# Effect of Prolonged Pressure on Hemodynamics of Sacral Tissues Assessed by Diffuse Optical Imaging: A Pilot Study

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**Abstract** Pressure injuries (PIs) are wounds resulting from prolonged pressure exerting on the skin and underlying tissues over bony prominences (e.g., lower back, heels, shoulders) in bed-bound patients and wheelchair users. Minimizing pressure has long been considered the most effective preventative method and current guidelines require visual skin inspection and repositioning every two hours. However, these strategies are often applied deficiently and do not adequately prevent PIs from becoming penetrating wounds. Recent studies attribute the development of PIs to cell deformation, inflammatory and ischemic damages that cumulatively propagate from the micro-scale (death of few cells) to the macro-scale (tissue necrosis) within one to several hours. Although the nature of the PI pathogenesis is complex and multi-factorial, measuring tissue alterations in real-time may elucidate the origination mechanism and ultimately allow detecting PIs at the earliest stage. In this pilot study, we evaluated the ability of diffuse optical imaging (DOI) to assess hemodynamic changes resulting from prolonged pressure on the sacral tissues in five healthy volunteers laying immobile in a supine position for two hours. A thin, body-conforming optical imaging probe encompassing 256 optodes arranged in a regularly spaced grid over a 160 x 160 mm area was used to construct DOI volumetric images representing changes of oxyhemoglobin ($HbO_2$) and deoxyhemoglobin (HHb) concentration from a zeroed baseline. After two hours of continuous body weight pressure, hemodynamic images in all subjects were substantially dissimilar from their individual baseline. We also found that hemodynamic similarity computed pairwise across subjects exhibited a high value and limited variability around the mean, thus denoting a consistent level of image similarity across subjects. These preliminary results indicate that prolonged pressure causes distinctive hemodynamic patterns that can be effectively investigated with DOI, and that monitoring functional changes over time holds potential for clarifying the development mechanisms of PIs.

# 1 Introduction

Pressure injuries (PIs), also known as pressure ulcers, are wounds localized to the skin and/or underlying tissues that develop as a result of prolonged pressure exerted by a bony prominence (most frequently sacrum and heels) or a medical device. Although all populations with limited mobility are at risk of developing PIs, the highest rates are found in non-ambulatory patients who have no self-ability to reposition their body, especially those who are bed-bound recovering from trauma, surgery or acute illness in intensive care units (ICUs), terminally ill patients and wheelchair users. The prevention, assessment and treatment of PIs are universally considered part of nursing care, and since minimizing the pressure over bony prominences has long been considered the most effective method of PI prevention, patients at high risk of PIs need to be repositioned every two hours or less and receive a visual skin inspection by nursing staff to detect any newly developing PIs. Despite the recommended guidelines, the PI prevalence remains high (i.e., 2.5 million cases annually in the US alone, resulting in 60,000 deaths [1]). To avoid these issues, effective methods for detecting PIs as early as possible are needed.

Recent studies attribute the development of PIs to a series of cascading, additive and damaging events consisting of weight-related cell deformation damage, followed by an inflammatory response-related damage and culminated in an ischemic damage [2]. These adverse events may originate within minutes of one another but then progress at different rates, cumulatively producing damage that propagates from the micro-scale (death of few cells) to the macro-scale (necrosis of tissue) within one to several hours. Despite the complexity of the PI pathogenesis, measuring tissue alterations in real-time may elucidate the origination mechanism and ultimately allow detecting PIs at the earliest stage.

In this pilot study, we evaluated the ability of diffuse optical imaging (DOI), i.e. an imaging technique based on near infrared spectroscopy (NIRS), to assess hemodynamic changes resulting from prolonged pressure on the sacral tissues of healthy individuals. Briefly, NIRS measures the optical absorption of two dominant chromophores in human tissues, i.e., oxygenated hemoglobin ($HbO_2$) and deoxygenated hemoglobin (HHb) by illuminating the tissue with near infrared (NIR) light and detecting the light that is partially back-scattered by optically-turbid tissues like skin, fat, muscle and bone. Since applying pressure on a slab of tissue significantly affects its hemodynamics by occluding small vessels (capillaries, arterioles and venules), NIRS can measure the effect of such pressure as soon as it manifests [3]. In the last decade, a few studies correlated NIRS-derived tissue oxygenation parameters to PI risk [4], although these were not designed to investigate the disease mechanism. In order to capture hemodynamic events of interest that may relate to the clinical development of PIs, we relied on DOI to 1) measure hemodynamics on a large area of tissue and at different of depths around a bony prominence, and 2) monitor structural features of such hemodynamic changes from the moment pressure is applied and continuously over time.

## 2 Methods

Building on our previous design of a small-sized imaging system for detecting vascular occlusion during surgery [5], we developed a DOI probe embedding 128 emitters (dual-wavelength LEDs at 680 and 780nm) and 128 detectors (silicon photodiodes) arranged alternatively on a 10-mm regularly-spaced grid (total field of view: 150x150 mm). To follow the curvature of the body (critical for wearability), the probe was built on a flexible printed circuit board (PCB) covered with a layer of optically clear, biocompatible silicone for safe and comfortable application to the human skin. Optical absorption measurements were taken at both wavelengths and in dark condition (LEDs off) to subtract any background contribution. A total of 1,736 optical channels with source-detector separations of 10mm (480 channels), 22mm (840 channels) and 30mm (416 channels) were used to reconstruct tomographic images of changes of $HbO_2$ and HHb with NIRFAST, i.e. a finite-element method often utilized for functional brain imaging [6, 7]. Hemodynamic images were reconstructed for a volume of 168 x 168 x 12 mm with a voxel size of 1 $mm^3$.

To assess the quality of optical readings and to conduct a preliminary assessment of hemodynamics in soft tissues exposed to prolonged pressure, we asked five healthy volunteers (four males, age 24.6 ± 4.4 yr., weight 71.2 ± 13.9 kg.) to lay supine on a cushioned bed for two hours, thus matching the time period for body repositioning recommended to avoid PI formation. The optical probe was manually placed on the sacral region with the sacrum prominence located in an approximate central position. Hemodynamic images were collected every minute after the body weight pressure was applied onto the sacral tissues for a total of 120 minutes.

The effect of two-hour body weight pressure on the sacral tissues was assessed in terms of patterns of hemodynamic activity (increase or decrease of $HbO_2$ and/or HHb from baseline) measured over time. We used the Structural SIMilarity (SSIM) index [8] as a measure of similarity between two volumetric hemodynamic images, where SSIM = 1 indicates perfectly overlapping activity patterns (e.g., co-located hemodynamically active volumes) while SSIM = 0 indicates maximally dissimilar activity patterns (e.g., a hemodynamically active volume in one image co-located to an inactive volume in the second image). For each individual subject, we quantified the similarity of activation volumes, separately for $HbO_2$ and HHb, captured one minute after baseline (i.e., reference image) and every minute after ($HbO_{2\ t=N}$ vs. $HbO_{2\ t=1}$, $HHb_{t=N}$ vs. $HHb_{t=1}$). We also evaluated the similarity over time between activity patterns of different hemoglobin species ($HbO_{2\ t=N}$ vs. $HHb_{t=N}$) within each subject. Across different subjects selected pairwise, we quantified the similarity between hemodynamic patterns within-species measured at the same time during the experiment ($HbO_{2\ sbj=X,\ t=N}$ vs. $HbO_{2\ sbj=Y,\ t=N}$, $HHb_{sbj=X,\ t=N}$ vs. $HHb_{sbj=Y,\ t=N}$). To avoid saturation effects in computing SSIM, all hemodynamic images were normalized to the maximum activation value (either positive or negative) measured over the entire experiment. In addition, we chose to mask the hemodynamic images back-

ground (i.e., voxels with less than 10% of peak activation value) to avoid considering spatially overlapping, inactive areas that would have resulted in an overestimation of SSIM. To present these results concisely, we computed the average and standard deviation of SSIM values computed for all comparisons of interests.

## 3 Results

The similarity of hemodynamic changes evaluated over time within each subject is shown in Fig. 1. Expectedly, the SSIM values at the start of the experiment approached unity, as hemodynamic images acquired only few minutes apart were structurally very similar. Subsequently, the average SSIM decreased with the passage of time due to pressure-induced hemodynamic activity that increasingly differed from the initial pattern. Also, the variability of SSIM around the mean value increased over time, reflecting subject-specific downtrend rates.

A decreasing SSIM trend was also observed when $HbO_2$ image patterns were compared to HHb patterns within the same individual (Fig. 2). However, similarity across species decreases less compared to similarity within species (Fig. 1), confirming the physiological relation between co-located $HbO_2$ and HHb activities.

The hemodynamic similarity computed pairwise across subjects and then averaged is shown in Figure 3. The initial SSIM value was found to be lower than the corresponding within-subject value due to inter-subject differences between hemodynamic patterns. The mean SSIM for $HbO_2$ slightly increased during the first 30 minutes and reached a plateau thereafter, whereas the SSIM for HHb was essentially constant over time. The SSIM trends also exhibited a limited variability around the mean value, thus denoting a consistent level of image similarity across subjects.

## 4 Discussion

To the best of our knowledge, this is the first study assessing the effect of a prolonged (i.e., 2-hour) body weight pressure on the hemodynamics of sacral tissues minute-by-minute. Although we designed the study around the overarching hypothesis, supported by a strong physiology rationale, that capillary occlusions induced locally by the sacrum pressing onto the interfacing muscle and skin would cause the tissue hemodynamics to change over time, the novelty of our imaging approach made this study partly exploratory in nature, as the measurements of specific patterns of hemodynamic activity were unprecedented. Diffuse optical imaging provides rich information about tissue hemodynamics, i.e. it delivers tomographic images for $HbO_2$ and HHb concentrations, separately and independently, that may locally increase or decrease as a function of time, making the summarization and interpretation of those images inherently challenging.

To address this matter, we evaluated such complex image features with structural similarity index (SSIM), that is a quantitative measure that reflects, with both fidelity and simplicity, hemodynamics changes over time within the individual subject and also across subjects with different anatomy and physiology.

Our results show that, in all subjects, body weight pressure induced hemodynamic changes that began immediately after pressure exertion and continued throughout the 2-hour experiment, thus confirming the overarching hypothesis. This was particularly evident at the individual subject level, where the hemodynamic activity patterns of individual Hb species departed quite substantially from their initial pattern. Still at the subject level, the similarity across-species changed only moderately over time, thus suggesting that, from a hemodynamic imaging perspective, $HbO_2$ and HHb may provide some redundant information about the effect of prolonged pressure. More interestingly, the similarity of hemodynamic pattern across subjects was fairly high and stable over time, which indicates that subjects exhibited consistent image features.

## 5 Conclusion

This pilot study shows that diffuse optical imaging is a valid tool for investigating hemodynamics effects of prolonged pressure. In the longer term, DOI could elucidate the origination mechanism of PIs and potentially lead to their early detection.

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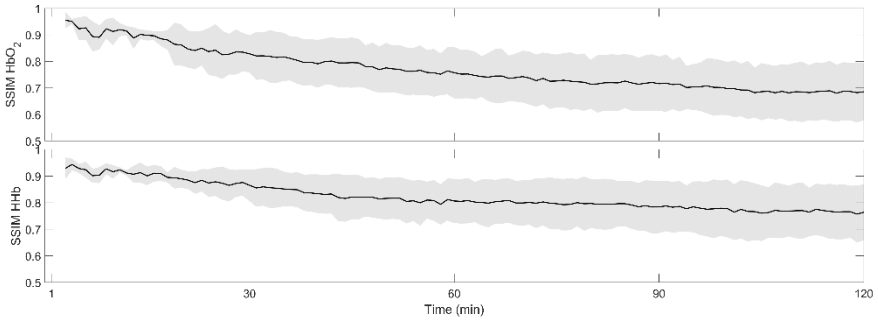


**Fig. 1.** Structural similarity index of time-evolving $HbO_2$ (top) and HHb (bottom) images using the subject-specific initial hemodynamic image as reference. Mean (black line) and standard deviation (gray bands) computed across all subjects.

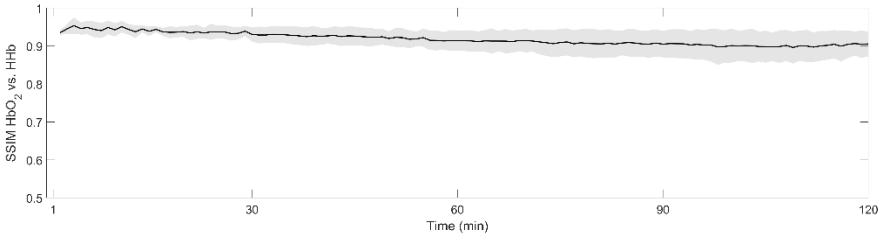


**Fig. 2.** Structural similarity index between $HbO_2$ and HHb images acquired simultaneously within a subject. Mean (black line) and standard deviation (gray bands) computed across subjects.

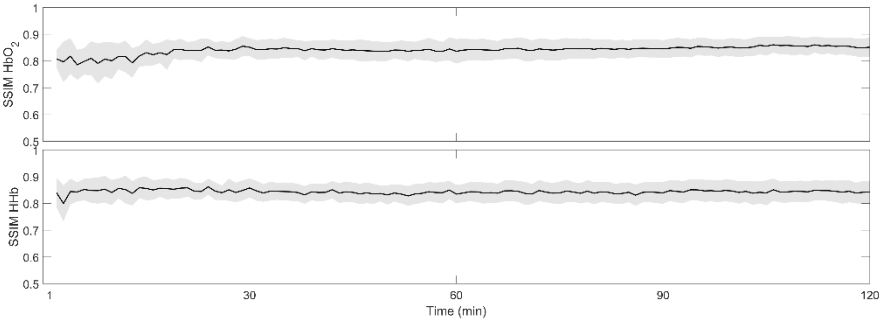


**Fig. 3.** Structural similarity index of time-evolving $HbO_2$ (top) and HHb (bottom) images computed across two different subjects. Mean (black line) and standard deviation (gray bands) computed across all pairwise combination of subjects.