

Transcutaneous Oxygen Measurements Under Hyperbaric Oxygen Conditions as a Predictor for Healing of Problem Wounds

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ABSTRACT

Controversy exists as to what transcutaneous oxygen (P_{tO_2}) levels are required for wound healing and what role hyperbaric oxygen has for this. Current information suggests that 30 to 40 mmHg juxta-wound oxygen tensions in room air are required. We recorded P_{tO_2} measurements in room air and with hyperbaric oxygen in 190 patients with foot wounds; then looked retrospectively and prospectively whether there was any effect on healing. Transcutaneous oxygen measurements under hyperbaric oxygen conditions defined a responder group ($P_{tO_2} > 200$ mmHg) with a sensitivity of 0.80 and a positive predictive value of 0.88 for healing, regardless of room air measurements when hyperbaric oxygen was used as an adjunct to wound management. This information helps to objectify the indications for hyperbaric oxygen and predict healing especially in those patients with problem wounds of the foot and ankle.

INTRODUCTION

The patient with a slow healing or non-healing wound is at risk for a transtibial or higher amputation. Invariably these wounds are associated with compromised host factors such as peripheral vascular disease, diabetes, collagen vascular diseases, venous stasis disease, nutritional deficiencies, radiation injury, vasculitis or steroid use.

Problem wounds may be more objectively defined by use of the Wagner or Strauss wound scoring systems

(Table 1).^{1,2} In the Wagner system, Grade 2 to 4 wounds by our definition define a problem wound. Scores of four to seven do so in the Strauss system (Fig. 1). Wagner uses Doppler Monitoring to help in the decision making process. We have used juxta-wound transcutaneous oxygen measurements for the same reason. With appropriate treatment strategies, 80% of problem foot and ankle wounds are expected to heal.³ This paper compares outcomes with P_{tO_2} measurements in room air and with hyperbaric oxygen (HBO) in 190 patients who had wounds of the foot and ankle. The majority met the above criteria for a problem wound. Transcutaneous oxygen measurements with HBO defined a responder group, which had a very high positive predictive value for healing of problem wounds of the foot and ankle with HBO as an adjunct to management, whether or not the wounds were hypoxic in room air. We used the criteria of healing regardless of the level of foot amputation as success since in this group of patients the level of ambulation was not markedly altered by the surgery.

Hypoxic wounds have been defined by laboratory studies and clinical observations. The highest success rates for healing occurred with readings over 30 mmHg.^{4,5,6,7,8,9,10,11} Wyss¹² showed that there was an increasing probability of failure of amputations with low P_{tO_2} s at the level of amputation.

Controversy also exists as to what transcutaneous measurement techniques provide the best predictive value. We feel that juxta-wound measurements made with the O_2 sensor as close to the wound area as possible is an efficient P_{tO_2} measuring technique and provides sufficient information to make relevant clinical recommendations. All of our measurements were based on the juxta-wound measurement technique.

We used HBO as an adjunct to accepted orthopaedic strategies for managing problem foot wounds. These include optimal preparation of wound environment (debridement of necrotic tissues and bone, correction of bony deformities and release of joint contractures), protection of wound environment and proper dressing materials. Appropriate antibiotic selection, nutrition

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management, revascularization and/or angioplasty when feasible are the other primary interventions for management of the problem wound.

The subject of this study is to answer the question whether or not $P_{tc}O_2$ measurements under HBO conditions predict outcomes of problem wounds in the foot and ankle if adjunctive HBO is used for wound management.

When HBO was used as an adjunct to healing, healing of problem wounds in the responder group approached 90%.

MATERIALS AND METHODS

We measured $P_{tc}O_2$ s (Radiometer, TCM-3 $P_{tc}O_2$ / $P_{tc}CO_2$ Monitor, Copenhagen, Denmark) in the foot and ankle regions of 190 patients who had wounds in these areas. The O_2 sensor was placed as close to the wound as feasible, that is to say, the juxta-wound position. Before applying the O_2 sensor the skin was shaved (if necessary), cleansed of oils and dried. The adhesive side of the fixation ring was firmly pressed onto the skin. The fixation ring was filled with the "contact liquid electrolyte solution" specified by the manufacturer and the calibrating TCM 3 electrode was tightened securely into the fixation ring. The electrolyte heating element was set to 43° Centigrade for our studies.

Initial transcutaneous oxygen tensions were recorded after the patient breathed room air for 10 to 15 minutes. Next the patient was pressurized in a monoplace hyperbaric chamber (Sechrist 2500 monoplace hyperbaric

chamber, Sechrist Industries, Inc., Anaheim, CA, 92807) to two atmospheres absolute pressure over a 15 minute period. Transcutaneous oxygen readings were made every 30 minutes until the 1-1/2 to 2 hour HBO treatment was completed. Usually the $P_{tc}O_2$ measurements stabilized after 45 minutes. The highest recorded $P_{tc}O_2$ during the HBO treatment was used as the HBO $P_{tc}O_2$ value for each patient's study. Transcutaneous carbon dioxide measurements ($P_{tc}CO_2$) were recorded simultaneously. If the $P_{tc}O_2$ and $P_{tc}CO_2$ measurements were not consistent or there were marked variations in the $P_{tc}O_2$ readings during the HBO treatment, the information was discarded and measurements were repeated at another time.

Outcomes were designated as "healed" or "failed". Foot and ankle wounds that healed even if amputations up to the mid foot level were done were placed in the healed group. For this group of patients the ability to preserve their leg and be able to ambulate independently was their primary goal. This contrasts to the high performance individual where a major toe or a partial foot amputation could change their level of athletic ability and/or other activities. No Symes amputations were done in our series. The failed group were those patients who required amputation at the transtibial or higher level within one year of the time HBO treatments were given. Our first 31 patients were studied retrospectively and included 11 patients whose wounds were healthy, for comparison purposes (Fig. 1). Patients who died within one year of the study were not included in the

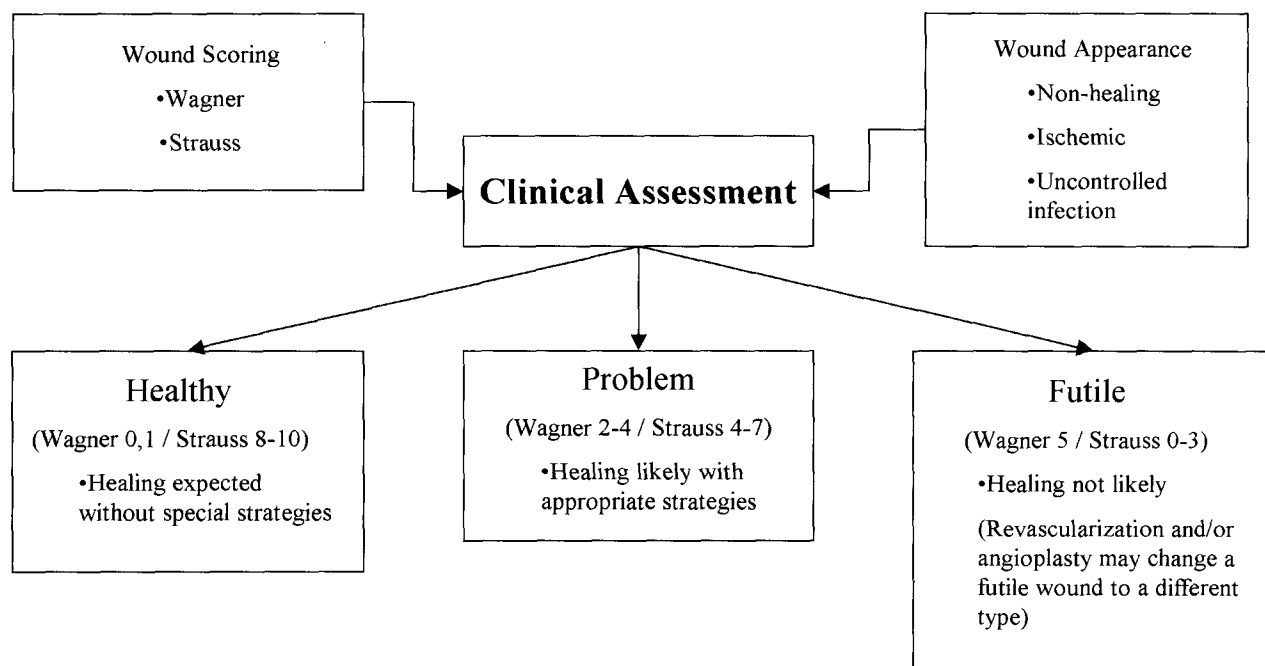


Fig. 1: Wound evaluation

Table 1: Wound scoring and grading

Wagner Score		Strauss Score	
Pre-ulcer	0	0 to 2	Appearance (Black=0, White-Yellow=1, Red=2)*
Superficial ulcer	1	0 to 2	Size (>Fist=0, Thumb to Fist=1, <Thumb=2)*
Full thickness ulcer	2	0 to 2	Depth (Bone to Joint=0, Muscle to Tendon=1, Skin to Sub-cutaneous=2)*
Osteomyelitis	3	0 to 2	Infection (Septic=0, Cellulitis=1, Colonized=2)*
Gangrene of toes/forefoot	4	0 to 2	Perfusion (None=0, Doppler=1, Pulse=2)*
Gangrene of mid/hindfoot	5		*Use half points when intermediate between two findings
Wagner score is based on one finding: 0 (Best) to 5 (Worst)		Total score is based on five criteria, each graded from zero to two: 10 (Best) to 0 (Worst)	
Problem = 2-4 Scores (With associated wound hypoxia)		Healthy = 8-10 Scores Problem = 4-7 Scores Futile = 0-3 Scores	

data analysis, regardless of whether or not their wounds healed. The remainder of the patients in this study were followed prospectively and included only wounds in the problem (Strauss Score 4-7) or futile (Strauss Score 0-3) groups.

RESULTS

Of the 190 patients with foot and ankle wounds, 158 (83%) healed without major (transtibial or higher) amputations with comprehensive wound management including adjunctive HBO treatments. (Table 2) Thirty-two patients (17%) had major amputations. Age and gender analysis was not indicative of any trends, which would change the interpretation of our data.

Further analysis revealed that 126 (87.5%) of 144 patients whose juxta-wound foot and ankle wounds $P_{tc}O_2$ s increased to 200 mmHg or greater during HBO avoided major amputations. Eighty-two patients had $P_{tc}O_2$ values less than 30 mmHg in room air, 72 (88%) of this subgroup's wounds healed. Healing was observed also in a high percentage of patients who had $P_{tc}O_2$ s in the 100 to 200 range with HBO, but the number of subjects was much less. In patients with $P_{tc}O_2$ s under 100 mmHg with HBO, only 17 (59%) of 29 patients avoided major amputations.

This data reveals that in our group of patients with problem foot and ankle wounds, the sensitivity of healing if $P_{tc}O_2$ s increased to over 200 mmHg with HBO and subsequently adjunctive HBO was used in the management

Table 2: Transcutaneous oxygen measurements in room air and with HBO: Outcomes in 190 foot wounds.

Group	Patient Numbers (%)	Healed (%)	Analysis (Healing with $P_{tc}O_2 > 200$)
I. Responder ¹ ($P_{tc}O_2 > 200$ with HBO)	144 (of 190) (76)	126 (87.5)	Sensitivity = 0.80 Specificity = 0.44 Positive predictive value = 0.88 Negative predictive value = 0.30 Accuracy = 74%
Room air $P_{tc}O_2 < 30$ mmHg ²	82 (57)	72 (88)	
Room air $P_{tc}O_2$ 30-40mmHg	25 (17)	23 (92)	
Room air $P_{tc}O_2 > 40$ mmHg	37 (26)	34 (84)	
II. Intermediate Responder ($P_{tc}O_2$ 100-200 mmHg with HBO)	17 (of 190) (9)	15 (88)	
III. Non-Responder ³ ($P_{tc}O_2 < 100$ mmHg with HBO)	29 (of 190) (15)	17 (59)	

Notes:

- Eleven (7.6%) of 144 foot wounds were "healthy" by clinical criteria (Fig. 1) and all healed. The remainder were classified as problem or futile wounds.
- This is the subgroup where healing would not have been expected to occur. $P_{tc}O_2$ under HBO conditions predicted healing and with adjunctive HBO therapy 72 of 82 (88%) healed.
- Although 12 (41%) of 29 patients in the non-responder group avoided amputation for one year or more, none did whose $P_{tc}O_2$ studies with HBO were less than 50 mmHg.

was 0.80. However, the specificity was only 0.44 which indicates that with our treatment protocols including adjunctive HBO, wound healing may occur even if $P_{tc}O_2$ s with HBO were less than 200 mmHg.

DISCUSSION

A single measurement of juxta-wound $P_{tc}O_2$ tensions over 200 mmHg under HBO conditions has a high predictive value (0.88) for healing of problem wounds in the foot and ankle when HBO was used as an adjunct to wound management. This observation contrasts to Dooley et al.'s¹³ statement that " $P_{tc}O_2$ measurements in recumbent patients can [not] be sufficiently discriminative in the prediction of healing or non-healing of recalcitrant wounds". Although this statement appeared to be appropriate when our patients' $P_{tc}O_2$ s were measured breathing room air, measurements under HBO conditions were able to discriminate a healing from a non-healing group in nearly 90% of our patients with measurements made in the recumbent position.

Spurious readings were observed when measurements were done over scarred, edematous, indurated, cellulitic, callused, telangiectatic, and hemosiderin stained skin or directly over blood vessels. Such conditions contribute to inaccurate $P_{tc}O_2$ readings. Other transcutaneous oxygen measurement techniques such as $P_{tc}O_2$ mapping, limb ratios, and precordial-limb indices would, in our opinion, not improve the predictability of $P_{tc}O_2$ readings when these conditions are present.

The low specificity and negative predictive value (0.30) for our observations indicates that we observed healing in some problem wounds even though the juxta-wound $P_{tc}O_2$ s did not increase to over 200 mmHg with HBO. Consequently, we do not base our decision for major amputation of the problem foot and ankle wound entirely on the juxta-wound $P_{tc}O_2$ level under HBO conditions. Healing of problem wounds in patients with $P_{tc}O_2$ s less than 200 mmHg with HBO was attributed to our team approach including distal revascularizations, pharmacological augmentation of tissue oxygenation with pentoxifylline (Trental®), nitroglycerin (Nitro-Dur®) patches, nifedipine (Procardia®) or combinations of these, and innovative surgeries.^{14,15,16}

Other reasons for the low specificities include: first, the measurements were made at the initiation of the patient's care. It is conceivable that the $P_{tc}O_2$ readings could have improved as edema reduction and angiogenesis occurred. Second, approximately one third of the patients in this group underwent revascularization and/or angioplasty. Although we observed marked improvements in the $P_{tc}O_2$ s when these vascular interventions were successful, we used the $P_{tc}O_2$ readings obtained at the initiation of care for our study since we

desired to test the predictability of the initial readings. Third, spurious readings may have resulted from edema, etc. as mentioned before. Approximately half of the intermediate and non-responder group that avoided major amputations, had various degrees of postoperative wound slough, dehiscence or both. Due to the motivation of the patient and meticulous wound care, approximately 90% of these wounds with initial postoperative, post-HBO treatment failures avoided major amputations.¹⁷

Due to the low specificities observed in this review, we are now revising our interpretations such that a $P_{tc}O_2$ reading of 50 to 200 mmHg defines an "intermediate" responder group and $P_{tc}O_2$ values less than 50 mmHg are defined as the "non-responder" group. Our expectations are that the specificities and negative predictive values will increase markedly with these changes and will further differentiate the problem wound group that will benefit from comprehensive management from the group that will not.

An analysis of the failures to our hypothesis, that is to say problem wounds that had juxta-wound $P_{tc}O_2$ values greater than 200 mmHg but went on to major amputations, revealed several reasons. In general, the patients in our study were followed by the first author for a minimum of one year after the patients completed their HBO treatments as an adjunct to wound management. Failures included patients with collagen vascular diseases, residual mechanical problems in the foot that caused recurrent wounds after ambulation resumed, refractory osteomyelitis especially in diabetics with methicillin resistant *Staphylococcus aureus*, and new peripheral vascular occlusive episodes.

SUMMARY

$P_{tc}O_2$ measurements under HBO have a high predictive value for healing of problem foot and ankle wounds if the readings increase to over 200 mmHg and HBO is used as an adjunct to optimal wound management. However, we observed healing in a sizable proportion of wounds that had lower readings. Consequently, juxta-wound $P_{tc}O_2$ measurements with HBO should be used as an adjunct to the clinical evaluation. Information from $P_{tc}O_2$ s under HBO conditions predict which problem wounds will heal, whether or not adjunctive HBO is indicated, if revascularization or angioplasty is needed or should a major amputation be recommended.

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