REVIEW

Measuring tissue oxygen tension: a review

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Sheffield PJ. Measuring tissue oxygen tension: a review. Undersea Hyper Med 1998; 25(3):179–188.—Because of technological advances in tissue oximetry, clinicians and scientists have a better understanding of the role of oxygen in wound healing. In wound care and hyperbaric medicine applications, an oximeter is principally used with vascular assessment to help determine amputation level and to estimate healing potential. With the current emphasis on cost savings in the managed care setting, transcutaneous oximetry ($PtcO_2$) has gained importance as a tool for predicting potential candidates for hyperbaric oxygen (HBO_2) therapy. It is used to identify the presence of hypoxia in wounded tissue, to predict the responders to hyperoxia and in some instances to determine when HBO_2 treatment is complete. This literature review describes the principal current methods for measuring tissue O_2 and the values obtained in normal and wounded tissue under both normobaric and hyperbaric conditions. The review includes the Jefferson C. Davis Wound Care and Hyperbaric Medicine Center protocol for $PtcO_2$ assessment of potential HBO_2 candidates and suggestions for obtaining reproducible $PtcO_2$ data.

tissue oxygen measurement, tissue oxygen tension, oxygen electrodes, normal oxygen tension, wound oxygen tension, transcutaneous oximetry, oxygen in wound healing, vascular assessment

Much has been written about the role of oxygen in wound healing and the technological developments to measure it. Hunt (1) and Niinikoski (2) demonstrated the hypoxic nature of wounds and postulated that healing and incidence of infection were related to O_2 supply. Silver (3) precisely analyzed the environment in and around experimental wounds and revealed an O_2 gradient between the dead space of the wound and the wound edge. Investigations of severely hypoxic wounds in animal models suggested that elevation of O_2 tension up to normal would enhance healing, since the rate of healing is O_2 dependent (4). Direct relationships have been demonstrated between wound O_2 tension and production of collagen (5), epithelialization (6), resistance to infection (7), and promotion of healing (1,7,8). Because of technological advances in O_2 monitoring, clinicians and scientists now have a better understanding of wound healing mechanisms and the role of O_2 in wound healing.

Sheffield (9) demonstrated that hyperbaric oxygen (HBO_2) elevated O_2 tension in severely hypoxic wounds. HBO_2 elevates arterial Po_2 (10), increases the steepness of the Po_2 gradient within tissue (3), and increases the O_2 diffusion distance from functioning capillaries (11). Thus, HBO_2 corrects severe hypoxia in some inadequately perfused wounds. In wound care and hyperbaric medicine applications, O_2 monitors are principally used with vascular assessment to help determine amputation level and estimate healing potential.

This review includes a discussion of methods used at the Jefferson C. Davis Wound Care and Hyperbaric Medicine Center, San Antonio, Texas.

WHY MEASURE TISSUE OXYGEN TENSION?

Tissue oxygen tension is a direct, quantitative assessment of O_2 availability to tissue. Tissue O_2 data are used in medical decision making by several medical specialties, including wound care and hyperbaric medicine. With the current emphasis on cost savings in the managed care setting, tissue oximetry has gained importance as a tool for predicting potential candidates for HBO_2 therapy. These data aid in vascular assessment to help predict non-responders to treatment and to choose successful amputation sites. They are also used to select candidates for HBO_2 by identifying the presence of tissue hypoxia and the responders to hyperoxia. In some instances tissue O_2 data are used to determine when treatment is complete.

Present methods of measuring wound oxygen tension

Principal methods presently used in assessing tissue oxygenation are invasive polarographic electrodes, mass spectroscopy, tissue tonometry, blood gas analysis, and transcutaneous oximetry (12,13).

Invasive polarographic electrodes: The first application of O_2 polarography in animal tissues is credited to Davies and Brink (14) who used a 25-µm platinum bare-wire electrode to show that the O_2 value in tissue differed from that in a fluid-filled recess of the tissue. As electrode technology improved, the cathode was constructed of a

semi-noble metal (silver, platinum, or gold) with a reference anode of silver/silver chloride. To prevent protein coating of the electrode, the cathode was usually coated with a collodion membrane that was permeable to water and oxygen. Clark and associates (15) improved the design by placing both the anode and cathode in an electrolyte solution behind a polyethylene membrane. Because of its large size, its application was limited to fluid and organ surfaces until it was miniaturized by Silver (16). The probe is calibrated before insertion into the tissue. An 18- to 22-gauge wire electrode has a sensing area of about 450 μm, 4–6 times the diameter of the tip (17). Invasive electrodes were used to confirm hypoxia in chronic, indolent human wounds and to show that oxygen is delivered to wounds during HBO_2 treatment (9).

Mass spectroscopy: The mass spectrometer can simultaneously analyze several tissue gases, such as O_2, carbon dioxide, nitrogen, and anesthetic gases. It has been used for both normobaric (18) and hyperbaric (19) applications. Two types of permeable membranes are commonly used for the tissue probe: a fast-response Silastic membrane for flowing blood, and a slow-response Teflon membrane for tissue. The inner face of the membrane is exposed to a low pressure (average, 10^{-6} mmHg), whereas the outside face is in contact with the tissue gas to be measured. Gas molecules from the tissue pass through the permeable membrane and are drawn via tubing into the mass spectrometer, where they are separated and measured quantitatively (20). Wells et al. (19) used mass spectroscopy to record P_{O_2} and other tissue gas values for healthy subjects under normobaric and hyperbaric conditions (Table 1). The authors reported that following a HBO_2 exposure of 1 h, the subject's skin O_2 tension remained elevated >10% for up to 3 h.

Tissue tonometry: A method of tissue tonometry was developed by Hunt (21) in which about 14 cm of Silastic tubing was passed into the skin via an 18-gauge cutting-tip spinal needle. Physiologic saline was slowly injected into the tubing, allowing time for tissue gases to equilibrate with the saline in the tube. A 25-μm polarographic O_2 electrode was then inserted into the end of the tonometer for continuous measurement of O_2 tension. As an alternative, the saline can be withdrawn from the tonometer and measured by blood gas analysis. This method gives a single, integrated, mean value of extracellular fluid O_2 tension across the length of the tonometer. The reading is proportional to regional blood supply, arterial O_2 tension, and microvascular perfusion. The electrode can be calibrated in situ, and tissue O_2 tension can be read continuously (22).

Blood gas analysis: Procedures are now available for collecting arterial blood gases during HBO_2 treatments in both walk-in and single-occupant chambers. The blood gas analyzer can be placed inside a walk-in chamber and the sample analyzed while under pressure (23). A portable, battery-powered blood gas analyzer (StatPal II Blood Gas Analyzer, PPG Industries) was evaluated and found to be effective at 2.5 atm abs (24), but when greater pressure is applied, the pressure-sensitive keys on the electronic keyboard are depressed, causing the analyzer to continually cycle and rendering it unusable (Martindale VE. 1994, personal communication). In a single-occupant chamber, arterial blood samples are aspirated from the subject and passed through the chamber wall for analysis outside the chamber (25). Analysis must be immediate to avoid false low readings due to off-gassing of the sample. Arterial blood gases measured at 1 atm abs have been used to predict arterial O_2 tension under HBO_2 conditions (26). Howe and associates (27) reported a correlation between arterial O_2 tension and transcutaneous oxygen tension at the level of the chest, but on the leg and foot, the correlation is not clear.

Transcutaneous oximetry: Transcutaneous oximetry ($PtcO_2$, a.k.a. TcPO2, TCOM) was developed as a noninvasive method to monitor tissue O_2 tension. Baumberger and Goodfriend (28) immersed a subject's finger in a phosphate buffer solution heated to 45 °C for about 60 min to demonstrate that the O_2 tension of the buffer solution approximated the subject's arterial O_2 tension. Huch et al. (29) developed $PtcO_2$ by modifying a Clark electrode with a heating element and thermistor to maintain a preset temperature of 42°–45 °C. A fixation ring filled with contact solution is used to attach the electrode to the skin surface.

To aid O_2 migration to the skin surface where it can be analyzed, the noninvasive sensor must cause physiologic changes in the underlying tissue. Heating the sensor to 42°–45 °C transfers heat to the skin surface, dilating capillaries, opening skin pores, decreasing O_2 solubility, and shifting the oxyhemoglobin curve to the right for ready release of O_2 (30). In the absence of heat, diffusion of O_2 from tissue to skin surface contributes less than 3.5 mmHg to the P_{O_2} at that location (31). A control electrode is placed on the skin at the second intercostal space of the chest. As of this writing, transcutaneous sensors will not adhere to a moist surface, thus $PtcO_2$ values are collected near the wound at standardized locations. The interpreter uses periwound $PtcO_2$ in combination with other assessment methods (e.g., temperature, pulse, presence of hair, general appearance of the tissue) to predict the behavior of the wound.

Transcutaneous oximetry was originally used in neonatology (32), and is now commonly used in pediatric intensive

Table 1: Tissue Oxygen Tension Values for Progessively Increased Inspired Po_2

Ambient Pressure (atm abs) / Breathing Media	1.0 Air	1.0 O_2	2.0 O_2	2.4 O_2	3.0 O_2
	Representative tissue oxygen tension values, mmHg				
Ambient Po_2, mmHg	159	760	1520	1,824	2280
Ideal alveolar Po_2	104	673	1433	1,737	2193
Ideal arterial Po_2	100	660	1400	1,700	2150
Arterial Po_2[a]	–	550±100	1,150±250	–	1,750±250
Venous Po_2[b]	36±4	60±9	101±36	–	–
Muscle Po_2[b]	29±3	59±13	221±72	–	–
Subcutaneous Po_2[b]	37±6	53±10	221±72	–	–
Subcutaneous Po_2[c]	65±7	–	–	–	–
Subcutaneous Po_2[d]	30–50	90–150	200–300	250–500	–
Typical chronic wound Po_2[d]	5–20	200–400	–	1,000–1,700	–
Transcutaneous Po_2[e]	69±6	440±95	–	1,350±220	–
Transcutaneous Po_2—chest[f]	67±12	450±54	–	1,312±112	–
Transcutaneous Po_2—calf, male[f]	49±14	281±78	–	1,027±164	–
Transcutaneous Po_2—calf, female[f]	59±12	367±59	–	1,174±127	–
Transcutaneous Po_2—midfoot[f]	63±13	280±82	–	919±214	–
Transcutaneous Po_2—limb[g]	49	325	696	–	–

[a]Blood gas analyzer data from (10); [b]mass spectrometer data from (19); [c]implanted tissue tonometer data from (40); [d]implanted polarographic O_2 data from (12); [e]transcutaneous O_2 data from (41); [f]transcutaneous O_2 data from (42); [g]transcutaneous O_2 data from (43).

care units (33), plastic surgery (34), vascular surgery (35), anesthesiology (36). orthopedics (37), and hyperbaric medicine (38,39). In 1994, Matos and Nunez (38) reviewed a series of tissue oxygenation studies and concluded that $PtcO_2$ was clinically useful in determining healing potential, selecting amputation level, evaluating revascularization procedures, and assessing severity and progression of peripheral vascular disease.

MEASUREMENTS OF NORMAL O_2 TENSION

No single value can be specified "normal" O_2 tension for all tissue. Rather, there exists a series of gradients, the steepness of which varies with arterial O_2 tension, type of tissue, inter-capillary distance, and cellular metabolic rate. Normal values will vary by method of measurement. Table 1 contains tissue O_2 values measured by blood gas analyzer (10), mass spectrometer (19), tissue tonometer (40), implanted polarographic electrode (12), and $PtcO_2$ (41–43) at pressures of 1.0, 2.0, 2.4, and 3.0 atm abs. The data of Dooley et al. (42) contain "normal" $PtcO_2$ values obtained in 72 subjects (53 males, 19 females) for chest, calf, and midfoot, and reveal a significant gender difference at the calf.

MEASUREMENTS OF WOUND OXYGENATION DURING A COURSE OF NORMOBARIC OR HYPERBARIC OXYGEN

Studies of human ischemic wounds revealed that many problem wounds were severely hypoxic and that HBO_2 corrected the severe hypoxia by daily bringing wound oxygenation (PwO_2) up to normal levels (9). Specific findings were:

- *Problem wounds have low Po_2*: Invasive O_2 electrodes in chronic, indolent, soft-tissue human wounds revealed that non-healing wounds were often severely hypoxic, with PwO_2 values ranging from 5 to 20 mmHg as compared to control tissue of 30–50 mmHg (12). Values in the center of the wound were lower than values at the wound edge. $PtcO_2$ showed evidence of severe hypoxia adjacent to problem wounds, with $PtcO_2$ values adjacent to the wound falling below 20 mmHg, as compared to 65 ± 15 mmHg in healthy control tissue (44).
- *Wounds respond to O_2*: Invasive polarographic O_2 electrodes in two diabetic wounds revealed PwO_2 values less than 20 mmHg during air breathing, with subsequent increases of 10–400 mmHg during periods of 100% O_2 breathing at 1 atm abs (9).
- *Wound Po_2 has minute-to-minute variability*. Invasive O_2 electrodes revealed fluctuations in PwO_2 reflecting the local tissue demands for O_2 (9).
- *Hyperbaric oxygen elevates wound Po_2*: Invasive oxygen electrodes showed that HBO_2 demonstrably increased PwO_2 to above 1,000 mmHg in previously hypoxic wounds (9,45).
- *Multiple HBO_2 exposures increase wound response*: Measured invasively, baseline PwO_2 values that were below 15 mmHg while breathing air at 1 atm abs increased to above 30 mmHg as angiogenesis and vascularity improved with multiple (usually 20–30) HBO_2 exposures (9).

- *Irradiated tissue responds like a wound*: Invasive electrode assessment during O_2 breathing at 2.4 atm abs revealed PwO_2 frequently exceeding 1,000 mmHg, but intact skin values rarely exceeded 500 mmHg, because of its ability to vasoconstrict. Invasive Po_2 values in irradiated skin were 600–1,100 mmHg (like a wound) during the first 7 wk of HBO_2 treatment (45), but declined to 250–400 mmHg (like healthy skin) in subsequent treatments, indicating new blood vessel maturity in radiation-damaged tissue. $PtcO_2$ attains values that are greater than invasive electrode values. Marx et al. (46) found that transcutaneous oxygen values in irradiated tissue changed from an initial value of 20% to an end value of 80% of non-irradiated control tissue over a course of about 20 HBO_2 treatments. In experimental burn wounds of rats, Ketchum et al. (47) had previously demonstrated extensive capillary proliferation by Day 18 of daily HBO_2 treatments. Angiogenesis in irradiated tissue was shown to exhibit a dose response to O_2 that improved as the partial pressure of oxygen was increased in 0.5 atm increments up to 3 atm abs (48,49).

TISSUE OXYGEN ASSESSMENT WITH $PtcO_2$

Transcutaneous oximetry has become increasingly popular as a tool for vascular assessment of amputation sites and for wound assessment for HBO_2 treatment. Tissue O_2 assessment is used to help define those patients within a given diagnosis that will benefit from HBO_2 treatment and, in some cases, to determine when treatment is complete.

Transcutaneous oximetry as a predictor of successful amputation: A number of studies of patients who did not receive HBO_2 have confirmed that normal wound healing of an amputation site requires a $PtcO_2$ value of about 40 mmHg or an extremity-to-chest ratio (limb $PtcO_2$ / chest $PtcO_2$) of about 0.6.

White and Klein (50) reviewed eight patient studies of $PtcO_2$ values for 260 amputees who did not receive HBO_2 and concluded that a $PtcO_2$ value of 40 mmHg or greater was required for successful outcome of amputation. Values less than 40 mmHg suggested an unsuccessful outcome unless revascularization could be combined with the amputation.

In a case-controlled study, Reiber et al. (51) computed odds ratios for a number of risk factors associated with lower extremity amputation in diabetic patients, where <1 suggested a protective effect and >1 suggested increased risk. Patients with below-knee and dorsal foot $PtcO_2$ values above 40 mmHg served as a reference group against which the study groups were compared. Patients with $PtcO_2$ values of 20–40 mmHg had an odds ratio of 7.5 (CI 4.0–14.1), whereas $PtcO_2$ values <20 mmHg yielded an odds ratio of 161 (CI 55–469). Thus, the lower the $PtcO_2$, the greater the risk of amputation.

In a blinded prospective study of 119 amputations, Harward and colleagues (52) compared $PtcO_2$ values before and after 10 min of 100% O_2 inhalation, and concluded that an increase above 10 mmHg was predictive of successful outcome.

Hauser (53) prospectively assessed 159 wounds (93 local debridements and 66 amputations) in 113 high-risk patients with diabetes mellitus and peripheral vascular disease who did not receive HBO_2. They measured $PtcO_2$ values at four sites on the limbs and compared extremity-to-chest ratios (RPI = wound $PtcO_2$ / chest $PtcO_2$) that reflected healing success. Of 93 local procedures, 48 healed (RPI = 0.72 ± 0.10) and 45 failed (RPI = 0.25 ± 0.12). Of 66 amputations, 45 healed (RPI = 0.64 ± 0.09) and 21 failed (RPI = 0.28 ± 0.11). Data in Table 2 reveal excellent outcome when RPI was >0.6, and poor outcome when RPI was <0.4.

Thus, patients whose $PtcO_2$ values at the amputation site are below 40 mmHg or whose PRI values are below 0.6 are potential candidates for HBO_2 and aggressive wound management (12,38,54). In many cases, mapping of the skin surface with $PtcO_2$ values at multiple amputation sites will offer the surgeon options for better limb salvage.

Transcutaneous oximetry as a predictor of wound healing: $PtcO_2$ values exceeding 30–40 mmHg are generally reported to be required for wound healing, but institutions vary in the absolute values.

Wyss et al. (55) reviewed a series of 188 diabetic patients with peripheral vascular disease. They reported that those with leg/foot $PtcO_2$ values below 20 mmHg were significantly more likely to have ulcers, rest pain, and amputation of the limb, as compared to those with $PtcO_2$ values above 20 mmHg.

Wyss et al. (37) measured $PtcO_2$ at the foot and proximal

Table 2: Wound Healing vs. Regional Perfusion Index (Hauser)

Wound Status	RPI = 0–0.4	RPI = 0.41–0.6	RPI > 0.61
Healed, n = 86	2	22	61
Delayed healing, n = 8	2	5	1
Failed, n = 73	60	11	2

and distal to the knee in 162 patients who then had 206 amputations. An increasing probability of failure was correlated with decreasing $PtcO_2$. Values >40 mmHg were associated with good healing, 20–40 mmHg with intermediate healing, and <20 mmHg with poor healing.

Gorman (56) conducted a review of diabetic foot wounds in which he used relative $PtcO_2$ (percent of chest control) and ankle perfusion pressure to predict treatment outcome. He concluded that patients who have relative $PtcO_2$ values >85 % and ankle perfusion pressure >90 mmHg will heal without O_2. Conversely, those with relative $PtcO_2$ values <20% and ankle perfusion pressure <75 mmHg are unlikely to heal. Gorman's conclusions are summarized at Table 3.

In 1983, Sheffield and Workman (41,44) reported the first known $PtcO_2$ data recorded under hyperbaric conditions (100% O_2 at 2.4 atm abs, 238 kPa). Using a Radiometer TCM1 oximeter to monitor both healthy subjects (n = 18) and patients (n = 4), values exceeding 1,000 mmHg were reported (41). During the course of HBO_2, two patients healed (1 diabetic, 1 scleroderma) whose baseline air $PtcO_2$ values were elevated >30 mmHg, but two diabetic patients did not heal whose $PtcO_2$ values fell below 30 mmHg. In 1994, Matos and Nunez (38) concluded that transcutaneous oxygen measurement was the best presently available method to determine the need for HBO_2 before initiation of therapy.

Pecoraro et al. (57) found $PtcO_2$ values to be useful as predictors of healing in diabetic patients and in selecting patients for adjunctive HBO_2 to correct underlying tissue hypoxia, either alone or in combination with revascularization. Marx et al. (46) reported an RPI of 0.8 in irradiated tissue of the face and neck within 4 wk of starting HBO_2 therapy. Sheffield and Workman (58) reported improved baseline $PtcO_2$ at the wound site taken at 7-day intervals while the patients received HBO_2 therapy. Sheffield (59) retrospectively found that diabetic patients with forefoot wounds (n = 84) had an 8-fold increase in likelihood of successful outcome with HBO_2 when baseline transmetatarsal $PtcO_2$ values were >30 mmHg as compared to $PtcO_2$ values <30 mmHg ($P < 0.05$).

Measurements of $PtcO_2$ under hyperbaric conditions: There is controversy as to which environment for measuring $PtcO_2$ has the best predictive value: atmospheric conditions or HBO_2. A number of investigators have suggested that the best predictor of wound healing success would be $PtcO_2$ conducted under hyperbaric conditions, but the suggested minimum values vary widely.

Myers and Emhoff (60) concluded that diabetic patients (n = 11), with below-knee $PtcO_2$ values <20 mmHg, would heal if 900 to 1100 mmHg could be achieved on the initial HBO_2 exposure (100% O_2 at 2.5 atm abs, 252 kPa). Healing did not occur if the values were below 900 mmHg.

Wattel et al. (61) found that in diabetic foot lesions (n = 59), $PtcO_2$ values on normobaric O_2 did not discern between healing and failure. Conversely, $PtcO_2$ values above 450 mmHg during HBO_2 (100% O_2 at 2.5 atm abs, 252 kPa) were predictive of healing in diabetic patients with plantar ulcers, with the healing group having significantly higher $PtcO_2$ than the failed group (786 ± 258 vs. 323 ± 214 mmHg; $P < 0.005$). Campagnoli et al. (62) reported that diabetic patients (n = 24) healed if $PtcO_2$ values were above 400 mmHg during HBO_2. The authors observed that the faster the rise, the greater likelihood of an efficient support microcirculation, and the better the patients' chances of a favorable outcome. Hart et al. (43) measured seven patients with ischemic limbs (100% O_2 at 2.5 atm abs, 202 kPa) and reported that limb salvage occurred in four patients with $PtcO_2$ values above 100 mmHg, but three amputees had $PtcO_2$ values below 100 mmHg. Strauss et al. (63) measured $PtcO_2$ in 87 patients with problem foot wounds and reported that 98% healed when $PtcO_2$ measured over 200 mmHg during HBO_2 (100% O_2 for 90 min at 2 atm abs, 202 kPa). In contrast, only 17% (2 of 12) of foot wounds healed when $PtcO_2$ adjacent to the wound was less than 100 mmHg.

SPECIAL CONSIDERATIONS FOR REPRODUCIBLE $PtcO_2$ DATA IN THE CLINICAL SETTING

At this writing, $PtcO_2$ is as much an art as a science. Data collection requires a skilled technician using a rigorous protocol. Interpretation of data requires a complete understanding of the limits of the technology. To obtain repro-

Table 3: Use of $PtcO_2$ to Predict Healing of Diabetic Wounds of the Foot (Gorman)

	Ankle Pressure, mmHg	Relative $PtcO_2$, % Chest Control
Will heal without O_2	>90	>85
Probably will heal with O_2	75–90	20–85
Unlikely to heal	<75	<20[a]

[a]Exception: when $PtcO_2$ rises >50% within 15 min of initiating O_2 breathing.

ducible results, it is important to standardize the technique. At this writing, however, there is no consensus of the best method to collect the data.

Method of assessment: A number of methods have been used to assess healing potential: 1) a single $PtcO_2$ value adjacent to the wound; 2) a map of multiple sites around the wound; 3) a map of several sites on the affected limb; and 4) a comparison of periwound or amputation site values expressed as a percentage of control values at the chest. The number of sites to be measured is usually determined by the number of sensors available. The preferred method seems to be a map of at least three sites. But regardless of the assessment method, it is important to be consistent.

Selection of the monitor: Monitors from several manufacturers have been used for $PtcO_2$ studies (43,50,64). As of this writing, the TINA TCM3 and TCM30 (Radiometer, Copenhagen) are the only monitors with sensors that have been tested and shown to be compatible with operation in a chamber filled with pure O_2 (64). Although the sensor is inside the pure O_2 chamber, fire safety considerations require the monitor to remain outside, connected to the sensor via a through-hull penetrator.

Calibration of sensor: It is advisable to install a new membrane weekly and to follow the manufacturer's instructions for calibration. It is also advisable to use a two-point calibration in the range of values that are anticipated and to correct for ambient temperature and barometric pressure. Some devices have the zero point determined electronically rather than requiring a zero-oxygen gas or zero-oxygen solution.

Selection of sensor temperature: Transcutaneous sensors measure the approximate arterial O_2 values at the site chosen. Heating the skin causes physiologic changes beneath the sensor: opens pores, dilates capillaries, increases skin perfusion, increases metabolism, and causes hemoglobin to release O_2. A sensor temperature of 45°C produces maximum arterialization of P_{O_2} and can be tolerated by most patients. An occasional patient with poor perfusion will experience a blister beneath the electrode if it remains in place in excess of an hour. For this reason, a 44°C sensor temperature is used at the Jefferson C. Davis Wound Care and Hyperbaric Medicine Center. Thus, values obtained in this laboratory will be about 2% lower than other laboratories that collect $PtcO_2$ at 45°C. For whatever sensor temperature setting is chosen, it is important to be consistent, and to report the temperature in scientific reports.

Standardized site of measurement: Considering normal circulation to the limb, there should be a standard approach to positioning the sensor. This will provide more consistent data and allow a means of comparing data among a group of patients.

Site preparation for electrode placement: The sensor site should be shaved, cleaned with alcohol, and stripped of superficial layers of dry, loose skin cells using adhesive tape. The sites should not overlie a bony prominence, superficial vessels, or pulse sites (65). Flat or slightly convex areas provide the most reliable sensor contact. The fixation ring should be checked for tightness of seal from the surrounding air. If multiple sites are to be measured, the fixation rings should be positioned in the same direction so that the electrode wires will all be positioned in the same direction. This reduces movement artifacts and risk of electrode displacement should the patient move.

Adequate time for electrode equilibration and $PtcO_2$ evaluation: For 15 yr the Jefferson C. Davis Wound Care and Hyperbaric Medicine Center, has conducted $PtcO_2$ assessment of candidates for HBO_2. The procedure has evolved into a 45–min assessment as shown in Table 4. Acquiring a baseline $PtcO_2$ value of the supine patient takes 20 min. As the sensor heats the skin, equilibration of the electrode (Fig. 1) occurs within 10–15 min for subjects with normal circulation, but requires about 15–20 min for patients with compromised circulation (Vesterager P, 1997, personal communication). The limb is elevated 45° as a challenge to identify presence of large or small vessel disease that would cause P_{O_2} to fall and not recover until the patient is returned to the supine position. After the sensor is allowed to return to baseline, a 10-min O_2 challenge is administered to determine the response to O_2 of the wounded area. The sensor is allowed to return to baseline after each physiologic challenge to check for electrode drift. Some would argue that this assessment takes too much time and would be satisfied with a 30-min assessment that includes only baseline P_{O_2} and the O_2 challenge.

Interpretation of data: Methods of interpreting the data vary among investigators. Some investigators predict success by interpreting the raw data from the actual $PtcO_2$ values. Some use a "relative value", which is the value near

Table 4: Time Required for $PtcO_2$ Assessment by Mapping the Skin Surface

Assessment	Time Required, min
Electrode equilibration, air	15
Baseline $PtcO_2$, air	5
Elevate limb, air	5
Baseline $PtcO_2$, check for electrode drift	5
100% Oxygen challenge	10
Baseline $PtcO_2$, check for electrode drift	5
Total evaluation time	45

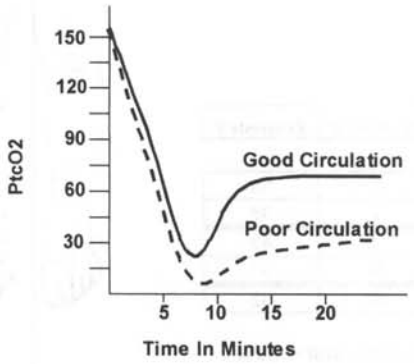

FIG. 1—Electrode behavior during equilibrium (*as drawn by P. Vesterager, 1997*).

the wound as compared to the chest control, or a mirror image site on the opposite limb, and expressed as a percentage. Others calculate a limb-to-chest ratio, called a "regional perfusion index" (RPI = limb $PtcO_2$ / chest $PtcO_2$). As of this writing there is no consensus on the best method for interpreting the data. However, it is clear that interpretation demands careful assessment of the tissue on which the sensor is placed. $PtcO_2$ values can be elevated if the sensor is positioned over superficial vessels or if there is a leak under the fixation ring. $PtcO_2$ values can be lowered if the sensor is positioned over bony protuberances or if the patient uses tobacco products. $PtcO_2$ values in smokers were 10% below nonsmokers (41) and remained significantly reduced for about an hour after smoking (40). But there is evidence of improved tissue oxygenation after a few days of smoking cessation (66).

Transcutaneous oximetry values may also be lowered by several pathologic conditions: edema, active infection/inflammation, thick or sclerotic skin, occluded vessels, severed vessels (flap), ischemic lesions, or irradiated tissue. Plantar $PtcO_2$ readings are different from non-plantar and should be avoided or used with an understanding of how they should be interpreted. The interpreter of the data must consider all these factors.

Interpretation of $PtcO_2$ in case AAI 530 TG. This 50-yr-old, non-insulin-dependant diabetic patient with acute arterial insufficiency had an open left 3rd ray amputation. There was an ischemic wound margin, edema, and inflammation in the wound area. The typical $PtcO_2$ map of standardized sites on the leg is at Fig. 2. $PtcO_2$ assessment showed presence of vascular disease (electrodes A, D, E, and F), severe hypoxia over the foot (electrodes C and E), but a good response to the O_2 challenge at 1 atm abs (electrodes A, B, D, and E). The physician interpreting the results recommended aggressive wound care and adjunctive HBO_2 to help control infection and prevent spread of necrosis (67).

A PROTOCOL FOR $PtcO_2$ ASSESSMENT OF HBO_2 CANDIDATES

Assessment protocol: The $PtcO_2$ assessment of potential HBO_2 candidates usually consists of four basic questions about whether the wound: 1) is severely hypoxic, 2) will respond to O_2, 3) will respond to HBO_2, and 4) is to the point that it will heal without further treatment (54). The questions and their respective tests are shown in Table 5.

Transcutaneous oximetry values used to select HBO_2 candidates. Not all problem wounds are hypoxic, but may fail to progress for other reasons. Some patients with $PtcO_2$ values near zero will heal, whereas others with values above 40 mmHg will not. As indicated in the above studies, there is a wide range of proposed threshold values for healing, but the numbers are not absolute. Each wound care and hyperbaric medicine center has established its own criteria for selection of HBO_2 patients.

At the Jefferson C. Davis Wound Care and Hyperbaric Medicine Center, transcutaneous mapping of the affected extremity is essential in the acceptance or rejection of patients for HBO_2 (54). Candidates who meet the following criteria are generally accepted for HBO_2 (54). Since at least six sites are being evaluated simultaneously, not all sites will satisfy every test. However, the sensors must show the presence of hypoxia (test 1) and a reasonable response to oxygen (test 2 or 3).

- Test 1: Baseline air value at 1 atm abs. If all measured sites are above 30 mmHg (>40 mmHg for diabetic patients), tissue oxygenation is considered adequate for healing and the patient is usually not selected for HBO_2. If sites near the wound fall below these values, wound healing is complicated by hypoxia and the patient is accepted for HBO_2, provided test 2 or 3 is successful. Values of 20–40 mmHg are considered to be of intermediate healing potential, and values below 20 mmHg are associated with poor healing. A $PtcO_2$ value that is less than 10 mmHg is usually not a good prognostic sign for successful HBO_2 outcome (54). However, individual cases may vary and some patients with $PtcO_2$ values near zero are treated if clinical judgment justifies it.
- Test 2: Oxygen challenge at 1 atm abs. An oxygen challenge is essential to the $PtcO_2$ assessment to determine if the wounded area will respond to O_2 administration. The value should at least double the baseline, and above 30 mmHg is desirable (59). However, an increase of 10 mmHg has been shown to be successful (52). If a baseline value of 10 mmHg only reaches 20 mmHg during O_2 challenge, the patient would be selected for HBO_2, but would probably have a prolonged course of treatment unless there is some underlying temporary cause for the low O_2 response. The O_2 challenge is

		Control	Electrode A	Electrode B	Electrode C	Electrode D	Electrode E	Electrode F
		PtcO2						
Supin	20 min. Air	57	44	50	2	45	9	58
45 Elev Supin.	5 min. Air	54	25	39	1	24	2	39
Supin	5 min. Air	50	40	41	2	43	7	49
Supin	10 min. O2	290	79	88	4	178	40	67
Supin	5 min. Air	96	48	47	3	47	10	62

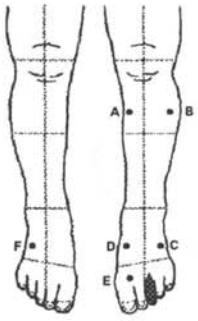

FIG. 2—Typical $PtcO_2$ mapping of the limb with 6 electrodes plus chest control.

Table 5: Protocol for $PtcO_2$ Assessment[a]

Question	Test
Is wound healing complicated by severe hypoxia?	1. Baseline air value at 1 atm abs; hypoxia exists if $PtcO_2$ <40 mmHg for diabetics, < 30 mmHg for non-diabetics.
Does the wound site respond to O_2 breathing?	2. O_2 challenge at 1 atm abs; value should be at least double the baseline value.
Does the wound site respond to HBO_2?	3. O_2 challenge 2–2.5 atm abs; value should be well above normobaric O_2 value.
Is the patient's wound at the point where it will heal without further treatment?	4. Repeat $PtcO_2$ evaluations at 1 atm abs in 2- to 4-wk intervals; normalization of baseline values would indicate that the healing process is in place.

[a]Values are from experience at the Jefferson C. Davis Wound Care & Hyperbaric Medicine Center (Heimbach RD, 1998, personal communication).

sometimes conducted in the hyperbaric chamber (61).

- Test 3: Oxygen challenge at 2–2.5 atm abs. The HBO_2 challenge is used to document that the patient is responding to the prescribed HBO_2 dose. The test is usually limited to one to three sites. Recommend minimum values range from 100–450 mmHg (61,63). At Baystate Medical Center in Springfield, Massachusetts, pressure in the chamber is increased beyond 2 atm abs until the prescribed oxygen dose ($PtcO_2$ = 400–600 mmHg or above) is achieved (Emhoff TA, 1998, personal commu nication).
- Test 4: Repeat baseline air value at 1 atm abs. Baseline $PtcO_2$ values should increase over a course of HBO_2 (44). Normalization of the $PtcO_2$ values (usually above 30–40 mmHg) indicates that the healing process is in place. An increase in $PtcO_2$ baseline over a course of HBO_2 should achieve a value that is normal for that patient. If the chest control value in an elderly patient is only 25 mmHg, it is unlikely that a greater value will be achieved in the affected limb, even though wound healing is achieved.

In summary, tissue O_2 measurements have confirmed hypoxia in chronic, indolent human wounds and have demonstrated that HBO_2 elevates wound O_2 tension. Tissue O_2 assessment is a valuable tool in the medical decision-making process for healing both acute and chronic soft-tissue problem wounds, and for helping define amputation levels. Sufficient clinical experience is published to justify $PtcO_2$, but measurement requires rigorous protocol and the interpreter must understand the limits of the technology. Best results are obtained from a dedicated, qualified technician who measures at standardized sites on the limb. The data suggest that the best predictor of success with HBO_2-treated cases would be $PtcO_2$ collected under hyperbaric conditions.

Manuscript received April 1998; accepted July 1998.

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