either a family member or a home health care nurse specialist. The endpoints for determining treatment success or failure were complete wound healing or relief of ischemic rest pain. All limbs, except four, reached these endpoints. Follow-up ranged from 2 to 15 months (mean 8 months). No patient was lost to follow-up.

In the conservative treatment group (38 feet, 57.6%) mean ABI was 0.91 in the involved limb and mean initial tcpO₂ levels were as follows: AK, 49 mmHg; BK, 54 mmHg; TM, 50 mmHg. A pedal pulse was palpated in 21 feet, whereas 17 feet did not have a palpable pedal pulse. Conservative treatment consisted of local wound care (16 feet, 42%), local wound debridement (18 feet, 47%), or a minor foot amputation (4 feet, 11%). Thirty-six of 38 feet were monitored to the selected endpoints. Two patients (two limbs with palpable pedal pulses) excluded from outcome analysis died 2 and 4 months after initiation of conservative care but before complete resolution of their presenting foot problem.

Thirty-one of 36 (86%) limbs in this group were treated successfully including 73% (11/15 feet) of limbs without a palpable pedal pulse. The mean time to wound healing was 6.85 weeks. There were five treatment failures. One patient healed a TM amputation after conservative efforts failed to heal multiple nonhealing toe ulcers. The other four patients underwent arterial reconstruction (2 femoral-popliteal, 1 femoral-tibial and 1 popliteal-popliteal), with three successes and one failure necessitating a below-knee amputation (BKA).

In the operative treatment group (28 feet, 42.4%) mean ABI of the involved limb was 0.57 and tcpO₂ mapping demonstrated the following mean values: AK, 55 mmHg; BK, 41 mmHg; TM, 11 mmHg. No patient in this group had a palpable pedal pulse and all patients with rest pain had low TM tcpO₂ measurements. Interventions based on arteriography included: arterial reconstruction (16 limbs, 57%), angioplasty (8 limbs, 29%), primary major amputation (2 limbs, 7%) and pedal vessel exploration (1 limb, 3.5%). One other limb (3.5%) demonstrated only proximal occlusion of the lateral branch of the plantar artery without another significant arteriographic abnormality. Twenty-six of 28 feet were followed to the selected endpoints. There were no deaths, but two patients without a distal target
vessel suitable for bypass had primary major lower extremity amputation and were excluded from outcome analysis.

After either bypass or angioplasty, 20 of 24 (83.3%) limbs achieved a TM tcpO₂ level ≥ 30 mmHg. The tcpO₂ improvement was most marked at the TM level, where the mean value increased from 11 to 42 mmHg (p = 0). At the BK and AK positions, mean tcpO₂ levels improved from 40 to 49 mmHg (p = 0.11) and from 56 to 60 mmHg (p = 0.43), respectively. Twenty-two of 26 (85%, p = 0.0003) limbs in this group had complete resolution of their presenting foot problem. This includes one limb with a persistent TM tcpO₂ level < 30 mmHg despite successful peroneal artery bypass and one limb that had an unnecessary angiogram as the follow-up TM tcpO₂ level after edema cellulitis resolution was > 30 mmHg. The mean time to wound healing was 9.52 weeks. Treatment failures eventually led to three below-knee amputations (one failed necessitating revision to the above-knee level) and one above-knee amputation.

Overall, pedal pulse examination was more accurate than the ABI in predicting tcpO₂ values above or below 30 mmHg at the foot level (74%, p = 0.000006 vs. 68%, p = 0.011). An abnormal angiogram was predicted by both a low TM tcpO₂ level and the absence of a palpable pedal pulse (27/28 threatened limbs, 96%), but not an ABI < 0.60 (52%). The presence of a pedal pulse was 100% accurate for identifying limbs with a TM tcpO₂ ≥ 30 mmHg (21/21 feet), but there were an additional 17 limbs with a measurement ≥ 30 mmHg and no palpable pedal pulse. Following arterial reconstruction or angioplasty, a TM tcpO₂ level ≥ 30 mmHg was highly accurate (96%, p = 0.0003) in predicting a successful outcome. Ultimately, an initial or post-intervention TM tcpO₂ level ≥ 30 mmHg was more accurate (90%, p = 0.001) than a palpable pulse (65%, p = 0.009) in predicting wound healing or resolution of rest pain. An ABI ≥ 0.60 was also associated with a successful outcome (89%, p = 0.06), but due to noncompressible vessels, the ABI could be calculated in only 41 of 62 (66%) limbs.

As expected, in this group of diabetic patients an ABI could not be calculated in all limbs. Even with compressible vessels, ABIs were not reliable in predicting either abnormal arteriograms or tcpO₂ levels (≥ 30 mmHg) adequate to support major wound healing. However, the absence of a pedal pulse was highly predictive of an abnormal arteriogram and a palpable pedal pulse was 100% (21/21 limbs) correct in identifying feet with a TM tcpO₂ ≥ 30 mmHg, 20 of which were successfully treated. Nevertheless, 11 of 15 limbs without a palpable pulse, but a TM tcpO₂ ≥ 30 mmHg, also healed with conservative care only. Thus, neither ABIs nor pedal pulses were sufficiently discriminating to be used to make a clinical decision with regard to ultimate wound healing or resolution of rest pain. Therefore, in diabetic patients a TM tcpO₂ level ≥ 30 mmHg at the onset of conservative treatment or following arterial reconstruction/angioplasty appears to be highly accurate (90%, p = 0.001) in predicting ultimate resolution of pedal gangrene, nonhealing ulceration or ischemic rest pain.

Total cost for tcpO₂ mapping of a lower extremity in our region is $93.88. This figure includes direct and indirect facility costs ($56.70) for the 30 min study with no variation in cost for a unilateral or bilateral study except for the increased time (an extra 30 mins) involved for the vascular technician, plus the current physician reimbursement based on the Medicare-RVU scale ($37.18). Total cost for a diagnostic lower extremity arteriogram including nursing staff, supplies, usual room time of 2 hours and the procedure code is $1052.73 ($485.45 for staff, supplies and angiographic suite, plus $567.29 for outpatient charges, plus $459.35 for the allowable professional component based on Medicare-RVU scale).

If absence of pedal pulses had been the indication for arteriography, 45 limbs would have been subjected to this examination. In fact, only 31 limbs needed arteriography (27/28 limbs with an initial TM tcpO₂ level < 30 mmHg, and 4/5 treatment failures with an initial TM tcpO₂ level ≥ 30 mmHg). The nonessential 14 arteriograms would have cost $14,738.22. In contrast, the 14 tcpO₂ studies cost $1,314.32.

Certainly diabetic patients without pedal pulses do have arteriosclerotic lesions, some of which can be reconstructed. However, this prospective study demonstrated that such surgical revascularization is not obligatory. In fact, well-performed tcpO₂ measurements predicted distal ischemic wound healing in 90% of cases. Further, conservative management was not only cost-effective when compared with surgical or angioplasty revascularization, but time to lesion healing was not statistically significantly
different between the two groups (6.84 weeks vs 9.52 weeks, p = 0.169).

A critical analysis of treatment failures and incorrect treatment selection demonstrated the fallibility of tcpO₂ measurements in certain clinical situations and the complex nature of diabetic foot problems. In the conservative treatment group, four of five treatment selection failures had a TM tcpO₂ value < 34 mmHg and had calcaneal gangrene or nonhealing ulceration. The fifth patient failed not only conservative care but also arterial reconstruction, and had a below-knee amputation despite an initial TM tcpO₂ level of 42 mmHg. In the group of patients with an initial TM tcpO₂ < 30 mmHg, one patient's TM tcpO₂ level improved from 1 to 19 after superficial femoral artery angioplasty, but the ulcerated foot lesion did not heal. She then had femorotibial bypass and a vascularized free-flap to cover the dorsum of her foot. The TM tcpO₂ level improved to 30 mmHg. This combined procedure was ultimately successful. One patient had pedal vessel exploration but no suitable distal target was found. He then failed a minor foot amputation. Two patients had a major amputation for ascending pedal sepsis despite a patent bypass graft. One other patient with pedal edema, cellulitis, and a TM tcpO₂ measurement of 25 mmHg had an unnecessary arteriogram, as the foot problem resolved with conservative care. Follow-up tcpO₂ mapping demonstrated the TM value to be > 30 mmHg after resolution of pedal cellulitis and edema.

As demonstrated in the study by Ballard et al., an absolute TM tcpO₂ level ≥ 30 mmHg appears to be an accurate cutoff point for the selection of conservative or operative treatment for almost all diabetic foot problems. The conservative management scheme, however, requires diligent patient follow-up. There must be a commitment by the surgeon to perform office debridements and staged procedures (i.e., minor foot amputations or split-thickness skin grafts). Proper outpatient wound care is essential. A higher TM tcpO₂ threshold (40 mmHg) may be required to successfully manage calcaneal gangrene or some very severe non-healing ulcerations. Table 30.1 demonstrates the current algorithm used at Loma Linda University Medical Center for the elective management of diabetic patients with limb-threatening ischemia.

Padberg et al. recently confirmed that tcpO₂ measurements alone are sufficient to objectively stratify degree of lower extremity arterial ischemia. They compared tcpO₂ measurements with arterial segmental pressures (ASP) and arterial segmental indices (ASI) in 204 ischemic lower extremity sites in patients with either diabetes, chronic renal failure or neither disease process. Stepwise multiple regression analysis demonstrated tcpO₂ mapping to be superior to ASP and ASI for all endpoints. As demonstrated by others, predictive accuracy of tcpO₂ measurements was unaffected by the presence of diabetes and ASP and ASI were misleading and inaccurate. Interestingly, because of reduced accuracy of ASP and ASI, tcpO₂ remained the diagnostic modality of choice even for the nondiabetic patient with arterial ischemia of the lower extremity.

### Table 30.1. Algorithm for elective management of the diabetic patient with limb-threatening foot ischemia

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<th>Step</th>
<th>Action</th>
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| A. | If forefoot/hindfoot tcpO₂ level > 30 mmHg (with or without a palpable pedal pulse):  
Outpatient wound care, wound debridement or minor foot amputation |
| B. | If forefoot/hindfoot tcpO₂ level < 30 mmHg or conservative treatment is unsuccessful after 4–6 weeks:  
Arteriography with revascularization as needed |
| C. | If forefoot/hindfoot tcpO₂ < 30 mmHg and there is pedal edema or cellulitis:  
Repeat test after resolution, before proceeding with arteriography |
| D. | If there is calcaneal gangrene/nonhealing ulcer:  
Use higher hindfoot tcpO₂ threshold of 40 mmHg and obtain arteriogram after 2–4 weeks of unsuccessful conservative treatment |

### Prospective Treatment of Nondiabetic Patients with Chronic Lower Extremity Ischemia

Much the same as described above for the treatment of diabetic patients, tcpO₂ measurements can be useful for patients, particularly the elderly, with ill-defined leg/foot complaints. For instance, an adequate tcpO₂ level (≥ 30 mmHg) at the forefoot and hindfoot may obviate the need for an arteriogram and support nonoperative management. On the other hand, a low tcpO₂ level likely indicates a situation that will require a higher level of care. The potential need for arteriography and arterial revascularization can be discussed extensively with the patient and family prior to treatment. This insures reasonable expectations. Finally, a dramatic
improvement in tcpO₂ measurement following treatment is not only gratifying, but at least 90% of patients will experience a successful outcome.

References

SURGICAL TEXTS

RECOMMEND COMPREHENSIVE TEXTS (for Core Topic List):

Essentials of General Surgery, 3rd edition by Lawrence (Williams & Wilkins)
Essentials of Surgical Specialties, 2nd edition

ALTERNATIVE COMPREHENSIVE TEXTS:

Current Surgical Diagnosis and Treatment, 11th edition by Way (Lange) ISBN 0-8385-1456-1

SUPPLEMENTAL TEXTS OF INTEREST

Cope’s Diagnosis of the Acute Abdomen, Edited by William Silen, MD ISBN 01-951-367-99

REFERENCE TEXTS:

ISBN 0-079-1231-8-X

ISBN 0-721-6586-7-3