1-1-2007

How heel oxygenation changes under pressure

Vivian K. Wong
San Jose State University, vivian.wong@sjsu.edu

N. A. Stotts
University of California - San Francisco

H. W. Hopf
University of Utah

E. S. Froelicher
University of California - San Francisco

G. A. Dowling
University of California - San Francisco

Recommended Citation
Vivian K. Wong, N. A. Stotts, H. W. Hopf, E. S. Froelicher, and G. A. Dowling. "How heel oxygenation changes under pressure" *Wound Repair & Regeneration* (2007): 786-794. https://doi.org/10.1111/j.1524-475X.2007.00309.x

How Heel Oxygenation Changes Under Pressure

Submitted to Wound Repair and Regeneration

Feb 7, 2007

Edited and Resubmitted March 31, 2007 and June 3, 2007

Vivian K. Wong, RN, PhD,[1] Nancy A. Stotts, RN, EdD, FAAN,[2] Harriet W. Hopf, MD,[3]

Erika S. Froelicher, RN, PhD, FAAN[2] ,Glenna A. Dowling, RN, PhD, FAAN,[2]

San Jose State University, San Jose, CA;[1] University of California San Francisco,

San Francisco, CA;[2] University of Utah, Salt Lake City, UT[3]

Work should be attributed to:

School of Nursing, University of California, San Francisco

Corresponding author:

Vivian Wong, RN, PhD
School of Nursing, San Jose State University
One Washington Square,
San Jose, CA 95192-0057
Tel: (408) 924-3155
Fax: (408) 924-3135
Email: Vivian.wong@sjsu.edu
Request for reprint should be sent to the corresponding author.

ABSTRACT

The mechanism of heel pressure ulcers after hip surgery is not entirely understood. The purpose of this one-group, prospective, repeated measures design study was to examine how the external pressure of the bed surface affects heel skin oxygen tension in adults in the first 3 days after hip surgery. Transcutaneous oxygen sensors were placed on the plantar surface of each foot, close to the heels. Measures were taken on room air and with an oxygen challenge with the heels 1) suspended above the bed surface (preload), 2) on the bed surface for 15 minutes (loading), and 3) again suspended above the bed surface for 15 minutes (unloading). Eighteen hip surgery patients (mean age 58.3 ± 16.1 years) from two hospitals participated. When compared with preload on room air, both loading and unloading in all three days resulted in a reduction in heel oxygen tension bilaterally ($p < 0.001$). Heel oxygenation decreased without the anticipated hyperemic response, raising the question of whether this is a sign of increased pressure ulcer risk. Further work is needed to understand why this short period of external pressure results in decreased oxygenation and why oxygen tension does not return to baseline when pressure is removed.

INTRODUCTION

Pressure ulcer incidence is high in patients with hip fractures and hip surgeries.[1,2] After hip surgery, an immobilizer (abduction pillow) is used to keep the hip in alignment and prevent prosthetic dislocation.[3,4] The heels are often in contact with the surface of the bed. The non-operative leg is used by the patient for turning and repositioning in bed and the heel of this leg may be used as pivot point, making it susceptible to repeated friction and pressure. The less mobile heel on the operative side may also be subjected to external pressure from the bed surface leading to heel ulcers.[5] External pressure causes a reduction in skin oxygen tension,[6,7] thus both heels are at risk for development of pressure ulcers in hip surgery patients.

With surgery, the sympathetic system is stimulated by circulating catecholamines such as epinephrine and norepinephrine leading to vasoconstriction, which in turn may reduce PO_2 in subcutaneous tissue and subsequently the skin. Vasoconstriction may be caused by catecholamine excess due to hypovolemia,[8] epinephrine infusion,[9] pain,[10] cigarette smoking,[11] and changes in temperature.[12] Patients undergoing hip surgery are at high risk for heel ulcers due to the combination of increased external pressure from immobility, friction, shear, and decreased blood flow due to vasoconstriction.

During hip surgery, the elevation of lower extremities may reduce perfusion in the afflicted leg.[13] Factors affecting vascular status of the contralateral limb include increased pressure at the groin intraoperatively, the lateral decubitus positioning of the patient in the operating room table, the use of hypotensive anesthesia,[14] and existing vascular diseases.[15] The proximal femoral blood flow in the operative leg is reduced during total hip arthroplasty.[16] Arterial insufficiency is reported on the contralateral leg in persons undergoing total hip replacement.[15] The compromised vascular status peri-operatively predisposes both legs to pressure ulcer development. Whether heel skin oxygen tension in the operative leg is different from the non-operative leg is not known.

This study was conducted to examine the relationship between external pressure and heel oxygen tension in the non-operative and operative leg in the first three days after hip surgery in adults and was designed to answer the following questions:

1. Is there a difference in heel skin oxygen tension in the non-operative leg as compared to the operative leg during the loading and unloading conditions in hip surgery patients for 3 days on room air and with an oxygen challenge?
2. Is there a correlation between heel skin oxygen and pain in the first 3 days after hip surgery?

Skin oxygen tension is the transcutaneous oxygen level on the heel of the foot. External pressure refers to the pressure exerted by the bed when an object is placed on the bed surface. Preload is the time period before loading when heels are kept off the bed surface. Loading is when the legs are placed on the bed surface with heels touching the bed. Unloading is when the heels are kept off the bed surface after a period of loading. An oxygen challenge is giving inspired oxygen at 7-10 liters per minute.

METHODS

Design

A one-group, prospective, repeated measures design was used.

Sample

A convenience sample of 18 subjects was recruited. Inclusion criteria were as follows: patients 21 years or older undergoing hip surgery, both legs present, a score ≥ 5 on the Mental Status Questionnaire (MSQ) indicating adequate cognitive functioning, an ankle-brachial index

(ABI) $\geq$ 0.9 in both legs indicating normal arterial blood flow, intact sensory perception on the plantar surface of the foot measured with a 5.07 Semmes-Weinstein (S-W) monofilament, and for diabetics, fasting plasma glucose < 140 mg/dL or random plasma glucose range from 120-180 mg/dL before surgery. Exclusion criteria were: existing chronic foot ulcers and/or medical conditions that result in carbon dioxide retention, including documented chronic obstructive airway diseases. There has been no data indicating a difference in oxygen tension values by gender, race, or ethnicity and therefore, no attempt was made to include or exclude any subjects by gender, race, or ethnicity. Eligibility was determined by chart review, interview with potential subjects, and performing the MSQ, ABI, and S-W monofilament tests.

Recruitment of sample

Subjects for this study were recruited from two acute care hospitals. IRB approvals were obtained from both hospitals and the university. Written informed consent was obtained by the researcher. Medical charts were reviewed to screen for exclusion criteria.

Instruments/Measures

Demographic variables gathered from the medical record/interview included the subject's age, gender, ethnicity and race, smoking history and current smoking status, comorbid conditions, type of anesthesia, length of surgery, estimated blood loss, mobility, and pain medications and sedatives.

Arterial oxygen saturation (SaO_2) was measured by a handheld pulse oximeter (Novametrix, model 512). The accuracy of this oximeter at 80-100% is ± 2% SpO_2 ± 1 standard deviation.[17]

Skin oxygen levels on the heel was measured by transcutaneous oxygen tension ($PtcO_2$).[18] Transcutaneous oxygen tension ($PtcO_2$) was measured noninvasively with a

Novametrix Transcutaneous Oximeter (Model 840).[21] A modified Clark electrode is applied to the skin using a double-sided adhesive ring and contact solution. The local skin is warmed by the sensor to 44°C, enhancing diffusion of oxygen through the skin to the sensing electrode.[22]

The accuracy of oximetry readings ≤ 150 mmHg is ±1% of the value ± 2 mmHg. At readings > 150 mmHg, accuracy is ± 1% of the value ± 4 mmHg (Novametrix Medical Systems, 1991). Construct validity of using oxygen tension as an indicator of skin blood flow has been established.[19, 23-26] Sensitivity is greater when skin is warmed to 44°C than when lower temperatures are used. Reported instability due to electrode drift occurs at a rate of 1 mmHg per hour. Calibration of the machine is completed before starting the measurement.[27] Individual data specificity and sensitivity were established for assessment of oxygen partial pressure changes.[19]

The study was conducted under two conditions: breathing room air and receiving an oxygen challenge. Supplemental oxygen has been shown to increase PaO_2 which in turn increases tissue oxygen tension.[8, 33-35] In humans, administering 40-60% (0.4 – 0.6 FiO_2) of oxygen via a facemask with oxygen flow set at 7-10 liters per minute is considered an oxygen challenge. Giving inspired oxygen magnifies the changes in oxygen tension that occurs with changes in blood flow.

Pain was assessed using the Visual Analog Scale (VAS) and a picture of a body outline. VAS measures pain intensity on a 10 cm scale (0 mm = no pain, 100 mm = worst pain you can imagine). The person places a mark through the line at the point that best describes how much pain he/she is experiencing at that particular moment.[28] Many studies have demonstrated the reliability of using VAS to assess subjective pain in the clinical setting.[28-31] Location of pain in any part of the body is identified by the use of a body outline.[32] The drawings of the body are used to assess the spatial distribution of pain.

Study Protocol

After surgery, all subjects were placed on Hill-Rom pressure-reduction mattresses (Model Advanta) with built-in heel-relief function (set at pressure-relief mode during the study). The transcutaneous oximeter was calibrated and the following data collection procedure was performed on each of the three post-operative day:

1. The $PtcO_2$ sensor was applied to the heel (Figure 1). For subjects who had compression stockings, the plantar foot part of the stockings was pulled back through the opening at the posterior aspect of the toes. The $PtcO_2$ sensor was slipped in through the posterior opening of the stocking and placed on the plantar aspect of each foot as close to the heel as possible and attached using double sided adhesive. If the subject was using Intermittent Pneumatic Compression Device (IPC), the device was not maneuvered.
2. With the subject supine in bed, the heels were suspended at about 15º from the bed surface by placing a pillow under the calf for 15 minutes (this duration allows stabilization of $PtcO_2$ measurement).
3. The legs were covered with a single bed-sheet throughout the procedure.
4. Pain intensity and location were assessed using Visual Analog Scale (VAS) and a body outline.
5. Oxygen saturation was measured using the Pulse Oximeter.
6. The preload $PtcO_2$ was recorded. The preload $PtcO_2$ was considered as a baseline value after approximately 15 minutes when there were no more fluctuations in reading for one minute.

7. Loading pressure was applied by placing the heels onto the bed surface. Heel $PtcO_2$ was recorded every three minutes during the loading duration of 15 minutes and at the end of loading.
8. At the 14th minute of the loading duration, pain was assessed using VAS and the body outline.
9. After the 15th minute of loading, external pressure was relieved (pressure unload) by lifting the heels and replacing the pillow under the calf to keep pressure off the heels.
10. Heel $PtcO_2$ was measured every three minutes for the next 15 minutes during unloading.
11. At the 14th minute of unloading, pain was assessed using VAS and the body outline; and
12. After the 15th minute of unloading, all sensors were removed and the heels were suspended unless otherwise indicated.

The above procedure was carried out twice: once with the subject breathing room air and again with the subject breathing oxygen at 7-10 liters per minute via a simple face mask. Heel skin condition was recorded during each visit.

Data Analysis

The Statistical Package for the Social Sciences, version 13.0 was used to manage and analyze data. Descriptive statistics were used to examine each variable. The overall design was a 3-way repeated measures analysis of variance (RMANOVA) with three within subjects' factors: leg, day, and time. The three within subjects factors were analyzed using: 1) leg with two levels: operative leg and non-operative leg; and 2) day with three levels: post-operative day 1, day 2, and day 3; and 3) time with 11 levels: preload, during loading (loading time at 3rd, 6th, 9th, 12th, and 15th minute), and during unloading (unloading time at 3rd, 6th, 9th, 12th, and 15th minute). The analysis allowed trending of $PtcO_2$ for the overall study period. The 3-way

RMANOVA design allowed for testing of : 1) the main effect of day; 2) main effect of leg; 3) main effect of pressure loading time; 4) interaction of day x leg; 5) interaction of day x pressure loading time; 6) interaction of leg x pressure loading time; and 7) interaction of day x leg x pressure loading time. If any of the main effects were significant, follow-up contrast testing was done. If the interaction was significant, tests of simple effects or tests of trends were performed. For these post-hoc tests, the overall family of contrasts (alpha) was kept at 0.05. The criteria for significance for any one contrast equaled 0.05 divided by the total number of contrasts. Consequently, an alpha of < 0.01 was the criterion for significance of three contrasts, < 0.01 was the criterion for significance of five contrasts, and < 0.005 was the criterion for significance of 10 contrasts. Correlation analysis was used to determine if demographic variables were related to the dependent variable. Data on room air and data on oxygen challenge were analyzed separately but using the same analysis plan. The incidence of heel pressure ulcer and demographic data were described.

RESULTS

Sample

Forty potential subjects were approached for participation in the study and 18 participated. Twenty-two refused to participate because they did not want to do it (n = 16), or their surgery was cancelled or postponed (n = 6). Half of the sample was recruited from each hospital. The mean age of the subjects was 58.3 ± 16.08 years. The subject demographics are reported in Table 1.

Mean ankle-brachial index (ABI) of the non-operative leg and operative leg was 1.0 (SD 0.08) and 1.0 (SD 0.14) respectively, indicating that having lower extremity arterial disease was unlikely. ABI was not measured in five subjects due to subject refusal or pain on moving of legs.

These five subjects had no documented lower extremity vascular disease. No subjects had sensory loss of the feet when tested with the 5.07 S-W monofilament. None of the subjects reported having diabetes. All subjects met the Mental Status Questionnaire criteria, indicating that they were cognitively competent. One person reported being a smoker.

Less than half of the subjects (44.4%) had previous hip surgeries. Most of the subjects (90%) received autologous blood transfusion within the first 2 days of surgery.

Room temperature during data collection ranged from 21-23 ºC, humidity was 60%. Subjects wore either thigh-high or knee-high compression stockings (66.7 – 88.9%) during the 3 postoperative days. Less than half of the subjects were treated with the Intermittent Pneumatic Compression Device (IPC) over the 3 days. The IPC delivered intermittent compression at 45 mmHg during the 2-hour data collection visit in 7 subjects on the 1st post-op day, in 5 subjects on the 2nd post-op day, and in 4 subjects on the 3rd post-op day.

Study Question 1: Is there a difference in heel PtcO$_2$ in the non-operative leg as compared to the operative leg during the loading and unloading conditions in hip surgery patients for the first 3 post-operative days?

On room air

Heel PtcO$_2$ decreased significantly in loading and unloading as compared to preload baseline ($p < 0.001$) (Figures 1 & 2). Post-hoc tests showed that the decrease was significant at all the five loading and five unloading times ($p < 0.001$) not depending on the leg or day.

With an oxygen challenge

When the subjects were receiving oxygen at 7-10 liters per minute via a simple face mask, there was no overall change in heel PtcO$_2$ in either leg during loading and unloading as compared to preload in all 3 days (Figures 3 & 4).

Comparison of $PtcO_2$ response between room air and with an oxygen challenge conditions

When examining the heel $PtcO_2$ response during the loading and unloading conditions on room air and with an oxygen challenge, heel $PtcO_2$ was different when an oxygen challenge was given. RMANOVA was used in which the within subjects factors were time (preload, loading, and unloading on room air and preload, loading, and unloading with an oxygen challenge) and leg (non-operative and operative).

On post-op day 1, there was a main effect of time and a time by leg interaction (Figure 6). Heel $PtcO_2$ decreased over time ($p < 0.05$). Post-hoc tests revealed significance at all times during room air ($p < 0.001$) but not with oxygen challenge. The change over time depended on whether it was the non-operative or operative leg (time x leg interaction) ($p < 0.05$).

On post-op day 2, there was the main effect of time. Heel $PtcO_2$ decreased significantly over time ($p < 0.001$) on room air and with oxygen challenge (Figure 7). Post-hoc tests revealed significance at all times ($p <0.001$) except at preload and at the 6^{th} minute of loading with an oxygen challenge.

On post-op day 3, there was the main effect of leg. The difference in heel $PtcO_2$ depended on whether it was the non-operative or operative leg ($p < 0.05$) with the non-operative leg being higher on room air and with an oxygen challenge (Figure 8).

Study Question 2: Is there a correlation between heel $PtcO_2$ and pain score in hip surgery patients in the first 3 days after surgery?

Most subjects (n = 14) denied pain or reported a pain score of < 4 while resting in bed. Four subjects had pain scores of 7 – 10 due to muscle spasms. None of the subjects reported heel pain. Subjects complained of pain in the operative hip and/or leg. The mean pain scores over the three post-operative days were shown on Table 2.

On room air

RMANOVA was used in which the within subjects factors were day (post-op days 1, 2, and 3) and time (preload, loading, and unloading). There was no change in the pain score when the last minutes of loading and unloading were compared with preload on all three post-operative days.

Comparisons were made between heel $PtcO_2$ on each leg and pain score at preload, the last minutes of loading and unloading on each post-op day using Pearson's Product Moment Correlation. Heel $PtcO_2$ in the non-operative leg was inversely correlated with pain score at the last minute of unloading on post-op day 3 only ($r = -0.56$, $p < 0.05$).

With an oxygen challenge

The pain score decreased on post-op days 2 and 3 as compared to post-op day 1 (Figure 5). There was less pain at loading as compared to preload in all three days. RMANOVA was used in which the within subjects factors were day (post-op days 1, 2, and 3) and time (preload, loading, and unloading). There was a main effect of day ($p = 0.01$). There was a significant decreasing linear trend ($p = 0.01$) in all 3 post-op days. There was a main effect of time ($p < 0.05$). Post-hoc testing revealed that the pain score decreased significantly at the last minute of loading ($p < 0.05$) when compared with preload.

Comparisons were made between heel $PtcO_2$ on each leg and pain score at preload, the last minutes of loading and unloading on each post-op day using Pearson's Product Moment Correlation. Heel $PtcO_2$ and pain score were inversely correlated in the non-operative leg at the last minute of loading on post-op day 2 ($r = -0.57$, $p < 0.05$).

DISCUSSION

This is the first study to show that when subjects were breathing room air, heel $PtcO_2$ decreased during loading and unloading in both legs across all three post-operative days. There has been no documentation of measuring heel $PtcO_2$ in response to pressure loading in hip surgery patients. A study on hip and knee surgery patients examined $PtcO_2$ at the incision site, the contralateral site, and the chest site of patients (n = 24).[36] Measurements were taken pre-operatively, on the second post-op day and two months after surgery. $PtcO_2$ decreased at all sites on post-op day 2 as compared to pre-op and 2-month post-op.[36] Going through surgery predisposes a person to many external factors such as hemodynamic changes and hypoxia, which may affect $PtcO_2$.[37] In this study, the pre-operative preload heel $PtcO_2$ was not measured and could not be compared to the post-operative preload $PtcO_2$.

Half of the subjects in this study were on the Intermittent Pneumatic Compression Device (IPC) and most of the subjects had compression stockings with the percentage depending on day (67 – 89%). The compression stockings deliver a pressure of 18 mmHg at the ankle with gradual reduction in pressure gradient up the leg. The IPC is intended to prevent venous stasis by emptying deep veins in the legs while compression stockings are used to prevent distension of the veins.[38] The IPC device delivers sequential compression pressure from ankle to below the knee at 45 mmHg for 11 seconds and then decompresses every 60 seconds. Compression inflation and deflation cycles did not seem to affect $PtcO_2$ in the lower legs.[39] In fact, $PtcO_2$ decreased with each compression but returned to pre-compression values during the deflation time in both healthy younger adults (n = 14) and older patients (n = 14).[39] In a study on patients with post-thrombotic leg ulcers (n = 10), the use of IPC was positively correlated with reduction of leg edema ($r = 0.91$, $p < 0.001$).[40] The authors suggested that reduction in edema might increase $PtcO_2$. However, the reduction of leg edema in subjects with leg ulcers (n = 8) had not been shown to raise $PtcO_2$ at the ulcer site in another study.[41] These studies showed that edema may not affect oxygen diffusion to the skin.

When comparing legs, heel $PtcO_2$ in the non-operative leg was higher than that in the operative leg during both room air and with an oxygen challenge on post-op day 3. In other words, the heel skin of the non-operative side was better oxygenated than that of the operative side on the third post-operative day only. However, both heels were equally at risk of low oxygenation when subjected to external pressure on all three post-operative days.

Oxygen Challenge

Giving an oxygen challenge (FiO_2 = 0.4 - 0.6) increases PaO_2, $PsqO_2$, and $PtcO_2$ when there is normal subcutaneous tissue perfusion.[42] In subcutaneous tissue with normal peripheral tissue perfusion, partial pressure of oxygen is similar in both the tissue and the blood.[37] If perfusion decreases, oxygen extraction from the subcutaneous tissues increases, which in turn lowers the subcutaneous tissue tension[8] and subsequently affecting oxygen delivery to the skin. An increase in partial oxygen pressure after increased FiO_2 indicates normal tissue perfusion.[42]

In this study, oxygen saturation was 98 - 99% when subjects were receiving the oxygen challenge. All subjects had ABI >0.9 in both legs. Loading and unloading did not affect heel $PtcO_2$ while breathing oxygen at 7-10 liters per minute. During loading, flow is inadequate but perhaps arterial oxygen is still normal so that $PtcO_2$ does not change. It is possible that subjects in this study were relatively under-hydrated.

When examining heel $PtcO_2$ across both room air and oxygen challenge phases, $PtcO_2$ at preload with an oxygen challenge was higher than $PtcO_2$ at the last minute of unloading on room air in all three days. However, $PtcO_2$ at preload with an oxygen challenge was still lower than the preload value on room air.

Pain

In this study, the pain intensity did not change under loading/unloading conditions on room air but decreased with an oxygen challenge. Pain was not controlled in the present study, although it was measured and its effect on $PtcO_2$ evaluated. Subjects were encouraged to use patient-controlled-analgesia (PCA) and oral analgesic for maximum pain control. Pain assessment during preload, loading, and unloading yielded a range of scores from 0 to 8. Pain level did not fluctuate during the 2 hours of data collection. None of the subjects reported pain in the heels. Many subjects denied having pain while resting in bed. Most subjects complained of pain in the operative hip only when trying to get out of bed. An exception was four subjects with muscle spasms who reported a pain intensity of 7 – 10 on the VAS while resting in bed. The effect of pain on subcutaneous oxygen tension has been documented.[10, 43, 44] In general, adequate pain control during the immediate post-operative period attenuates vasoconstriction, improves perfusion, and increases tissue oxygen tension. Most subjects in this study did not report pain. The inverse correlation between pain and heel $PtcO_2$ was only seen in the non-operative leg once under room air and once with an oxygen challenge. Pain score had minimal effect on heel $PtcO_2$ overall.

Volume status also was not controlled in this study. All subjects had crystalloid replacement at least on the first post-op day and they all resumed their normal drinking and eating pattern by day 2. Subjects' hematocrit values were not recorded in this study but almost all subjects received an autologous blood transfusion within the first 2 days after surgery. The mean hematocrit in another study on post hip surgery patients (n = 58) was between 29.8 – 30.8 % in all 3 post-op days.[45]

Limitations of the Study

This study was done in the acute care setting, not controlling for covariates such as leg edema, wearing of compression stockings, and/or intermittent pneumatic compression device, or the interface pressure of the mattress.

There was a large variation in heel $PtcO_2$ within each individual over the 3 days. Most of the subjects were wearing compression stockings, reflecting usual clinical care. Sensors were applied on the plantar aspect of the foot as close to the heel and as consistently as possible. The same location of sensor placement could not be guaranteed each day. Standardizing stocking wear and placing the sensors on exactly the same location may have decreased the intra-subject variability.

Due to the limited sample size, it was not meaningful to analyze the data using multiple regression. It would be helpful in future studies to determine the unique contribution of each factor aforementioned to changes in heel $PtcO_2$.

Implications and Recommendations

The major finding of this study is that heel $PtcO_2$ decreased after placing the heels on the bed surface for 15 minutes. The decrease in heel $PtcO_2$ continued after the heels were removed from the bed surface. The anticipated hyperemic response did not occur. The heels of both the non-operative and operative leg responded similarly to external pressure. Post-operatively, movement of the lower legs is limited since the legs are strapped onto either side of the abductor foam. Therefore, heels on both the non-operative and operative legs are at risk of low skin oxygenation and pressure ulcer development after hip surgery. It is postulated that in order to ensure adequate heel skin oxygenation and blood flow, the heels should be kept off the bed at all times in the post hip surgery population.

Future studies should explore the following questions: 1) How does heel skin oxygenation respond to pressure loading and unloading in both legs in an age and gender matched population across three consecutive days? 2) Are these findings consistent with those of healthy (non-surgical) people? 3) Will edema and compression stockings affect heel skin oxygenation? 4) Will the response to loading and unloading in the sacral area be similar to that found for the heels? and 5) Is there a correlation between heel skin oxygenation and heel skin blood flow (using laser-Doppler flowmetry) in response to loading and unloading?

Acknowledgements

The authors are grateful to Dr. Steven Paul at the University of California, San Francisco (UCSF) for providing support in data management and analysis, to Dr. Harry Jergesen and Dr. Michael Ries at the UCSF Medical Center and the orthopedic physicians at El Camino Hospital for assisting with subject recruitment, to the staff at UCSF Medical Center (General Clinical Research Center, the orthopedic clinic, and 12 Long), to the staff at El Camino Hospital (5E and Admission Unit), and to all the participants at both hospitals. The study was funded by NRSA NR008317-04, the American Nurses Foundation Grant, the UCSF GCRC & Graduate Student Research Award, and the Wound, Ostomy, & Continence Nursing scholarship.

REFERENCES

1. Margolis DJ, Knauss J, Bilker W, Baumgarten, M. Medical conditions as risk factors for pressure ulcers in an outpatient setting. Age Ageing 2003;32:259-64.
2. Baumgarten M., Margolis D, Berlin JA, Strom BL, Garino J, Kagan SH, Kavesh W, Carson JL. Risk factors for pressure ulcers among elderly hip fracture patients. Wound Repair Regen 2003;11:96-103.
3. Rao JP, Bronstein R. Dislocations following arthroplasties of the hip. Incidence, prevention, and treatment. Orthopaedic Review 1991;20:261-264.
4. Yuan L, Shih C. Dislocation after total hip arthroplasty. Archives of Orthopaedic and Trauma Surgery 1999;119:263-266.
5. Kosiak M. An effective method of preventing decubital ulcers. Archives of Physical Medicine & Rehabilitation 1966;47:724-729.
6. Knight SL, Taylor RP, Polliack AA, Bader DL. Establishing predictive indicators for the status of loaded soft tissues. Journal of Applied Physiology 2001;90:2231-2237.
7. Colin D, Saumet JL. Influence of external pressure on transcutaneous oxygen tension and laser Doppler flowmetry on sacral skin. Clinical Physiology 1996;16:61-72.
8. Gottrup F, Firmin R, Rabkin J, Hallida BJ, Hunt TK. Directly measured tissue oxygen tension and arterial oxygen tension assess tissue perfusion. Critical Care Medicine 1987;15:1030-1036.
9. Jensen JA, Jonsson K, Goodson WH, Hunt TK, Roizen MF. Epinephrine lowers subcutaneous wound oxygen tension. Current Surgery 1985;42:572-574.
10. Akca O, Melischek M, Scheck T. Hellwagner K, Arkilic CF, Kurz A. Postoperative pain and subcutaneous oxygen tension. The Lancet 1999; 354:41-42.

11. Jensen JA, Goodson WH, Hopf HW, Hunt TK. Cigarette smoking decreases tissue oxygen. Arch Surg1991;126:1131-4.

12. Hopf HW, Viele M, Watson JJ, Feiner J, Weiskopf R, Hunt TK. Subcutaneous perfusion and oxygen during acute severe isovolemic hemodilution in healthy volunteers. Archives of Surgery 2000;135:1443-1449.

13. Martin JT. Positioning aged patients. Anesthesiology Clinics of North America 2000; 18:105-121.

14. Edwards JL, Pandit H, Popat MT. Perioperative analgesia: a factor in the development of heel pressure ulcers. British Journal of Nursing 2006;15:S20-5.

15. Smith JW, Pellicci PM, Sharrock N, Mineo R, Wilson PDJ. Complications after total hip replacement. The contralateral limb. J Bone Joint Surg Am 1989;71:528-535.

16. Hupel TM, Schemitsch EH, Aksenov SA, Waddell JP. Blood flow changes to the proximal femur during total hip arthroplasty. Can J Surg 2000;43:359-364.

17. Respironics [Homepage on the internet]. Murrysville: Respironics, Inc; c1985-2007 [updated 2007; cited 2007 Feb 5]. Specifications/Models 512 & 513 [2 screens]. Available from: http://model512and513.respironics.com/Specifications.asp

18. Talbot A, Neuman MR, Saidel GM, Jacobsen E. Dynamic model of oxygen transport for transcutaneous PO_2 analysis. Ann Biomed Eng 1996;24:294-304.

19. Kram HB, Appel PL, Shoemaker WC. Multisensor transcutaneous oximeteric mapping to predict below-knee amputation wound healing: Use of a critical PO2. Journal of Vascular Surgery 1989;9:796-800.

20. Gottrup F, Firmin R, Chang N, Goodson III WH, Hunt TK. Continuous direct tissue oxygen tension measurement by a new method using an implantable silastic tonometer and oxygen polarography. The American Journal of Surgery 1983;146:399-403.

21. Novametrix Medical Systems, I., PtcO2/PtcCO2 monitor model 840 users manual. Wallingford, CT: Author, 1991.

22. Soini HO, Takala J. Measurement of tissue oxygen tension: Comparison between two subcutaneous oxygen tonometers. Journal of Clinical Monitoring 1991;7:227-231.

23. Baldwin KM. Transcutaneous oximetry and skin surface temperature as objective measures of pressure ulcer risk. Advances in Skin and Wound Care 2001;14:26-31.

24. de Groote P, Millaire A, Deklunder G, Marache P, Decoulx E, Ducloux G. Comparative diagnostic value of ankle-to-brachial index and transcutaneous oxygen tension at rest and after exercise in patients with intermittent claudication. Angiology 1995;46:115-121.

25. Liu MH. Transcutaneous oxygen tension in subjects with tetraplegia with and without pressure ulcers: a preliminary report. Journal of Rehabilitation Research and Development 1999;36:202-206.

26. Planes C, Foray LM, Raffestin B. Arterial blood gases during exercise: Validity of transcutaneous measurements. Archives of Physical Medicine & Rehabilitation 2001; 82:1686-1691.

27. Wipke-Tevis DD, Stotts NA, Williams DA, Froelicher ES, Hunt TK. Tissue oxygenation, perfusion, and position in patients with venous leg ulcers. Nursing Research 2001;50:24-32.

28. McGuire DB. Measuring pain. In: Stromborg MP, Olsen SJ, editors. Instruments for clinical health-care research. Boston: Jones & Bartlett Publishers, 1997:528-544.

29. Bergh I, Sjostrom B, Oden A, Steen B. An application of pain rating scales in geriatric patients. Aging (Milano) 2000;12:380-387.

30. McCormack H, Horne D, Sheather S. Clinical applications of visual analog scales: a critical review. Psychological Medicine 1988;18:1007-1019.

31. Salo D, Eget D, Lavery RF, Garner L, Bernstein S, Tandon K. Can patients accurately read a visual analog pain scale? Am J Emerg Med 2003;21:515-9.

32. Melzack R. The McGill Pain Questionnaire: major properties and scoring methods. Pain 1975;1:277-299.

33. Gottrup F, Gellett S, Kirkegaard L, Hansen ES, Johannsen G. Continuous monitoring of tissue oxygen tension during hyperoxia and hypoxia: Relation of subcutaneous, transcutaneous, and conjunctival oxygen tension to hemodynamic variables. Critical Care Medicine 1988;16:1229-1234.

34. Hopf H.W, Hunt TK. Comparison of Clark electrode and optode for measurement of tissue oxygen tension. Advances in Experiemental Medicine and Biology 1994;345:841-847.

35. Jonsson K, Jensen JA, Goodson III WH, Scheuenstuhl H, West J, Hopf HW, Hunt TK. Tissue oxygenation, anemia, and perfusion in relation to wound healing in surgical patients. Annals of Surgery 1991;214:605-613.

36. McPhail R, Cooper LT, Hodge DO, Cabanel ME, Rooke TW. Transcutaneous partial pressure of oxygen after surgical wounds. Vasc Med 2004;9:125-7.

37. Gottrup F. Oxygen in wound healing and infection. World J Surg 2004;28:312-5.

38. Morris RJ, Woodcock JP. Evidence-based compression: prevention of stasis and deep vein thrombosis. Ann Surg 2004;239:162-71.

39. Rithalia SV, Edwards J, Sayegh A. Effect of intermittent pneumatic compression on lower limb oxygenation. Arch Phys Med Rehabil 1988;69:665-7.

40. Kolari PJ, Pekanmaki K, Pohjola RT. Transcutaneous oxygen tension in patients with post-thrombotic leg ulcers: treatment with intermittent pneumatic compression. Cardiovasc Res 1988;22:138-41.

41. Nemeth AJ, Falanga V, Alstadt SP, Eaglstein WH. Ulcerated edematous limbs: effect of edema removal on transcutaneous oxygen measurements. J Am Acad Dermatol 1989;20(2 Pt 1):191-7.

42. Hopf HW, Hunt TK, West JM, Blomquist P, Goodson III WH, Jensen JA. Wound tissue oxygen tension predicts the risk of wound infection in surgical patients. Archives of Surgery 1997;132:997-1004.

43. Buggy DJ, Doherty WL, Hart EM, Pallett EJ. Postoperative wound oxygen tension with epidural or intravenous analgesia: a prospective, randomized, single-blind clinical trial. Anesthesiology 2002; 97:952-8.

44. Buggy DJ, Kerin MJ. Paravertebral analgesia with levobupivacaine increases postoperative flap tissue oxygen tension after immediate latissimus dorsi breast reconstruction compared with intravenous opioid analgesia. Anesthesiology 2004; 100:375-80.

45. Whitney JD, Parkman S. The effect of early postoperative physical activity on tissue oxygen and wound healing. Biol Res Nurs 2004;6:79-89.

Table 1. Demographics of the study subjects

	n	Percentage
Gender		
Male	9	50
Female	9	50
Race/Ethnicity		
White	11	61.1
Black or African American	2	11.1
Asian	4	22.2
Hispanic	1	5.6
Primary Diagnosis		
Osteoarthritis	11	61.1
Degenerative joint disease	5	27.8
Fracture	2	11.1
History of disease and treatment		
Hypertension	5	27.8
Deep vein thrombosis	1	5.6
Foot surgery	1	5.6
Coronary artery disease	2	11.1
Other health conditions	12	66.7

Table 2. Mean pain score at preload, the end of loading, and the end of unloading over the first three post-operative days

Post-op days	Phases	Room Air Mean pain score (SD)	Oxygen Challenge Mean pain score (SD)
Day 1	Preload	3.3 (2.7)	3.3 (2.7)
	Loading	3.5 (2.8)	2.5 (2.4)
	Unloading	3.5 (3.0)	2.4 (2.3)
Day 2	Preload	2.3 (2.7)	1.9 (2.4)
	Loading	2.1 (2.5)	1.1 (1.2)
	Unloading	2.4 (3.2)	1.3 (1.7)
Day 3	Preload	2.5 (2.8)	1.4 (1.9)
	Loading	2.1 (3.1)	1.2 (1.9)
	Unloading	1.7 (2.8)	1.4 (1.8)

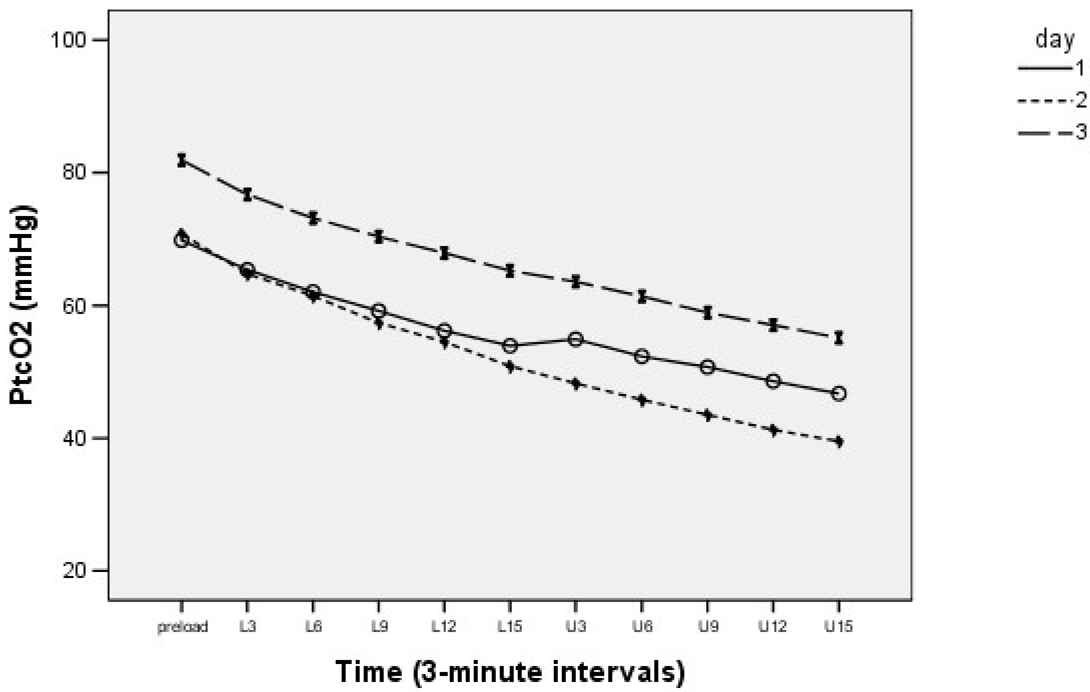

Figure 1. Mean heel $PtcO_2$ in the non-operative leg on room air during preload, loading (L3 – L15), and unloading (U3 – U15) on post-op days 1, 2, and 3. Heel $PtcO_2$ decreased significantly in loading and unloading as compared to preload ($p < 0.001$).

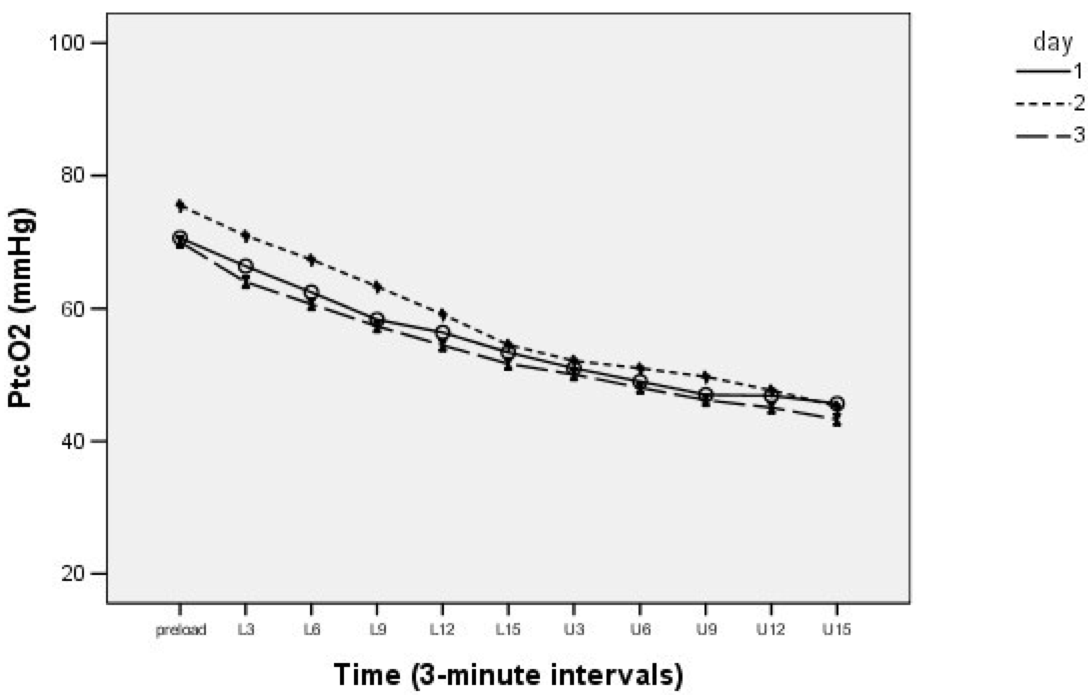

Figure 2. Mean heel $PtcO_2$ in the operative leg on room air during preload, loading (L3 – L15), and unloading (U3 – U15) on post-op days 1, 2, and 3. Heel $PtcO_2$ decreased significantly in loading and unloading as compared to preload ($p < 0.001$).

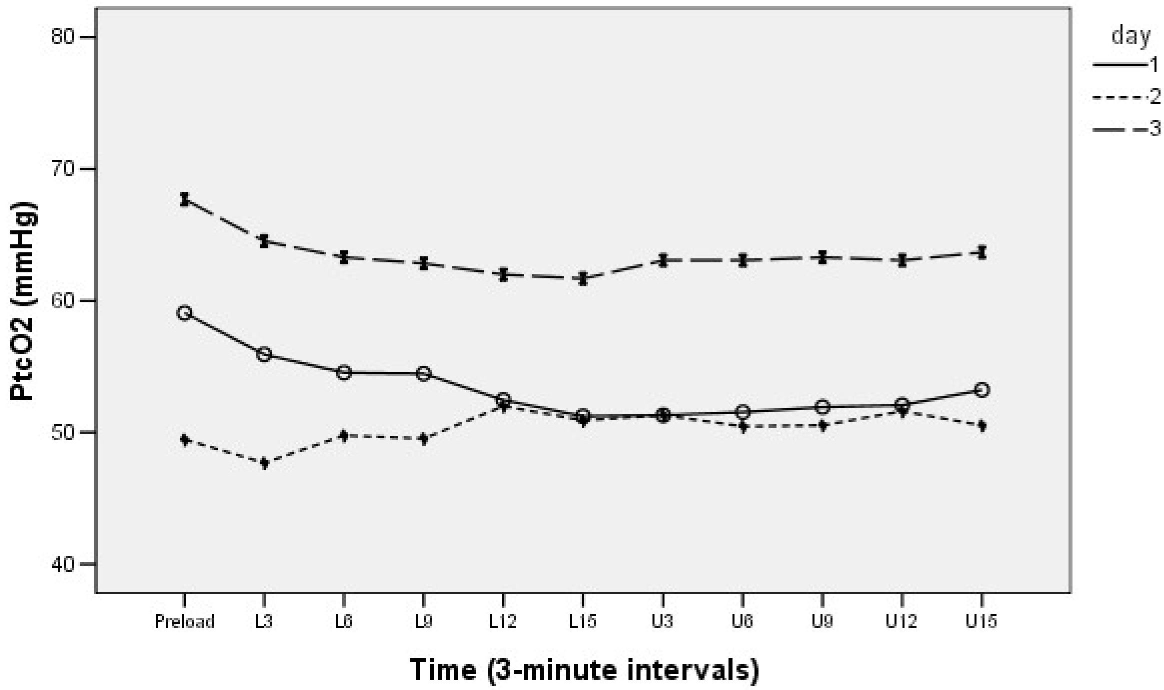

Figure 3. Mean heel $PtcO_2$ in the non-operative leg with an oxygen challenge during preload, loading (L3 – L15), and unloading (U3 – U15) on post-op days 1, 2, and 3. The overall change in heel $PtcO_2$ during loading and unloading as compared to preload was not significant.

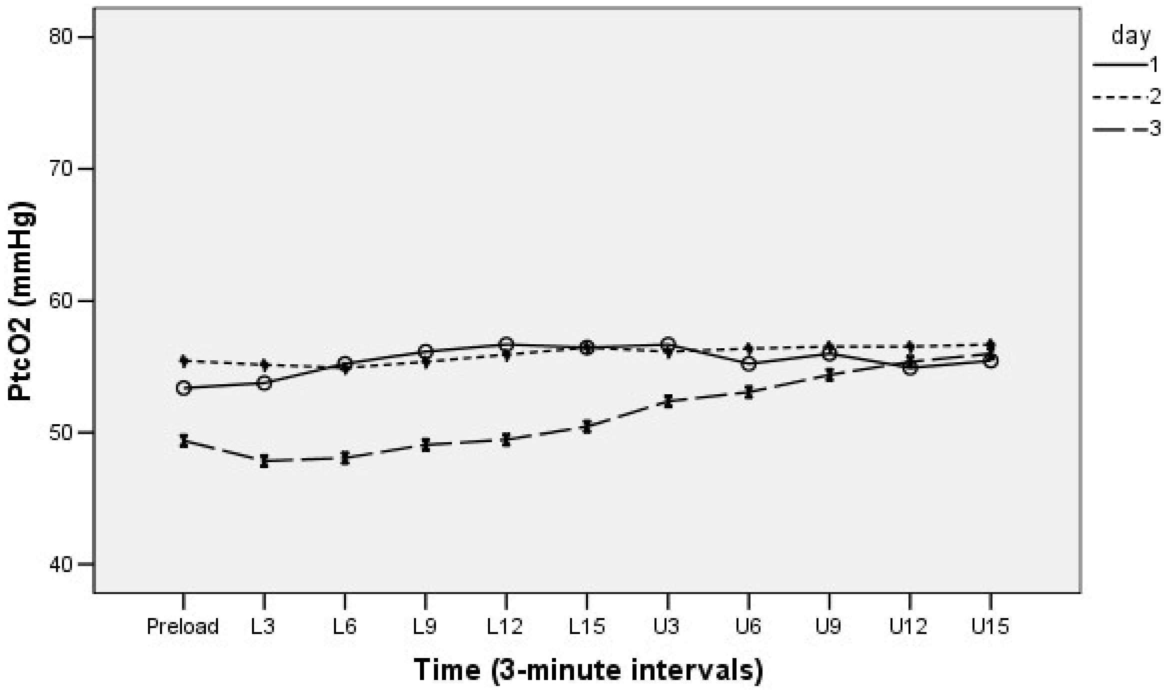

Figure 4. Mean heel $PtcO_2$ in the operative leg with an oxygen challenge during preload, loading (L3 – L15), and unloading (U3 – U15) on post-op days 1, 2, and 3. The overall change in heel $PtcO_2$ during loading and unloading as compared to preload was not significant.

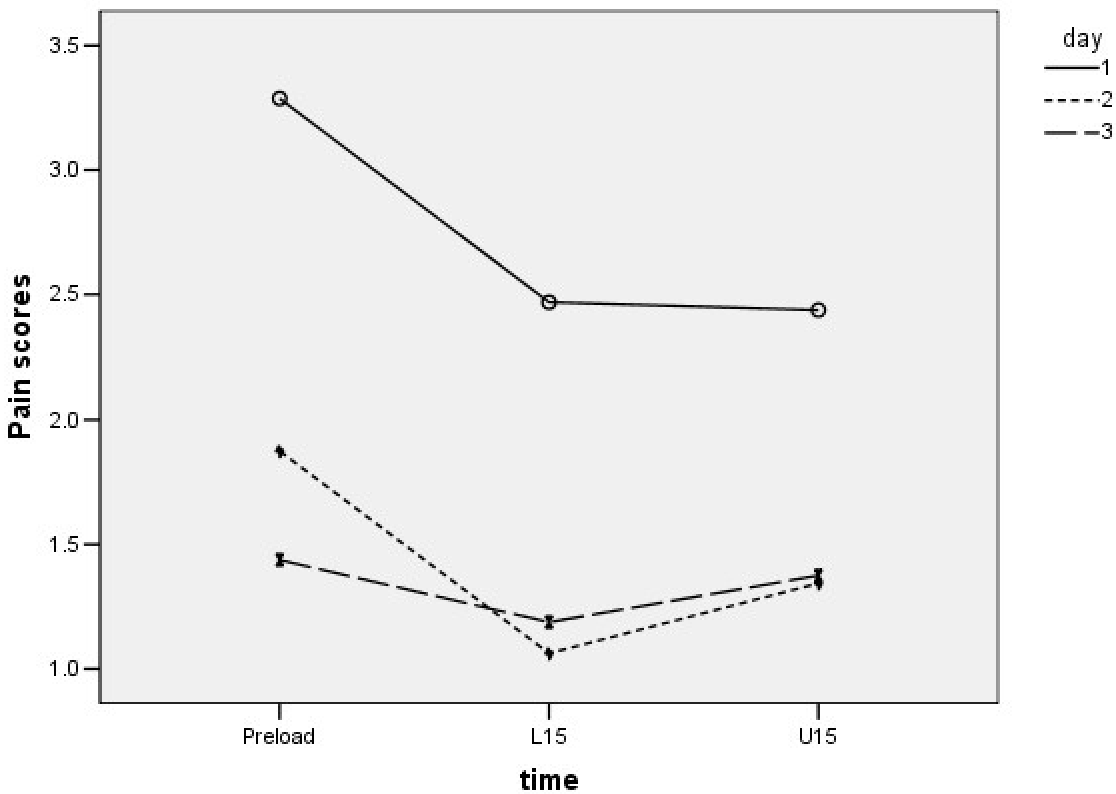

Figure 5. Trends of changes in mean pain score with an oxygen challenge at preload, the last minutes of loading (L15- 15th minute) and unloading (U15 – 15th minute) on post-op days 1, 2, and 3. There was a significant decreasing linear trend ($p = 0.01$) in all 3 post-op days. Post-hoc testing showed that the pain score decreased significantly at the last minute of loading (L15) when compared with preload ($p < 0.05$).

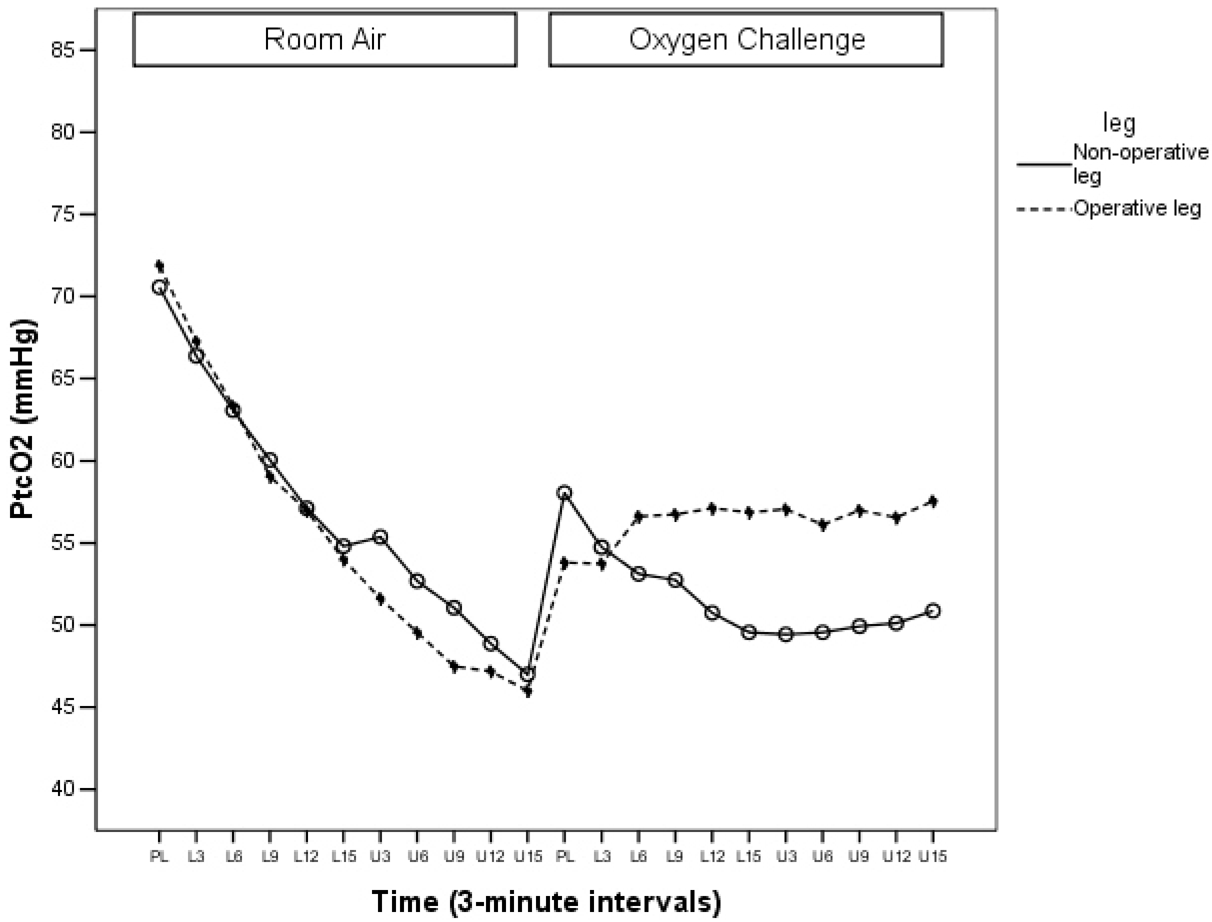

Figure 6. Mean heel $PtcO_2$ response in both legs on room air and with an oxygen challenge on day 1. Heel $PtcO_2$ decreased over time ($p < 0.05$). Post-hoc tests revealed significance decrease at all times during room air ($p < 0.001$) but not with oxygen challenge. The change over time was greater in the operative leg ($p < 0.05$) than the non-operative leg.

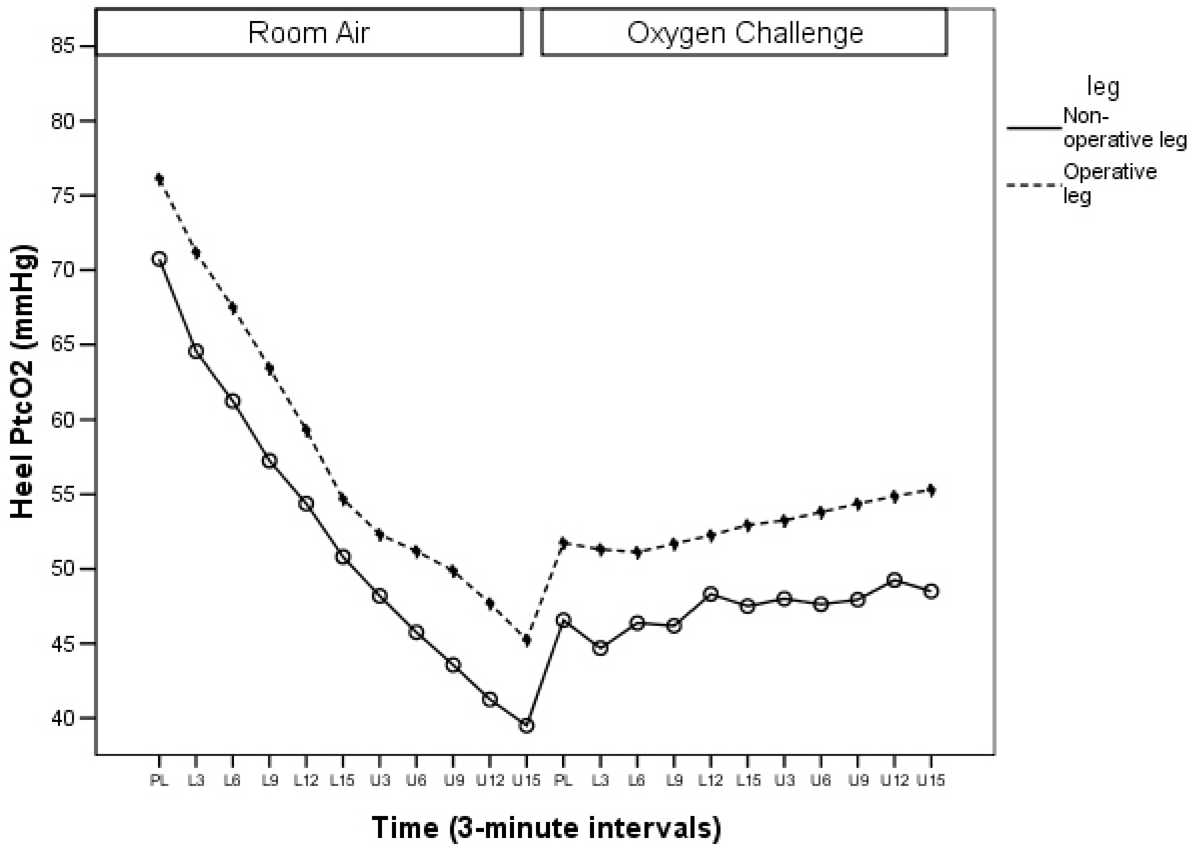

Figure 7. Mean heel $PtcO_2$ response in both legs on room air and with an oxygen challenge on day 2. Heel $PtcO_2$ decreased significantly over time ($p < 0.001$) on room air and with an oxygen challenge.

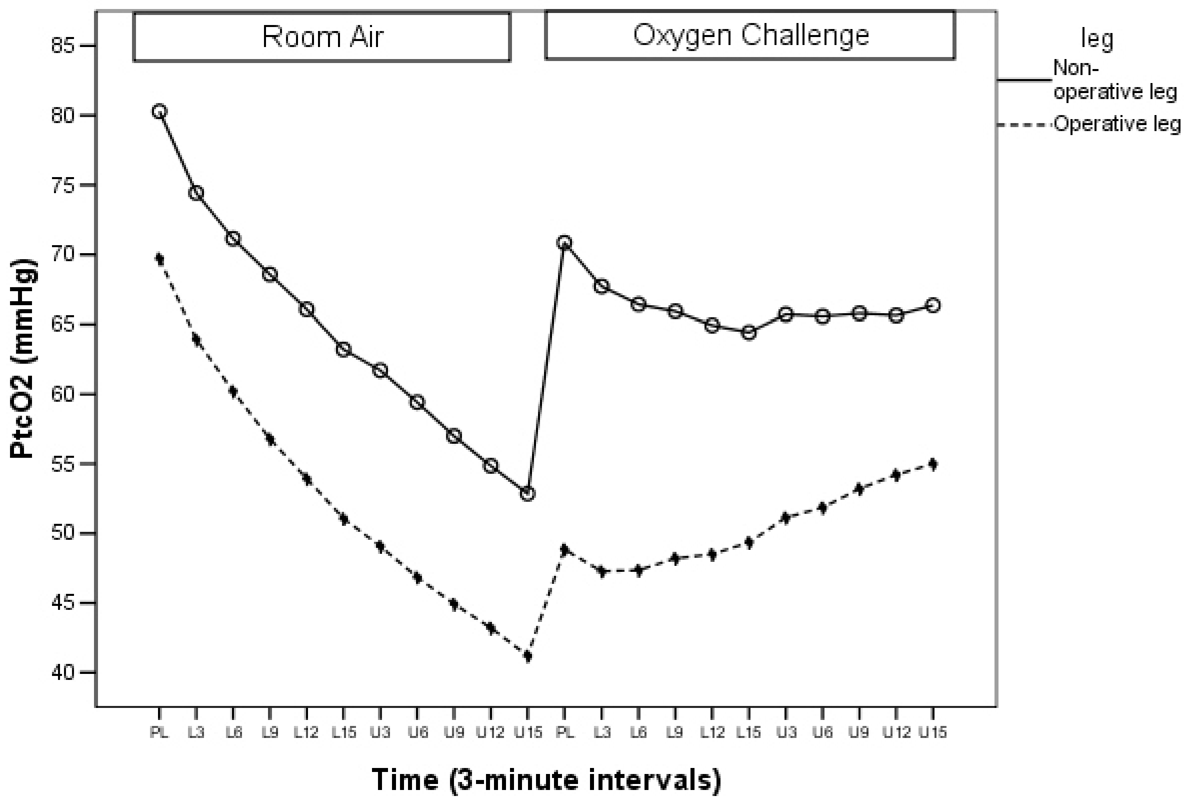

Figure 8. Mean heel $PtcO_2$ response in both legs on room air and with an oxygen challenge on day 3. Heel $PtcO_2$ was higher in the non-operative leg on room air and with an oxygen challenge ($p < 0.05$) as compared to the operative leg.