EXPLORING METHODS TO IMPROVE PRESSURE ULCER DETECTION: SPECTROSCOPIC ASSESSMENT OF THE BLANCH RESPONSE

by

Jeanne M. Zanca

Bachelor of Arts, Rutgers University, 1999

Master of Physical Therapy, University of Pittsburgh, 2002

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This dissertation was presented

by

Jeanne M. Zanca

It was defended on

July 17, 2006

and approved by

Margo B. Holm, Professor, Department of Occupational Therapy

Allan R. Sampson, Professor, Department of Statistics

Michael G. Sowa, Group Leader, Spectroscopy Group, Institute for Biodiagnostics, National Research Council

Dissertation Advisor: David M. Brienza, Professor, Department of Rehabilitation Science and Technology

EXPLORING METHODS TO IMPROVE PRESSURE ULCER DETECTION: SPECTROSCOPIC ASSESSMENT OF THE BLANCH RESPONSE

Jeanne M. Zanca, MPT

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Pressure damage in intact skin is difficult to detect, particularly in individuals with dark skin, because color changes and tissue blanching are masked by the skin's pigmentation. Tissue reflectance spectroscopy (TRS) may be able to detect the blanch response regardless of skin color by measuring the change in total hemoglobin (ΔtHb) that occurs when pressure is applied to the skin. The objective of this dissertation was to examine the ability of TRS to detect the blanch response at sites at risk for pressure ulcer development in individuals with various levels of skin pigmentation. Three studies were conducted to address this objective. In Study 1, ΔtHb was assessed at the heel and sacrum of light and dark-skinned healthy participants using a portable TRS system. Study 1 showed that a significant decrease ($p<0.001$) in tHb could be measured in both light and dark skinned-participants with good intra-rater reliability (ICC≥0.80) at the heel, but not at the sacrum. Study 2 was conducted to identify a reliable method of skin color description for use in subsequent studies of the spectroscopic blanch response. Two examiners (B and C) performed three skin color assessments at the volar forearm of ten healthy participants using Munsell color tile matching and colorimetry. Intra and inter-rater reliability was excellent for colorimetry (ICCs typically ≥0.90). Reliability for Munsell color tile matching was highest for Munsell value within Examiner B (93% agreement, kappa 0.87–1.00), which was determined to be sufficiently high for use in subsequent studies. In Study 3, ΔtHb was assessed at the heels of light, moderate, and dark-skinned elderly nursing home residents at risk for pressure ulcers. As in the pilot study, a significant decrease in tHb was observed in all skin color groups ($p<0.05$). Intra-rater reliability for ΔtHb was moderate or greater (ICC≥0.61). In combination, the results of Study 1 and Study 3 demonstrated that a significant spectroscopic

blanch response could be detected with moderate or greater intra-rater reliability at the heel regardless of age or pressure ulcer risk status.

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PREFACE

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1.0 INTRODUCTION

1.1 DISCUSSION OF PROBLEM

A number of research studies have described disparities in pressure ulcer incidence and prevalence between those with light and dark skin. Studies of long-term care and acute care patients have reported a higher incidence or prevalence of pressure ulcers in non-white patients compared to the overall patient population.[1,2] Researchers have also reported a higher incidence or prevalence of full thickness pressure ulcers in dark-skinned individuals compared to those with light skin.[3-6]

Many studies have suggested that higher stage ulcers are more prevalent in patients with dark skin because indicators of pressure damage in intact skin are difficult to detect in the presence of high skin pigmentation.[3,4,6-10] Traditionally, the blanch response as been used as one of the main indicators of pressure damage in intact skin. Healthy light skin appears pink in color because of blood flowing through vessels in the skin. When gentle pressure is applied to the skin, it temporarily becomes whiter in color, or "blanches", as blood is displaced from the area where pressure is applied. This change in color is known as the blanch response. Pressure damage in intact skin appears as a discolored area that does not blanch when pressure is applied to the skin (nonblanchable erythema). Because of its high level of pigmentation, dark skin typically does not blanch visibly even when it is healthy, making it difficult to detect pressure damage in intact skin by observing color changes in the skin alone.[9] Alternate indicators of pressure damage include changes in skin temperature, tissue consistency, or sensation.[10] However, these indicators are frequently difficult to assess in clinical settings due to the use of examination gloves, ambient fluorescent lighting, and difficulty communicating with patients at risk due to aphasia or impaired cognitive status.[9]

Improved detection of signs of pressure damage in intact skin, such as nonblanchable erythema, would yield several benefits. A number of research findings associate pressure ulcers in intact skin with the development of higher-stage ulcers[11-13] which are often accompanied by significant medical complications, pain, increased mortality, and higher health care costs.[14-17] Improved detection of nonblanchable erythema would facilitate earlier intervention to treat existing damage and prevent ulcer progression, reducing costs and medical complications associated with damage to deeper tissue layers. Improved detection would also provide more accurate information on the timing of pressure damage development than if pressure ulcer diagnosis were delayed until an opening in the skin is observed. Furthermore, incidence and prevalence data are incomplete without an accurate means of pressure damage detection in intact skin. Several incidence and prevalence estimates have intentionally excluded individuals with Stage I pressure ulcers because of the uncertainties involved in detecting these lesions.[13,16,18-20] An accurate means of pressure damage detection in intact skin would improve the quality of prevalence and incidence data. These data are essential to understand the clinical course of pressure ulcers, evaluate treatment and prevention outcomes, and develop health policy goals.

1.2 TISSUE REFLECTANCE SPECTROSCOPY: A POSSIBLE SOLUTION

Tissue reflectance spectroscopy (TRS) is non-invasive technique that provides information on the hemoglobin content of body tissues by analyzing light absorbed by tissue. Several researchers have developed TRS data analysis algorithms that account for the presence of skin pigmentation, allowing the concentrations of hemoglobin and deoxygenated hemoglobin to be measured in individuals with light and dark skin.[21-26] Researchers have used TRS to measure tissue hemoglobin levels in human subjects during venous and arterial occlusion,[27] orthostatic stress,[28] and exercise.[29] TRS has also been used to monitor hemodynamic changes in skin exposed to external loading. Investigators have successfully used TRS to track pressure-induced reactive hyperemia in healthy subjects[23] and in subjects at risk for pressure ulcers, including subjects with spinal cord injury and below-knee amputation.[30,31]

TRS provides a means of detecting the blanch response in light and dark skin. The whitening of light skin that is seen with pressure application occurs because of the displacement

of blood from the area. While this color change cannot be observed visually in dark skin, a "spectroscopic blanch response" can be quantified in both light and dark skin by comparing the total concentration of hemoglobin in skin in its resting state to that of skin during gentle pressure application. Two recent studies have used TRS to quantify the blanch response in light and dark skin. Matas, Sowa, and colleagues demonstrated that statistically significant decreases in total hemoglobin could be detected when pressure was applied to the forearms of light and dark-skinned healthy participants.[24] These results indicate that a blanch response can be "seen" with spectroscopy even when no visible color changes are identified with visual inspection. Sprigle and colleagues used TRS to assess the blanch response at areas of discoloration near bony prominences in a population of rehabilitation patients.[32] Sprigle reported that spectroscopic data from clinically blanching sites differed from that of clinically non-blanching sites, but there was wide variation in the extent of blanching measured by spectroscopy. More information is needed to determine the diagnostic value of spectroscopic blanch response assessment.

1.3 OBJECTIVES AND HYPOTHESES

The objective of this dissertation was to examine the ability of tissue reflectance spectroscopy (TRS) to detect the blanch response in individuals with various levels of skin pigmentation. Three studies were performed to accomplish this goal. Study 1 was a laboratory-based study in which the blanch response was assessed at the heel and sacrum of light and dark-skinned healthy participants using a portable TRS system. Study 1 had two objectives: (1) to test the hypothesis that total hemoglobin will decrease significantly when pressure is applied to light and dark healthy skin, and (2) to assess the intra-rater reliability of spectroscopic blanch response measurement in participants with healthy skin.

A second study (Study 2) was conducted to identify a reliable means of skin color description to assist subject recruitment in subsequent spectroscopic blanch response studies. This laboratory-based study was conducted in a population of light, moderate, and dark-skinned healthy participants with one objective: to examine the reliability of skin color assessments performed using Munsell color tile matching and colorimetry.

Finally, a third study was conducted to determine whether a spectroscopic blanch response could be measured at the heel in a population of light, moderate, and dark-skinned elderly nursing home residents at risk for pressure ulcers. Study 3 had two objectives: (1) to test the hypothesis that total hemoglobin will decrease significantly when pressure is applied to the skin of elderly nursing home residents at risk for pressure ulcers, regardless of skin color, and (2) to assess the intra-rater reliability of spectroscopic blanch response measurement in elderly nursing home residents at risk for pressure ulcers.

1.4 ORGANIZATION OF THE DISSERTATION

Six chapters follow this introduction. Chapter 2 provides clinical background information on pressure ulcers and the problem of pressure ulcer detection in intact skin. Chapter 3 discusses non-invasive technologies to assess tissue viability with an emphasis on the operating principles of tissue reflectance spectroscopy and its application to the problem of pressure damage detection. The methods, results, and conclusions of Studies 1-3 above are discussed in Chapters 4-6, respectively. Finally, Chapter 7 summarizes key findings of each of these studies, their limitations, contributions, and recommendations for future work.

2.0 OVERVIEW OF CLINICAL PROBLEM

2.1 PRESSURE ULCER BACKGROUND

2.1.1 Pressure Ulcer Definition

A pressure ulcer is defined as "any lesion caused by unrelieved pressure resulting in damage of underlying tissue."[7] Pressure ulcers are also known as bedsores, pressure sores, or decubitus ulcers. Pressure ulcers may develop in soft tissue overlying a number of bony prominences on the body, including the sacrum, coccyx, heels, greater trochanters, ischial tuberosites, malleoli, scapula, elbow, and occiput.[33]

2.1.2 Relevant Soft Tissue Structures

Pressure ulcers may damage any of the soft tissues overlying bony prominences.[34,35] The outermost layer of soft tissue is the epidermis, which consists of several layers of cells and is avascular. The outermost epidermal layer consists of hardened, flattened, cells containing a protein known as keratin. The thickness of the epidermis varies from 70 to 120 μm in most areas of the body to 1.4 mm thick in callused areas on the hands or feet.[35] Below the epidermis is the dermis, which contains blood vessels, lymphatic vessels, hair follicles, sweat glands, and sensory nerve endings. The dermis is 1–2 mm thick on average, but can be up to 3 mm thick on the soles of the feet.[35] The interface between the epidermis and dermis contains a series of ridges, or papillae, in which the epidermis extends downward into the dermis and dermal tissue containing blood vessels extends upward between the epidermal extensions. Together, the epidermis and dermis comprise the skin. Below the dermis is a layer of subcutaneous fat and loose connective tissue. Blood vessels supplying the skin travel through the fatty tissue. Below the subcutaneous

fat is a layer of fascia, a connective tissue made primarily of collagen that is avascular. Muscle tissue lies below the fascia, and is highly vascularized. Beneath muscle tissue is periosteum-covered bone.

2.1.3 Pressure Ulcer Etiology

The pathophysiology of pressure ulcer development is not fully understood. Researchers and clinicians typically attribute pressure ulcers to pressure exerted on soft tissue structures overlying bony prominences.[34,36-39] Pressure is defined as force per unit area. Pressure is thought to create ischemia in soft tissues by occluding blood flow in tissue vasculature, depriving soft tissues of oxygen and other nutrients and allowing the buildup of toxic by-products of cellular metabolism. The buildup of toxic by–products is thought to create tissue acidosis which results in increased capillary permeability, edema and cell death.[37] In addition to creating vascular occlusion, pressure may disrupt lymphatic circulation, further disrupting the removal of wastes and contributing to tissue necrosis.[37,39] Pressure may also create interstitial fluid flow in the tissue that may disrupt cellular functioning.[40] Tissue damage may also result from "reperfusion injury" in which the return of blood to an ischemic area produces an inflammatory reaction and tissue injury.[38,41] Histological studies of animal and human tissues exposed to pressure have shown a variety of inflammatory changes, including tissue edema and infiltration of neutrophils and macrophages.[36,42] The magnitude and duration of pressure needed to create tissue injury are thought to be inversely related, such that injury may result from low pressure over a prolonged period of time or high pressure over a brief period of time.[37,43]

While pressure is thought to be the primary cause of tissue injury, friction and shear forces are also contributing factors. Friction has been defined by NPUAP as "resistance to motion of the external tissue sliding in a parallel direction relative to the support surface" (draft definition, 2006).[44] Friction is thought to damage or remove the epidermis, making tissue vulnerable to infection and further weakening its ability to tolerate vascular compromise by pressure.[37,39,42,45] Friction may also contribute to the production of shear. Shear has been defined by NPUAP as "an action or stress resulting from applied forces which causes or tends to cause two contiguous internal parts of the body to deform in the transverse plane (i.e., shear strain)" (draft definition, 2006).[44] A clinical scenario in which shear is likely imparted to soft

tissue is when a patient lies in bed with the head of the bed elevated. In this situation, superficial tissues adhere to the surface of the bed via friction, but deeper tissues and fascia continue to slide down the bed due to body weight.[37,45] Stretching and possible tearing of deep structures are thought to result from the shear stress. Large vessels that perforate muscle and fascia are thought to be particularly vulnerable to shear.[39,42]

Animal and human studies have demonstrated that shear and friction can enhance the damaging effects of pressure. Dinsdale reported that less pressure was required to create tissue ulceration when pressure was applied in combination with friction.[46] Goldstein and Sanders exposed pigs' skin to pressure and two levels of shear and observed that the time required for skin breakdown to occur was shorter when more shear was present.[47] Goosens and colleagues measured skin oxygen tension at the sacrum of young, healthy volunteers and found that the pressure required to reduce skin oxygen tension to 1.3 kPa was lower in the presence of shear.[48] Bennett and colleagues applied pressure and shear to the thenar eminence of healthy subjects and reported that the pressure necessary to produce vascular occlusion was reduced by approximately one half when shear was present.[49]

Pressure ulcers are thought to develop via two mechanisms. Pressure-related tissue damage may begin in superficial skin layers and progress to deep layers ("top down" mechanism) or begin in deeper layers, progressing to the surface of the skin ("bottom up" mechanism).[50] Shea stated that deeper wounds would result if appropriate actions were not taken to prevent further damage in individuals with superficial wounds, suggesting that tissue damage begins in superficial layers and later progresses to deeper layers.[34] Witkowski and Parish reported that upper dermal structures were the first to show signs of pressure-related injury, based on histological analysis of 6 mm punch biopsies taken from humans with various types of pressure damage.[42] Expert opinion and research data also suggest bottom-up pressure ulcer development. Several experts have described pressure being transmitted from the skin surface to bone in a cone-like distribution, such that the area of tissue affected and/or the magnitude of pressure is greatest near the bone.[34,37,39,51] Some research data support the suggestion that deep vessels may be occluded first, producing deep tissue necrosis while more superficial structures appear normal. Bouten and colleagues modeled the mechanical response of buttock soft tissue supported by a foam cushion and showed high internal stresses in deeper fat and muscle layers.[38] Animal models also suggest that damage may occur first in deeper layers. Daniel and colleagues

performed histological analysis of porcine soft tissue exposed to pressure, and reported that damage to muscle layers was observed without damage to overlying skin.[43] Salcido and colleagues applied pressure to the greater trochanter of rats and reported that samples taken from skin with no visible signs of damage upon inspection showed signs of muscle damage upon histological examination.[52] More data are needed regarding top-down versus bottom-up mechanisms of pressure ulcer development.

2.1.4 Pressure Ulcer Risk Factors

Pressure ulcer risk factors affect: (1) the duration and intensity of pressure applied to soft tissue, or (2) the ability of soft tissue to tolerate pressure.[45] Immobility is a major risk factor for pressure ulcer development.[37,45,53] Standing and walking relieves pressure on bony areas of the body. The ability to shift body position while seated or lying allows pressure to be redistributed as needed, preventing pressure buildup in any area of the body. Those who have weakness, paralysis, or other conditions that affect movement and ambulation are unable to redistribute pressure without assistance, exposing them to potentially damaging pressure. Those with mobility impairments are also frequently unable to completely lift themselves up during transfers. The result is sliding of the soft tissue along bed or seating surfaces, creating friction and shear that may damage tissue. Regression analyses have shown impaired mobility or ambulation to be a significant predictor of pressure ulcer development.[11,19,54]

Impaired sensory perception is also a risk factor for pressure ulcer development.[37,45] Pain and discomfort are signals of excessive pressure buildup and potential tissue damage. Those who are unable to perceive pain or discomfort or who cannot respond purposefully to discomfort due to cognitive impairments are not aware that pressure buildup is a problem and will not take steps to relieve excessive pressure. Fisher and colleagues demonstrated that sensory perception is significantly associated with pressure ulcer development.[54]

Moisture is thought to reduce the skin's tolerance to external forces.[37,45] Moisture may be present on the skin due to urinary or fecal incontinence, perspiration, wound drainage, food spillage, or use of moist heat therapy. Moisture creates maceration of the epidermis, in which the epidermis becomes softened and more susceptible to breakage. Depending on the type of moisture present, the epidermis may be exposed to toxins or bacteria that may create

inflammation and infection. Moisture may also cause the skin to adhere to bedding or other support materials, allowing friction and shear to occur in addition to pressure. Moisture as been identified a significant predictor of pressure ulcer development.[19,54]

Poor nutrition, particularly insufficient protein intake, is thought to weaken skin integrity.[37,45,53] Insufficient protein is thought to create interstitial edema, which impairs flow of nutrients and wastes in tissue and may affect the health of soft tissues.[37] Bergstrom and Braden reported that mean protein intake and mean serum albumin was significantly lower in nursing home residents who developed pressure ulcers compared to those without pressure ulcers.[6] Pieper and colleagues also found lower serum albumin levels in acute care, rehabilitation, and home care patients with pressure ulcers compared to those without pressure ulcers.[55] Regression analyses have identified oral eating problems[56], difficulty feeding oneself[19], dietary protein or iron [6], and nutrition[54] as significant predictors of pressure ulcer development.

Advanced age has been shown in several research studies to be a risk factor for pressure ulcer development. Amlung and colleagues reported that 55% percent of all pressure ulcers that developed in their sample of acute care hospital patients occurred in those aged 71 to 90.[57] Bergstrom and colleagues reported that the mean age for those who developed a pressure ulcer was approximately 10 years greater than those who did not (71.6 years vs. 61.9 years, $p < 0.0001$) in a population of participants in tertiary care hospitals, Veterans Administration Medical Centers, and skilled nursing facilities.[58] Horn and colleagues reported the mean age of nursing home residents developing pressure ulcers was significantly greater than those who did not (82.5 vs. 80.8 years, $p=0.010$).[56] Pieper and colleagues studied patients in acute care, rehabilitation, and home care, and found that those who developed pressure ulcers were significantly older than those without pressure ulcers (mean age 70.4 vs. 53.9 years).[55] Several researchers have shown age to be a predictor of pressure ulcer development using survival[11] or regression analyses.[6,54,59] Several age-related soft tissue changes may make skin more vulnerable to pressure including thinning of the epidermis, loss of dermal blood vessels, reduced elastin content, and production of collagen that has increased stiffness and decreased mechanical strength.[11,37]

A number of other conditions have been described as possible risk factors for pressure ulcer development, including diabetes mellitus[19], male gender[19,54], previous history of a pressure ulcer[11,56], body weight[11,59], weight loss[56], increased body temperature[6], decreased blood

pressure[6], greater illness severity[56], number of illnesses[55], low hemoglobin[37,55], stroke or spinal cord injury[53], and smoking[45].

2.1.5 Diagnosis and Staging of Pressure Injuries

Pressure ulcers are currently diagnosed through a combination of visual and tactile inspection of the skin and consideration of patient-reported symptoms. Differential diagnosis of pressure ulcers versus other skin lesions is made considering several factors, including the wound's proximity to a bony prominence, historical factors that increase likelihood of excessive pressure exposure (i.e. immobility, sensory loss), and appearance of surrounding skin (typically normal, erythmatic if chronic wound).[60,61]

Several staging systems exist to describe pressure ulcers.[50] The system used most frequently in the United States is that of the National Pressure Ulcer Advisory Panel (NPUAP). The NPUAP has defined four stages of pressure ulcers based on the anatomical depth of tissue observed in the base of the ulcer (Table 1).[7] Lesions in which the wound base is not visible due to necrotic tissue (eschar, slough) or other factors are described as "unstageable".

While the definitions of Stage II – IV pressure ulcers have remained the same since the staging system's creation in 1989, uncertainty persists regarding the appropriate staging of pressure damage in intact skin. The definition of Stage I has been revised twice, largely due to differences between individuals with light versus dark skin, as will be discussed further in section 2.4.[62] Debate is also ongoing regarding a category of lesion known as "deep tissue injury under intact skin" (DTI). There is consensus among clinicians and researchers that pressure-induced necrosis may be present in deeper tissue layers while the skin remains intact.[50] However, this phenomenon is not described in the current NPUAP staging system. In 2001, the NPUAP drafted a definition of DTI as "a pressure-related injury to subcutaneous tissues under intact skin." DTI has been described as "dark purple or bruised areas over bony prominences with intact skin,"[50] "deep purple ecchymosis"[51] or "thin blistered skin with a dark base, which eventually presents as full eschar".[51] DTI lesions are thought to deteriorate rapidly and are attributed to the effects of shear and pressure on deep blood vessels and tissues.[34,50,51,62] At present, NPUAP recommends that DTI be considered an "unstageable" ulcer.[62] Discussions continue regarding the appropriate definitions and staging of pressure ulcers in intact skin.

Table 1. NPUAP staging system

Stage	Current NPUAP Definition
I	An observable pressure-related alteration of intact skin whose indicators as compared to an adjacent or opposite area on the body may include changes in one or more of the following: skin temperature (warmth or coolness), tissue consistency (firm or boggy feel), and/or sensation (pain, itching). The ulcer appears as a defined area of persistent redness in lightly pigmented skin, whereas in darker skin tones, the ulcer may appear with persistent red, blue, or purple hues.
II	Partial thickness skin loss involving epidermis, dermis, or both. The ulcer is superficial and presents clinically as an abrasion, blister, or shallow crater.
III	Full thickness skin loss involving damage to, or necrosis of, subcutaneous tissue that may extend down to, but not through, underlying fascia. The ulcer presents clinically as a deep crater with or without undermining of adjacent tissue.
IV	Full thickness skin loss with extensive destruction, tissue necrosis, or damage to muscle, bone, or supporting structures (e.g., tendon, joint, capsule). Undermining and sinus tracts also may be associated with Stage IV pressure ulcers.

2.2 PRESSURE ULCER IMPACT IN LONG-TERM CARE

2.2.1 Incidence and Prevalence

As of the 1999 National Nursing Home Survey, there were more than 1.6 million nursing home residents in the United States, 90% of whom were over age 65.[63] In addition to advanced age, long-term care residents often have mobility impairments, cognitive impairments, incontinence, nutritional deficiencies, and a host of cardiovascular and other comorbidities that place them at risk for pressure ulcer development.[53] A systematic review by the NPUAP (2001) reported incidence rates of 2.2% to 23.9% within the long-term care population as a whole.[7] However, pressure ulcer incidence has been reported to be as high as 73.5% for newly-admitted residents over age 65 at risk for pressure ulcers.[6] Estimates made since 2001 have described incidence rates of 24.5%[64], 29.1%[56], and 43.3%[65] for residents at risk for pressure ulcers. Prevalence estimates in the long-term care population range from 2.3% to 28% as of the 2001 NPUAP

systematic review.[7] A 2002 study of long-term care residents at risk for pressure ulcers reported that 27.7% of its overall sample had pressure ulcers at the beginning of the study.[64] The mean prevalence reported by the 95 facilities participating in the study was 9.8% (range 0.6 – 54.8%) for all residents in their care from 1996-1997[64], which is similar to the 8.5% overall prevalence rate reported in a study of data collected from 92 nursing homes between 1992 and 1998.[66] The prevalence of pressure ulcers in newly-admitted residents has been reported to be higher than that of current residents (17.4% vs. 8.9%).[67]

The heel and sacrum/coccyx are among the most frequently observed sites of pressure ulcer development in long-term care residents. Research data suggest that heel pressure ulcer incidence may be as high as 24.8% to 49.5% in newly-admitted long-term care residents 65 and older at risk for pressure ulcers.[6] Another study reported that 22% of all ulcers observed in long-term care residents at risk for pressure ulcers occurred at the heel.[64] Sacral pressure ulcer incidence has been reported as 11.8% in residents at risk for pressure ulcers[68] and 22% in a mixed population of residents who may or may not be at risk for pressure ulcers.[69] Others have reported that 25% to 30% of all pressure ulcers observed occurred in the sacrum/coccyx region.[6,64] Other sites of pressure ulcer development in long-term care residents include the buttocks, ankle, foot, toe, and greater trochanter area.[6,64,69] One study reported that over 47% of participants with pressure ulcers had ulcers at multiple sites.[64]

Stage II ulcers are typically the most frequently observed in long-term care, followed by Stage I, Stage III, and Stage IV. Brandeis and colleagues reported a 3.7% prevalence of Stage II ulcers in their sample, followed by 2.1% for Stage I, 2.0% for Stage III, and 1.1% for Stage IV in current long term care residents.[67] New admissions showed a similar ranking of stages, with a 6.3% prevalence of Stage II ulcers, 6.1% for Stage I, 2.6% for Stage III, and 2.4% for Stage IV. Berlowitz and colleagues excluded Stage I from analysis, but reported that 45.6% of the ulcers observed in their study were Stage II, 31.5% were Stage III, and 22.9% were Stage IV.[20] Horn and colleagues reported that 52% of the ulcers observed were Stage II at initial assessment, followed by Stage I (15%) , Stage III (10%) and Stage IV (10%).[64] Bergstrom and colleagues reported Stage I as the most frequently-observed stage at the time of detection (65.7% of all ulcers) followed by Stage II (31.6%), Stage III (2.1%), and Stage IV (0.3%).[6] Bergstrom's observation of Stage I ulcers may have been greater than in other studies because research staff conducted regular skin assessments in at-risk residents to track pressure ulcer incidence, whereas

many other studies collected pressure ulcer data from medical documentation. In addition, the definitions of incidence and prevalence frequently differed among studies, and these differences should be considered when comparing their results.

2.2.2 Pressure Ulcer Complications and Morbidity

Pressure ulcers may require considerable effort to heal, and are associated with medical and psychosocial complications. Once pressure ulcers develop, they may take weeks, sometimes months to heal.[14,16,64] During the healing process, prolonged bedrest may be required, preventing participation in social activities and rehabilitation.[14,70] In those with sensation, pressure ulcers may be associated with considerable pain.[14,70] Stage III and IV pressure ulcers may require surgery, which may be associated with complications. In a study of 22 elderly, non-ambulatory patients undergoing flap surgery, half of the patients developed complications, including reopening of the wound, infection, or seroma.[71] Even if healing is successful, the risk of developing a new pressure ulcer at the same site is thought to increase due to the presence of fragile scar tissue that is more vulnerable to pressure than the original tissue.[72] A study of 16 elderly long-term care patients who received flap surgery showed a 37.5% rate of recurrence of the pressure ulcer.[73]

Long-term care residents with pressure ulcers often experience medical complications. Residents with pressure ulcers have been reported to have a 37.7% greater rate of hospitalization than those without pressure ulcers.[67] Hospitalized individuals with pressure ulcers have been shown to develop more complications during their stay than those without pressure ulcers. Allman and colleagues reported that 86.5% of hospitalized individuals with pressure ulcers developed complications compared to 43% of those without pressure ulcers.[15]

Infection is perhaps the most dangerous complication of a pressure ulcer. The presence of an open wound provides an entry point for pathogens, increasing infection risk.[74] In hospitalized individuals age 55 and older with activity limitations, 45.9% of those with pressure ulcers developed nosocomial infections compared to 20.1% of those without pressure ulcers.[15] Infection in the wound may spread to surrounding tissues, resulting in cellulitis and osteomyelitis, which is commonly observed with Stage IV wounds.[74] Drainage from infected wounds in a nursing home resident may be spread to other residents, increasing the risk of

infection throughout the facility.[74] Infected pressure ulcers may lead to amputation to prevent spread of the infection.[6,70] If septicemia develops, it is often associated with death. Death certificate data has shown that pressure ulcer associated deaths were 11.3 times more likely to have septicemia listed as an underlying or contributing cause of death than matched control deaths.[75] Furthermore, it was found that 73% of certificates listing septicemia as an underlying or contributing cause of death listed the development of a pressure ulcer prior to the development of septicemia in the chain of events leading to death. These data strongly suggest that pressure ulcers increase risk of septicemia and its complications.

Whether due to septicemia or other medical complications, there are data to suggest that pressure ulcers are associated with increased mortality. Pressure ulcers were listed as a cause of death for 114,380 people according to death certificates completed between 1990 and 2001.[75] Nearly 80% of these deaths occurred in individuals aged 75 or older. Several studies suggest that nursing home residents with pressure ulcers are more likely to die than those without pressure ulcers. Brandeis and colleagues reported that rates of death were 129% greater for current residents with pressure ulcers and 88.1% greater for newly-admitted residents with pressure ulcers compared to those without pressure ulcers after 1 year of followup.[67] Horn and colleagues observed that 11.5% of residents with pressure ulcers died compared to 5.6% of those without pressure ulcers ($p<0.001$).[64] Berlowitz and colleagues reported that the relative risk of death was 2.37 for residents with pressure ulcers, although this risk decreased to 1.45 after adjusting for factors such as activity level and medical conditions.[20] In an earlier study, Berlowitz and Van B. Wilking reported relative risks of death for long term care hospital patients to be 1.9 for those with pressure ulcers on admission, 3.1 for those who developed new sores, and 3.3 for those with sores that failed to improve in 6 weeks.[16] The authors cautioned that increased risk of death was likely due to coexisting medical conditions and not necessarily due to the presence of the ulcer itself. Debate continues regarding the extent to which pressure ulcers increase risk of death, but there is considerable evidence to suggest that pressure ulcers are a contributing factor to mortality.

2.2.3 Financial Impact of Pressure Ulcer Care

Estimating the costs of pressure ulcer care are challenging, and study results are difficult to compare due to variation in the information and methodologies used to generate cost estimates. Despite these limitations, it is clear that pressure ulcer-related treatment costs are considerable, both in long term care and hospital settings. The cost per pressure ulcer has been estimated at $1,727 (excluding hospital costs)[76] and $2731 (including hospital costs) in long-term care residents.[53] Costs for hospitalized patients with pressure ulcers were reported to be $15,229 higher for those with pressure ulcers compared to those without pressure ulcers when adjusted for complications and admission characteristics.[15] The total cost in the United States for hospitalized patients with pressure ulcers has been estimated at $9.1 – 11.6 billion/year based on past literature and adjustments for inflation.[72] Costs increase considerably with the severity of the ulcer. The total cost of wound care is estimated at $125-451 for Stage I or II ulcers and $14,000-$23,000 for Stage III or IV ulcers.[17,77] The average daily cost of long-term wound care for Stage III and IV pressure ulcers is estimated as high as $240 per day—12 times the cost of daily care for Stage II ulcers.[17]

2.3 RACIAL DISPARITIES IN PRESSURE ULCER INCIDENCE AND PREVALENCE

A number of research studies have described disparities in pressure ulcer incidence and prevalence between those with light and dark skin. Spector and colleagues found that the prevalence of pressure ulcers in non-white individuals admitted to nursing homes was 32%, versus 20% for the overall sample.[1] In addition, non-white individuals had a 50% greater likelihood of being admitted to a nursing home with a pressure ulcer than whites.[1] In a study of acute medical and surgical hospital patients, Lyder and colleagues found a 32% incidence rate of pressure ulcers in African-American and Latino patients versus the typical incidence rate of 11% for all patients in that setting.[2] Individuals with darker skin often have a higher incidence or prevalence of full thickness pressure ulcers than individuals with light skin. Amlung and colleagues reported that rates of full-thickness ulcers (Stage III or IV) were highest in patients

with darker skin (58% of ulcers observed in American Indians, 54% for Pacific Islanders, and 40% for African Americans/Blacks). Caucasian/white (non-Hispanic) and Asian patients had the highest rate of Stage I pressure ulcers (48% for each group).[57] Barczak and colleagues found a 41% prevalence of full-thickness ulcers in African-American patients versus 20% in Caucasian patients in acute care hospitals.[3] Fuhrer and colleagues found a significant relationship between race and ulcer severity in individuals with spinal cord injury, reporting a 69% prevalence of Stage III or IV ulcers in African-American patients versus 32% for Caucasians.[4] Meehan and colleagues found that African-American acute care patients had the largest percentage of Stage IV ulcers of any ethnic group.[5] Bergstrom and Braden found that the first pressure ulcer diagnosed in non-Caucasian institutionalized elderly patients was more likely to be Stage II or higher than Stage I.[6]

2.4 CHALLENGES OF PRESSURE ULCER DETECTION IN INTACT SKIN

Many studies have suggested that higher stage ulcers are more prevalent in patients with dark skin because indicators of pressure damage in intact skin are difficult to detect in the presence of high skin pigmentation.[3,4,6-10,75] Traditionally, the blanch response as been used as one of the main indicators of pressure damage in intact skin. Healthy light skin appears pink in color because of blood flowing through vessels in the skin. When gentle pressure is applied to the skin, it temporarily becomes whiter in color, or "blanches", as blood is displaced from the area where pressure was applied. This change in color is known as the blanch response. Exposure to damaging pressure is thought to produce the engorgement and eventual hemorrhage of vessels in the papillary dermis.[78,79] These changes prevent the normal displacement of blood from the skin in response to gentle pressure. The result of this disruption is an area of "nonblanchable erythema of intact skin", as stated in the National Pressure Ulcer Advisory Panel (NPUAP)'s 1989 definition of a Stage I pressure ulcer (Table 2). Because of its high level of pigmentation, dark skin typically does not blanch visibly even when it is healthy, making it difficult to detect pressure ulceration in intact skin by observing color changes in the skin alone.[9] The NPUAP revised its Stage I pressure ulcer definition in 1992 and 1998 to include other indicators of pressure damage, including changes in skin temperature, tissue consistency, or sensation (Table

2).[62,80] However, the use of examination gloves, ambient fluorescent lighting, and difficulty communicating with patients at risk due to aphasia or impaired cognitive status make alternate indicators of pressure damage difficult to assess in clinical settings.[9]

Table 2. NPUAP's original and revised Stage I definitions

Year	NPUAP Stage I Definition
1989	Nonblanchable erythema of intact skin; the heralding lesion of skin ulceration.
1992	Nonblanchable erythema of intact skin; the heralding lesion of skin ulceration. In individuals with darker skin, discoloration of the skin, warmth, edema, induration, and hardness may also be indicators.
1998	An observable pressure-related alteration of intact skin whose indicators as compared to an adjacent or opposite area on the body may include changes in one or more of the following: skin temperature (warmth or coolness), tissue consistency (firm or boggy feel), and/or sensation (pain, itching). The ulcer appears as a defined area of persistent redness in lightly pigmented skin, whereas in darker skin tones, the ulcer may appear with persistent red, blue, or purple hues.

2.5 BENEFITS OF IMPROVED BLANCH RESPONSE DETECTION IN INTACT SKIN

A number of research findings associate pressure ulcers in intact skin with the development of higher-stage ulcers. Allman and colleagues found that 57.9% of hospitalized patients with Stage I pressure ulcers later developed Stage II or higher pressure ulcers at that site.[11] Halfens and colleagues found that 22% of Stage I pressure ulcers in acute care and 8.7% of Stage I ulcers in long-term care deteriorated to a higher stage.[12] Berlowitz and colleagues found that long-term care residents with Stage I pressure damage were twice as likely to develop a Stage II or higher ulcer than those without a Stage I ulcer.[13] Higher stage ulcers are associated with significant medical complications, costly treatment, and increased mortality.[14-17]

Considerable debate exists regarding whether lesions described as Stage I, typically associated with nonblanchable erythema, represent superficial pressure damage alone or may

indicate existing necrosis beneath intact skin that has not yet become an open wound, a lesion described as "pressure-related deep tissue injury under intact skin".[50] In either case, improved detection of nonblanchable erythema may assist clinicians in treating existing damage and preventing progression. If an area of nonblanchable erythema represents damage to superficial skin layers alone, later development of an open wound may occur if damage in the area progresses to involve deeper tissue layers. In this case, improved detection of nonblanchable erythema may facilitate earlier intervention to prevent damage to deeper tissue layers and their associated costs and complications. Alternately, an area of nonblanchable erythema may be a sign that necrosis is already present in deeper tissue layers and that the area will inevitably become an open wound. In this case, improved detection of nonblanchable erythema would facilitate faster initiation of interventions to treat existing damage.

Improved detection of nonblanchable erythema would also assist in reducing pressure ulcer-related health disparities between light and dark-skinned patients at risk for pressure ulcers. Research findings that higher rates of full thickness ulcers are present in darker-skinned individuals compared to those with light skin suggest that signs of pressure damage in intact dark skin are more difficult to detect, leading to progression of pressure damage without appropriate intervention. Furthermore, age-adjusted mortality rates have been reported to be more than 4 times higher in African-Americans with pressure ulcers compared to Whites with pressure ulcers.[75] Improved identification of nonblanchable erythema would enable clinicians to identify signs of pressure damage more readily in those with dark skin, facilitating their ability to provide prevention and treatment interventions in a manner similar to those of light-skinned individuals, and reducing the likelihood of fatal complications in those with dark skin.

Improved detection of nonblanchable erythema would also provide more accurate data on the clinical course, incidence, and prevalence of pressure ulcers. Information on the timing of pressure damage development would be more accurate if pressure damage could be identified in intact skin, rather than delaying diagnosis until an opening in the skin is observed. Incidence and prevalence data are incomplete without an accurate means of pressure damage detection in intact skin. Several incidence and prevalence estimates have intentionally excluded individuals with Stage I pressure ulcers because of the uncertainties involved with detecting these lesions.[13,16,18-20] An accurate means of pressure damage detection in intact skin would improve the quality of

prevalence and incidence data that is essential to understand the clinical course of pressure ulcers, evaluate treatment and prevention outcomes, and develop health policy goals.

3.0 TECHNOLOGY TO IMPROVE PRESSURE DAMAGE DETECTION

3.1 THE NEED FOR TECHNOLOGY

At present, clinical assessment of nonblanchable erythema is limited to the manual blanch test. In this test, an examiner observes the color of an area of skin, applies gentle pressure to the area with his/her index finger, removes his/her finger, and then inspects the skin to determine if lightening of the skin area—the "blanch response"—occurred as a result of pressure applied to the skin. An alternate method of assessing the blanch response is to use a transparent material, such as a watch glass or microscope slide, instead of one's finger to apply pressure to the skin. This method allows the examiner to observe color changes that may occur while pressure is being applied, as opposed to immediately after pressure application. In both manual blanch test methods, the absence of blanching is considered a sign that pressure damage is present in the region that was examined.

As described in the previous chapter, the manual blanch test is not effective in highly-pigmented skin because color changes are difficult to observe visually, even in healthy skin, due to the presence of the skin's pigment. Furthermore, the results of the manual blanch test are subject to interpretation by the observer, and are likely to be influenced by the skill and experience of that observer. The manual blanch test also does not provide quantitative data on pressure damage. There is a great need for an objective measure of nonblanchable erythema that is effective in both light and dark skin.

A variety of non-invasive technologies provide objective measures of indicators of tissue viability or tissue damage. Transcutaneous oxygen measurement, laser Doppler flowmetry, and temperature measurement have been used as measures of tissue viability in a variety of pressure ulcer-related research studies. More recently, ultrasound has been suggested as a means of assessing pressure-related tissue damage. While each of these technologies provides information

that relates to tissue viability or damage, none has been used to measure the blanch response or has been shown to otherwise address the challenges of pressure damage detection in darkly pigmented intact skin. Another technology, known as tissue reflectance spectroscopy (TRS), shows promise in improving blanch response detection in light and dark intact skin through its ability to obtain information on both skin pigmentation and blood content. The following sections provide an overview of existing non-invasive technologies for assessing tissue viability and discuss how TRS may improve pressure damage assessment by detecting a blanch response in skin regardless of its pigmentation.

3.2 TECHNOLOGIES IN CURRENT USE

3.2.1 Laser Doppler Flowmetry

3.2.1.1 Measurement Principles and Instrumentation

Laser Doppler flowmetry (LDF) is a measure of blood flow. In this technique, monochromatic laser light is transmitted to tissue via optical fibers encased in a probe applied to the surface of the tissue.[81-84] This light is typically red and is often emitted by a helium neon laser source. A second optical fiber in the probe collects light backscattered from the tissue. Information on blood flow is obtained from the backscattered light using the "Doppler effect". Through the Doppler effect, light striking a moving object, such as a red blood cell, undergoes a shift in frequency that is proportional to the velocity of the moving object.[82,83] The light collected from the tissue consists of light of the same frequency as that transmitted to the tissue and light that has experienced a Doppler shift caused by reflection off a moving object.[82] These two frequencies of light interact to create a "beat frequency" which is measured by photodetectors in the LDF device that subsequently create a voltage output.[82,85] The LDF device then calculates a quantity known as "flux" which is considered a function of the number of moving red blood cells in the sampling volume multiplied by the mean net velocity of their movement.[82,84]

LDF provides information on superficial tissue layers. Its depth of penetration is estimated to be 0.5–1.5 mm with penetration up to 2 mm in tissue containing few light-absorbing species.[81,82,84,86] The area of tissue sampled with a probe mounted on the surface of the skin is

small, estimated at 1 mm^2.[81,82] More complex laser Doppler imaging devices, which move the laser beam over an area of tissue, creating a 2-D image of flux information, can sample much larger tissue areas.[81]

3.2.1.2 Applications

LDF may be used to measure blood flow in a variety of clinical fields, including vascular surgery, dermatology, and plastic surgery.[87] LDF has been used in several studies related to pressure ulcers. LDF has been used to evaluate the effects of externally applied pressure on skin blood flow in both healthy participants and those at risk for pressure ulcer development.[88-91] The influence of different body positions and various support surface types on blood flow has also been studied using LDF.[92,93] Investigators have also used LDF to evaluate the effects of pressure experienced during surgical procedures and have studied the association between blood flow measured by LDF and subsequent pressure ulcer development.[94,95] LDF has also been used to characterize differences between pressure-damaged and normal tissues.[96,97]

3.2.1.3 Considerations

Several factors must be considered when interpreting LDF measurements. LDF devices express output in arbitrary units that do not provide absolute measures of tissue perfusion[83,84], although data expressed in absolute units may be estimated using theoretical models.[98] LDF is also known to show a flux signal even in tissue samples where blood flow has been completely occluded, suggesting some degree of background noise in the LDF signal.[84] Some have suggested that this "biological zero" should be subtracted from the total LDF signal before data analysis. LDF also does not provide information on the sources of flux in the tissue—all types of vessels in the sampling area contribute to the flux measurement.[83] Finally, LDF measurements are highly variable over time and location.[81,84]

3.2.2 Transcutaneous Oxygen Monitoring ($TCPO_2$)

3.2.2.1 Measurement Principles and Instrumentation

Transcutaneous oxygen monitoring ($TCPO_2$) is used to provide information on the presence of oxygen gas in blood and tissue.[83,99] In this technique, a small chamber is attached to the surface

of the skin using an adhesive ring. A few drops of solution are placed in the chamber and a transcutaneous gas probe connected to a monitoring device is attached to top of the chamber. The probe contains a heating element which warms the skin to approximately 42-45°C, depending on the device. Heat has several effects that facilitate diffusion of blood gases through the skin and into the chamber.[83] First, heat changes the structure of the stratum corneum, the outermost layer of the epidermis, such that it becomes more permeable to oxygen diffusion. Second, heat causes capillaries in the dermis to become hyperemic, bringing more gas-containing blood into the sampling region. Third, heat from the probe warms the blood, facilitating oxygen dissociation. Gases emerge from the tissue and enter the chamber where an electrochemical reaction takes place that can be measured by an electrode in the probe.[83,96]

3.2.2.2 Applications

Clinically, $TCPO_2$ is most frequently used to estimate arterial oxygen pressure in infants, whose thin epidermis allows greater diffusion of gases than in adults.[83,99,100] Other clinical applications include evaluation of peripheral hypoxia to determine prognosis for wound healing and assist in treatment selection.[101,102]

$TCPO_2$ has been used in several research studies related to pressure ulcers. Several researchers have used $TCPO_2$ to evaluate the effect of externally applied forces (pressure and/or shear) over bony prominences in healthy adults and those at risk for pressure ulcer development.[48,89,90,100,103,104] $TCPO_2$ has also been used to compare the effects of various kinds of bed support surfaces and seat cushions on tissue oxygen content.[93,103,105-107] Investigators have also characterized tissue oxygenation in pressure-damaged versus healthy skin using $TCPO_2$ measurements.[96]

3.2.2.3 Considerations

Heating is required in $TCPO_2$ to enable gases to reach the probe. However, it has been reported that some individuals undergoing $TCPO_2$ measurement experienced burns from the probe, requiring adjustment of the warming temperature and/or periodic changes in sensor position to prevent burns.[83,100,105] Individuals at risk for pressure ulcers may have a variety of conditions that affect skin fragility or impair thermoregulation, making the potential for burns a serious concern. In addition, those with conditions that impair vasodilation may show falsely low

$TCPO_2$ readings compared to those without such conditions because they do not experience changes in blood flow that facilitate diffusion of gases present in blood and tissue.[108] In addition, $TCPO_2$ measurements require a stabilization period of 15-20 minutes after application of the probe before readings can be taken, increasing the length of measurement protocols.[83] $TCPO_2$ equipment must also be calibrated frequently.[99] Finally, errors in gas measurement may be introduced if the chamber on the skin is inadequately sealed, allowing gases from the external environment to enter the chamber.[99]

3.2.3 Skin Temperature Measurement

3.2.3.1 Measurement Principles and Instrumentation

Skin temperature is frequently used as a measure of tissue viability, and is described by NPUAP as one of the possible indicators of Stage I pressure ulcers.[80] The temperature of skin is influenced primarily by blood perfusion, although heat produced by metabolic activity may also contribute to skin temperature.[109] Skin temperature may be measured using contact or non-contact methods. Thermistor probes, thermocouples, and liquid crystal thermometers attached directly to the surface of the skin may used to measure temperature.[32,92,110,111] Thermography is a non-contact technique that uses an infrared-sensitive camera to measure heat energy emitted from the skin in the form of infrared radiation, creating a 2-D image of heat emission from the region of interest.[109,112]

3.2.3.2 Applications

Thermography has been used to monitor a variety of health conditions, including inflammatory diseases, muscle injuries, diminished enervation, and frostbite.[112] Pressure ulcer researchers have used skin temperature measurement via contact sensors or thermography as an indicator of tissue perfusion or tissue damage. Skin temperature measurements were used to evaluate the response of tissue to external pressure application in healthy participants and those at risk for pressure ulcers.[92,105,109] Researchers have examined the relationship of skin temperature to subsequent pressure ulcer development in those at risk for pressure ulcers order to identify indicators of impending ulceration.[110,113] Temperature has been used to characterize discolored areas near bony prominences to determine if temperature measurements differentiate pressure

damaged versus healthy skin.[32,111] One animal study applied thermographic assessment of skin to the problem of identifying deep tissue injury under intact skin (DTI).[114] Skin temperature measurements were correlated with histological examination and classification of wounds induced in pigs. No differences in skin temperature were noted between normal and DTI sites, but when a cold stimulus was applied to the area, DTI sites showed a cooler skin temperature relative to surrounding skin than did normal sites. More research is needed to determine what role skin temperature measurement plays in assessment of DTI.

3.2.3.3 Considerations

Highly controlled environments are critical for conducting skin temperature measurements.[109] Fluctuations in external temperature create a confounding variable that complicates the interpretation of skin temperature changes. Particularly in cases when temperature is being measured at the skin-support surface interface, the heat insulating or conduction properties of the surface must be considered when interpreting skin temperature data. One researcher reported that thermographic findings did not correspond well with blood flow measures, suggesting that warmth at the skin surface resulted from the insulating properties of the support surface rather than an increase in blood flow.[105]

3.2.4 Ultrasound Imaging

3.2.4.1 Measurement Principles and Instrumentation

Ultrasound uses sound waves to obtain images of body structures. Ultrasound devices include a transducer that converts electrical energy to sound waves.[115] To obtain an image, the transducer is placed in contact with skin to which a coupling medium, typically gel, has been applied to allow transmission of sound waves from the transducer to the body.[116] Sound waves entering the body are absorbed, reflected, or scattered by tissues. "Echoes" are created at areas of transition between tissues with different densities or elastic properties.[112,116] Sound waves that are reflected back to the transducer are converted to electrical signals that are displayed visually by the device. Most ultrasound imaging uses B-mode (brightness mode) ultrasound, in which the device creates a cross-sectional image of the structure being examined.[115,116] Bright, or hyperechoic, areas correspond to structures containing a number of internal density transitions

that create backscattering of sound waves. Dim, or hypoechoic, areas arise from structures lacking internal density transitions, including fluids. Abnormalities in tissue may be identified by patterns of echogenicity that differ from healthy tissues.

The depth and resolution of ultrasound images depends on the frequency and power of sound produced by the transducer. Most conventional diagnostic imaging ultrasound devices operate in the 2-10 MHz range, with frequencies of 3.5 MHz recommended for deep scanning in adults.[115,117] More recently, high frequency devices using 20 MHz or greater sound waves have been developed to visualize superficial structures (less than 2 cm deep) with greater resolution than that of conventional ultrasound.[116-119]

3.2.4.2 Applications

Conventional ultrasound devices are widely used in clinical practice for diagnostic imaging of abdominal structures, developing fetuses, major blood vessels, musculoskeletal structures, and breast tissue.[115,120] High-frequency devices have been used clinically to examine skin lesions (skin cancers, psoriasis, scleroderma)[117,118], ophthalmic structures, vascular structures, and cartilage.[121]

Ultrasound assessment of wounds is not widespread, but has been reported in some investigations. Conventional ultrasound has been used to make volumetric measurements of chronic wounds up to 6 cm deep[122], measure burn scar depth[123], and scan post-surgical hip wounds for the presence of subcutaneous hematomas.[124] High-frequency ultrasound has been used to assess skin thickness in chronic wounds[97], and to measure depth and width of healing wounds created by punch biopsy[119,125,126] or cryosurgical removal of basal cell carcinoma.[127] Experts in the pressure ulcer field have suggested that ultrasound may be a valuable tool in assessing pressure damage, but there are little research data specific to pressure ulcer assessment by ultrasound.

3.2.4.3 Considerations

Ultrasound imaging requires a skilled operator for appropriate interpretation of images.[128] Ultrasound also requires the use of a gel or other medium to transmit sound waves to the tissue. Skin hydration due to these media may change the properties of the wound being evaluated, and efforts must be made to protect open wounds from contamination by gel.[97,119] The irregular

shape of wound sites further complicates imaging by making it difficult to maintain appropriate pressure and orientation of the transducer in order to avoid artifacts.[97,117] More information is needed to determine the feasibility and value of ultrasound imaging to assess pressure-related tissue damage.

3.3 EMERGING TECHNOLOGY: TISSUE REFLECTANCE SPECTROSCOPY

While laser Doppler flowmetry, $TCPO_2$, skin temperature measurement, and ultrasound are capable of providing information that relates to tissue damage, none of these technologies has yet been demonstrated to address the challenges of pressure damage detection in darkly pigmented intact skin. Pressure ulcer researchers have recently begun to explore the capabilities of another technology, known as tissue reflectance spectroscopy (TRS). TRS is a non-invasive method that uses light reflected from the skin to obtain information about the type and concentration of biochemical substances present in the skin tissue, such as melanin and hemoglobin. While TRS has been used in animal and human-subjects research studies for several years, the application of TRS to pressure damage assessment is relatively new. This section describes the mechanisms by which TRS provides information on factors relevant to tissue viability, and explores how TRS may improve the detection of pressure damage in darkly-pigmented intact skin by measuring the blanch response regardless of skin pigmentation.

3.3.1 Optical Properties of Skin Tissues

Light shone on the skin may be reflected, absorbed, or scattered. Approximately 5% of incident light is reflected off the outermost layer of the skin without entering the tissue.[129,130] Light that penetrates the surface of the skin may encounter a number of light-absorbing species, known as chromophores. The primary chromophores in skin include melanin in the epidermis and oxyhemoglobin (HbO_2) and deoxyhemoglobin (Hb) in the plasma of the dermal vessels.[129-131] Light that enters skin tissue also experiences considerable scattering due to differences in the refractive index of various tissue constituents, including collagen, cell membranes, intra and

extra-cellular fluids, mitochondria, ribosomes, and fat globules.[130-132] A portion of the light transmitted to the skin re-emerges as diffuse reflectance, which includes light that has been reflected and scattered within tissue.[133]

3.3.2 Measurement of Tissue Reflectance

Instrumentation used to measure tissue reflectance consists of several components, including a light source, fiber optics, and a spectrophotometer.[131,134] Quartz tungsten halogen light sources are frequently used to provide visible (400-700nm) and near-infrared (700-2500nm) illumination to the tissue.[23,24,31,131] Light in these ranges is considered to be non-ionizing, and falls below the longer infrared wavelengths capable of causing superficial thermal injury to skin.[135] Light from the source is carried to the skin via fiber optics.[134] A second set of fiber optics carries diffusely reflected light from the tissue to a spectrophotometer. The spectrophotometer contains photodetectors that convert light (photons) into electrical signals that are a function of the amount of light reaching the photodetector and the duration of light exposure.[131] Most photodetectors respond to light in milliseconds, providing fast readout of reflectance information from the tissue.[131]

The spacing of the illumination and collection optodes and the wavelengths of light transmitted to the tissue influence the depth of tissue sampled by the spectroscopy system. The path light takes between the illumination and collection optodes is thought to be "banana shaped" such that the maximum depth of tissue sampled falls between the optodes.[134] The greater the separation between the optodes, the greater the depth of light penetration. Inter-optode spacing of a millimeter of less is used to sample surface tissues[131], where as spacing of several centimeters may to used to sample deeper tissues such as muscle or brain tissue.[134] The sampling depth desired must be balanced with signal to noise levels as noise also increases with increased inter-optode spacing.[134] Sampling depth also increases with longer wavelengths of illumination. Depths of several centimeters may be sampled using near-infrared illumination, whereas shorter wavelengths in the visible and mid-infrared range may penetrate millimeters or less in the tissue.[134] Longer-wavelength near-infrared light is not as readily absorbed by tissue as light of shorter wavelengths, such as mid-infrared or visible light.[131] Its reduced absorption

allows near-infrared light to travel farther into the tissue before it is attenuated. Near-infrared light is also highly scattered, which may facilitate its travel to deeper tissues.[131]

The spectrophotometer calculates a quantity known as "log inverse reflectance" (LIR) which approximates the absorbance of light by the tissue.[22] LIR is calculated using the intensity of diffusely reflected light from the skin and light reflected from a white surface, recorded prior to taking measurements from the skin, as follows:

$$LIR = \log_{10} (\text{intensity of light reflected from white surface/intensity of light reflected from tissue})$$

The spectrophotometer displays an absorbance spectrum based on the calculated LIR. Light wavelength in nanometers is plotted along the x-axis of the spectrum, and the absorbance of light at each wavelength (expressed as "optical density") is plotted on the y-axis of the spectrum. Peaks in the spectrum represent regions of high light absorption (maxima) and valleys represent regions of low absorption (minima). Typical skin spectra recorded from light and dark healthy skin are shown in Figure 1.

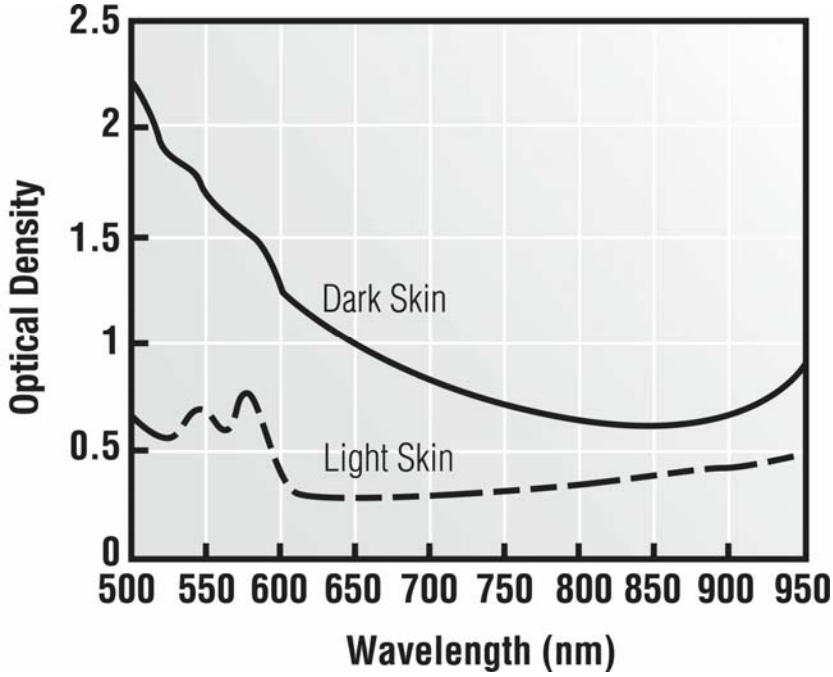

Figure 1. Typical spectra of light and dark skin

3.3.3 Derivation of Hemoglobin Data from Tissue Spectra

Tissue spectra provide information on the type and concentration of chromophores in the skin tissue. The shape of the spectrum obtained from the skin is a result of contributions from each of the skin's chromophores, principally melanin, oxyhemoglobin (HbO_2) and deoxyhemoglobin (Hb). Each of these chromophores absorbs light in unique patterns (Figure 2).[24,131] HbO_2 shows two absorption maxima in the visible light range near 540 and 577 nm, while Hb shows one maximum near 555 nm. Melanin's light absorption is high in the visible range, but decreases steadily toward the near-infrared region with very little absorption beyond 1100 nm.[24,131] The shape of the skin spectrum may be considered a composite of the shapes of the chromophores' spectra. This is particularly evident in the visible region. In lightly pigmented skin, two absorbance maxima and an absorbance minimum are clearly visible between 500 and 600 nm as a result of the combined presence of HbO_2 and Hb in the tissue. In darkly pigmented skin, the skin spectrum has a sloped shape in this region, due to the contribution of melanin. Thus, spectral shape provides information on the types of chromophores present in the tissue.

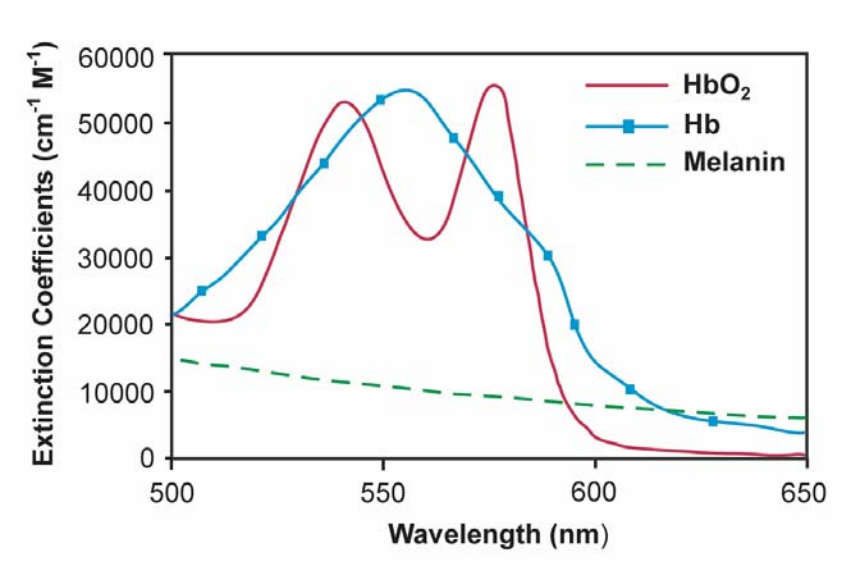

Figure 2. Spectra of hemoglobin (HbO_2)[136], deoxyhemoglobin (Hb)[136], and melanin[137] in the visible light region

While spectral shape provides information about the types of chromophores present in the skin, the amount of absorption provides information about the concentration of each of the chomophores present. For non-scattering media, absorbance (approximated by LIR) is directly proportional to the concentration of chomophores in the sample and the distance traveled between the illumination and collection optodes, as described by the Beer-Lambert Law[134]:

$$A = \sum C_i \varepsilon_i d$$

C_I = Concentration of i^{th} species, ε_i = Molar absorptivity of i^{th} species, d = Inter-optode distance

Thus, the concentration of a substance in a non-scattering medium can be assessed quantitatively using absorbance data. In a highly scattering medium such as skin, photons of light do not travel in a straight line between the illumination and collection optodes. Light follows any number of paths on its way to the collection fiber, such that the distance traveled in the tissue exceeds the inter-optode distance.[131,134] Absorbance in scattering media is described via a modified version of the Beer-Lambert Law, where a "differential pathlength factor" (DPF) is added to the expression to account for the difference between the actual pathlength traveled in the sample and the inter-optode distance[134]:

$$A = \sum C_i \varepsilon_i d \, DPF$$

Estimates of DPF fall in the 4–6.5 range, meaning that photons of light may travel a distance at least 4 times greater than the inter-optode distance.[134] Because DPF cannot be known exactly in highly scattering media such as skin, it is difficult to quantify the absolute concentrations of chromophores in skin. However, absorbance is considered a measure of relative concentration of the chromophores in the tissue sampled.[24]

Several researchers have developed TRS data analysis algorithms that account for the presence of melanin in the skin, allowing the concentrations of hemoglobin and deoxygenated hemoglobin to be measured in individuals with various levels of skin pigmentation.[21-26] One approach is to calculate indices for hemoglobin and melanin content. Dawson and colleagues calculated an "erythema index" (*E*) based on the area under the skin spectrum between 510 and 610 nm.[22] Dawson then adjusted *E* for skin pigmentation using a "melanin index" based on the differences in absorption at wavelengths in the 645-655 nm range compared to the 695-705 nm range. Feather and colleagues reported that the erythema index described by Dawson was

influenced by blood oxygenation, and described a new "hemoglobin index" (*H*) derived from absorbance data at isobestic points—wavelengths where absorption for oxyhemoglobin and deoxyhemoglobin are the same.[26] Feather calculated *H* via the difference in absorption gradients calculated for two sets of isobestic points (544 and 527.5 nm; 573 and 544 nm). Ferguson-Pell and Hagisawa calculated an index of blood content (IHB) using the method of Feather, but developed a melanin index (IMEL) for each tissue sample based on "bloodless" spectra obtained by applying firm finger pressure to the area of interest.[21] IMEL was calculated based on the linear regression of bloodless spectrum data in the 500-600 nm range.

Others have used regression analysis to calculate relative concentrations of hemoglobin in tissue. Riordan and colleagues scaled the slope of an in-vitro, concentration-independent absorption curve for melanin by the difference in absorption between 500 nm and 625 nm for each tissue spectrum of interest.[23] The scaled melanin spectrum was then subtracted from the corresponding tissue spectrum. The resulting spectrum was regressed against a standard in-vitro, concentration-independent absorption curve for hemoglobin. The resulting regression coefficient was considered a measure of hemoglobin concentration in the tissue. Matas and colleagues[24] calculated tissue hemoglobin content using regression analysis and in vitro extinction coefficients, a measure of the light absorbed by a 1 mole/liter solution of a pure substance measured in a 1 cm light path.[138] Matas and colleagues calculated the relative concentrations of Hb, HbO_2, and melanin by performing non-negative least squares fits of tissue spectra to the extinction coefficients for each of these species, including an offset term to account for light scattering. Total hemoglobin was calculated as the sum of the coefficients produced for Hb and HbO_2.

3.3.4 Research Applications of Hemoglobin Monitoring via Spectroscopy

TRS has been used to characterize hemoglobin content or oxygenation in a variety of animal and human studies. Several investigators have used TRS to monitor hemoglobin content in animal skin flaps[139-141] and to characterize burns in a porcine model.[142] In human subjects, investigators have demonstrated the ability of TRS to measure real-time changes in Hb and HbO2 content associated with arterial or venous occlusion during forearm occlusion protocols.[21,27,143] Muscle oxygenation has been assessed using TRS during exercise[29,144,145] or post-occlusive reactive

hyperemia[146] in healthy individuals and those with vascular disease. Cerebral oxygenation has been measured with TRS during motor tasks[147,148] or orthostatic stress.[28,149]

TRS has also been used to monitor hemodynamic changes in human skin exposed to external loading. Investigators have successfully used TRS to track pressure-induced reactive hyperemia in participants at risk for pressure ulcers, including participants with spinal cord injury and below-knee amputation.[30,31] TRS has also been shown to distinguish pressure-induced erythmatic sites from non-erythmatic sites with high levels of reliability (ICC 0.80-0.99), sensitivity (0.74 to 0.90) and specificity (0.64 to 0.91) in light and dark-skinned healthy participants using a variety of analysis algorithms.[23] TRS instrumentation has also been developed to monitor blood content changes in residual limbs to which a compressive garment has been applied.[150]

3.3.5 Pressure Damage Detection in Intact Skin via Spectroscopic Assessment of the Blanch Response

TRS provides a means of improving pressure damage detection in light and dark intact skin because of its ability to measure hemoglobin despite the presence of skin pigmentation. As described in Chapter 2, the blanch response is frequently used as an indicator of pressure damage in intact skin. In a clinical blanch test, whitening or "blanching" of the skin occurs with pressure application due to the displacement of blood from beneath the area where pressure is applied. While blanching cannot be observed visually in dark skin, a "spectroscopic blanch response" can be quantified by comparing the total concentration of hemoglobin in skin in its resting state to that of skin during gentle pressure application.[24] Because a variety of algorithms exist to account for the presence of melanin in the spectral signal, it is possible to measure the spectroscopic blanch response in both light and dark-skinned individuals.

Two recent studies have used TRS to quantify the blanch response in light and dark skin. Matas and colleagues applied pressure to the outer forearm of healthy participants whose skin visibly blanched with manual pressure (light skin group) and healthy participants whose skin did not blanch visibly (dark skin group).[24,25] Cyclic loads of up to a maximum of 50 mmHg were applied to the dorsal forearm via a fixed benchtop device containing a stepper motor, pressure sensor, and fiber optic probe. A statistically significant decrease in total hemoglobin was

detected in both the light and dark skin groups. These results indicate that a blanch response can be "seen" with spectroscopy even when no visible color changes are identified with visual inspection. Sprigle and colleagues assessed the blanch response in participants receiving inpatient and outpatient rehabilitation services.[32] Spectroscopic and manual blanch tests were conducted over areas of discoloration near bony prominences. Spectroscopic blanch tests were performed using an indenter containing a fiber optic probe and pneumatically driven piston that applied 150 mmHg pressure to the skin. Spectroscopic data from clinically blanching sites differed from that of clinically non-blanching sites, but there was wide variation in the extent of blanching measured by spectroscopy. More information is needed to determine the diagnostic value of spectroscopic blanch response assessment.

4.0 PILOT STUDY TO DETECT THE BLANCH RESPONSE IN LIGHTLY AND DARKLY-PIGMENTED SKIN USING TISSUE REFLECTANCE SPECTROSCOPY

4.1 GOALS AND OBJECTIVES

Little data exist in the literature describing spectroscopic assessment of the blanch response at sites at risk for pressure ulcer development. Therefore, a pilot study was conducted to establish a reliable protocol to assess the blanch response in lightly and darkly pigmented healthy skin using a portable reflectance spectroscopy system. The pilot study had two objectives: (1) to determine if a significant decrease in total hemoglobin can be observed when pressure is applied to light and dark healthy skin, and (2) to assess the intra-rater reliability of spectroscopic blanch response measurement in participants with healthy skin.

4.2 METHODS

4.2.1 Participants

Eligible participants were healthy, able-bodied males and females aged 18–50 years. Participants were excluded from the study if they (1) had skin disorders that produced scarring, flaking, rash, or discoloration of the skin at the sacrum or the dorsal aspect of the heel, (2) were diagnosed with diabetes, pulmonary disease, renal disease, collagen vascular disease or clotting disorders, (3) were taking vasoactive medications, or (4) were unable to lie prone and semi-sidelying without difficulty.

A total of 30 participants were recruited for this study, 15 with dark skin and 15 with light skin. Skin color classification was determined by manually applying gentle pressure to the

outer forearm of each participant. Participants whose skin showed no visually observed color change in response to pressure were placed in the dark skin group. All others were placed in the light skin group. The manual blanch test has been used both clinically and in previous investigations to define light versus dark skin.[9,24,32]

Participants' skin at the heel and sacrum was also matched to Munsell color tiles (Figure 3). Munsell color tile matching has been used in previous investigations to facilitate description of color.[23,151-153] The Munsell Color-Order system assigns alphanumeric designations to color samples based on three qualities: hue, value, and chroma.[153] The value quantity describes the lightness or darkness of a color, ranging from 0 for pure black, to 10 for pure white. The 5YR Munsell color tile card consisted of 33 tiles arranged in 7 rows of 2-6 tiles each mounted on neutral grey flexible cardboard. The card included tiles of Munsell value 2.5, 3, 4, 5, 6, 7, and 8 and Munsell chroma 1, 2, 3, 4, 6, and 8. The tiles were perforated to allow close comparison of each tile to the participant's skin. The investigators recorded the Munsell value and chroma of the tile that best matched each participant's skin at the heel and sacrum.

All study procedures, risks, and benefits were discussed and informed consent provided prior to the beginning of any study procedures in compliance with the policies of the Institutional Review Board at the University of Pittsburgh.

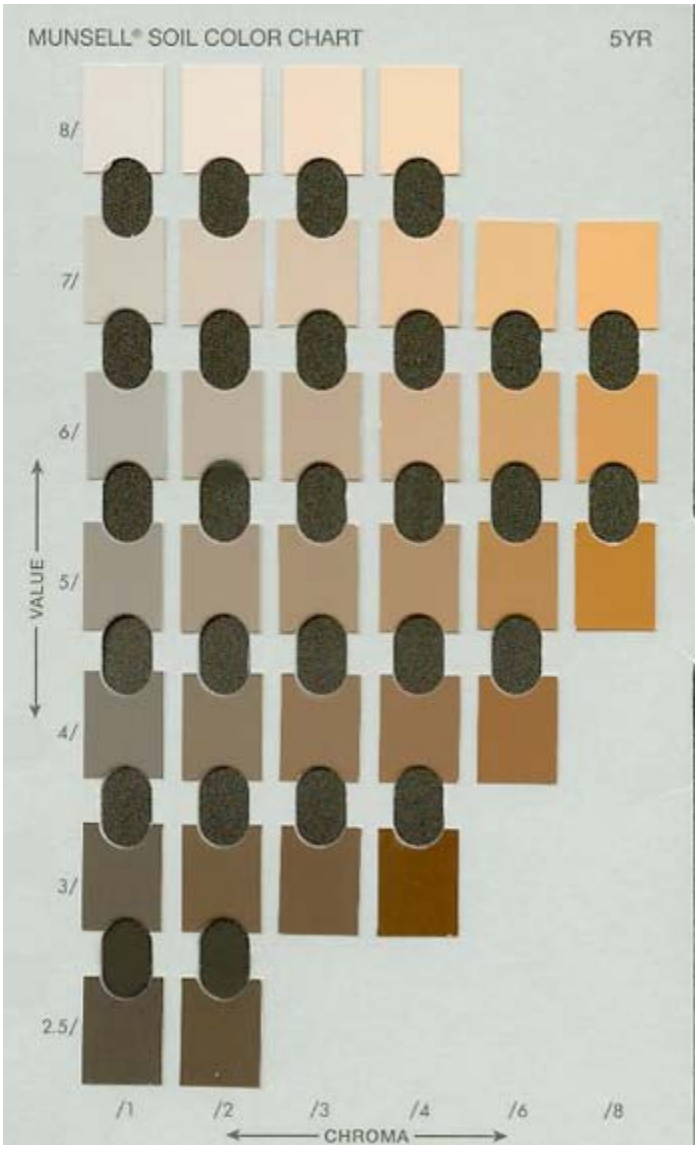

Figure 3. 5YR Munsell color tile card

4.2.2 Instrumentation

Skin reflectance data were acquired using a spectroscopy system made up of four major components (Figure 4): a spectrophotometer (Ocean Optics, Dunedin, FL, Model SD2000), a 100W quartz tungsten halogen light source (Oriel Industries, Stratford, CT, Model 77501), a bifurcated fiber optic reflectance probe (Fiberguide Industries, Caldwell, ID), and a computer with data acquisition software (OOIBase32, v. 2.0.0.3, Ocean Optics, Inc., Dunedin, FL). The probe included an outer ring of 32 illumination fibers and 7 central collection fibers. The collection and illumination fibers were separated by 1 mm. A custom-designed spring assembly and indenter head (radius 7.5 mm) were fabricated and mounted onto the fiber optic probe to allow the examiner to apply gentle pressure (up to 120 mmHg) to the skin (Figure 5), mimicking the pressure applied with the index finger during clinical assessment of the blanch response. The outer edge of the probe head was machined with a 0.9 mm radius of curvature to minimize edge effects. The radius of curvature was optimized using finite element modeling to minimize stress concentrations at the perimeter of the head.[154]

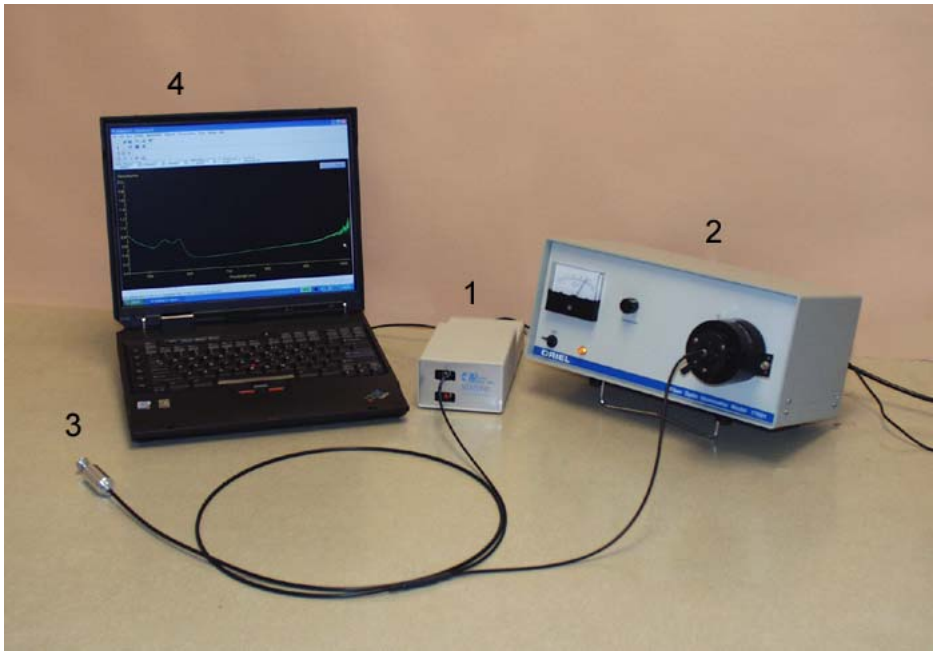

Figure 4. Spectroscopy system composed of: (1) spectrophotometer (2) light source (3) fiber optic probe (4) laptop computer

Figure 5. Fiber optic probe with indenter head and spring assembly

4.2.3 Procedures

The light source was allowed to warm up for at least 30 minutes prior to the participant's arrival. After this period, dark and reference spectra were recorded for later calculation of optical density. Reference spectra were recorded from a white reflectance standard (Halon, >97% reflectivity, StellarNet, Inc., Tampa, FL).

Informed consent was obtained, eligibility was verified, and skin color group classification was determined as described above. A total of six skin reflectance measurements were obtained at each body site (heel and sacrum): three with the participant positioned in prone, and three with the participant positioned in semi-sidelying (approximately 60° from supine). Each measurement contained spectra obtained in light contact and gentle pressure conditions. All spectra were acquired at a rate of 1 spectrum/second. The heel test site was located at the dorsal aspect of the heel, over the most prominent part of the calcaneus. The sacral test site was located at the apex of the curve of the sacrum, approximately 1 to 1.5 inches superior to the beginning of the gluteal cleft. The heel to be tested (left vs. right), and the order of body site testing and body positioning were determined using a coin flip.

The participant was asked to lie in position 1 (either prone or semi-sidelying) on a padded mat table. Pillows were provided as needed to provide support, comfort, and minimize movement during the study procedures. The skin over site 1 (either heel or sacrum) was inspected to verify that it was free of scarring, flaking, rash, or discoloration. A piece of transparent double-sided tape was applied to site 1 to mark the site and minimize movement of

the fiber optic probe during data acquisition. The investigator then placed the fiber optic probe in light contact (<5 mmHg) with the tape over the skin at site 1. Previous studies have reported that this contact pressure is sufficient to allow even contact with the skin's surface, but is insufficient to produce a blanch response.[24] The probe was positioned so that incident light was directed perpendicular to the skin surface.

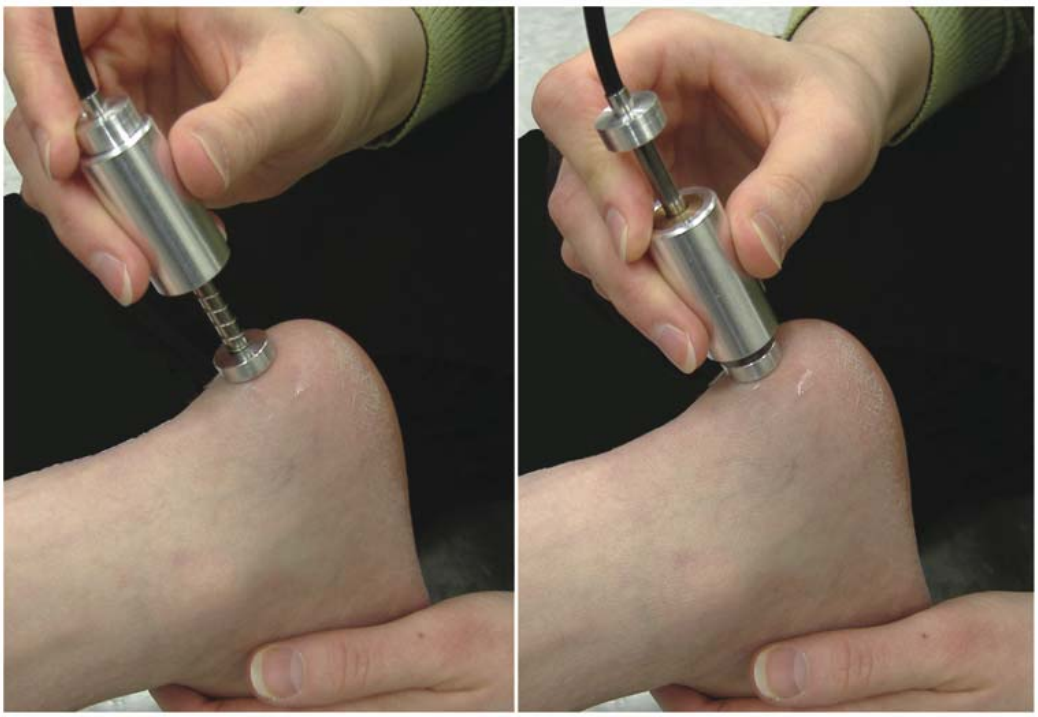

Figure 6. Hand-held indenter during light contact period (left) and gentle pressure period (right)

The probe was held in light contact with the skin for a total of 45 seconds. (The reflectance signal was allowed to stabilize for 15 seconds, followed by 30 seconds of reflectance data collection.) Without lifting the probe from the skin, the investigator gently increased the pressure delivered to the skin to 120 mmHg by depressing the plunger on the probe and compressing the spring to a predetermined length (Figure 6). This gentle pressure was maintained on the skin for 45 seconds while reflectance data was collected by the spectrophotometer. The probe was then lifted off the skin. A two-minute washout period was provided, and the process was repeated until three measurements were acquired in body position 1 at site 1. The tape was removed from the test site and the site was inspected to verify that the

participant experienced no irritation. Three measurements were then taken at site 2 in position 1 using the same process described above. The participant was provided an optional 10-minute break to move around and refresh him/herself as needed. After the break, the participant assumed body position 2 on the mat table and a new piece of double-sided tape was applied to site 1. Three measurements were acquired in position 2 at site 1 and site 2 using the same process described above.

4.2.4 Spectroscopic Data Processing

Reflectance data were converted to optical density units by the OOIBase32 software using the formula $\log_{10}$(reference – dark) – $\log_{10}$(skin reflectance – dark). The relative concentrations of oxygenated hemoglobin (HbO_2), deoxygenated hemoglobin (Hb), and melanin present in the skin in-vivo were determined by performing a non-negative least squares fit of in-vivo skin spectra to the extinction coefficients of HbO_2, Hb and melanin measured by in-vitro spectroscopy (Figure 2).[24,25] The regression coefficients represent a multiplication factor that describes the concentration of HbO_2, Hb, and melanin in the skin relative to their concentrations in the solutions from which the in vitro spectra were obtained. Because the skin is a scattering medium, the regression coefficients cannot be used to calculate the absolute magnitude of the concentration of each species in the skin.[131] However, the regression coefficients can be considered a relative measure of concentration for each of these species

Optical density data were analyzed in Matlab (v.6.5, Mathworks, Inc., Natick, MA). Fits were performed using data in the visible region of the spectrum between 525 nm and 580 nm. Melanin was assumed to be constant in both the light contact and gentle pressure conditions and an offset term was included to account for the scattering of light in skin. Total hemoglobin (tHb) was calculated as the sum of the HbO_2 and Hb signals. Percent tissue oxygen saturation (S_tO_2) was calculated from the HbO_2 and Hb signals according to the formula [HbO_2 / (HbO_2 + Hb)] x 100.

Fifteen Hb, HbO_2, tHb, and S_tO_2 values obtained during the middle of the light contact and gentle pressure periods were averaged to produce one light contact and one gentle pressure value for each spectroscopic blanch test. For each species, the light contact value was subtracted from the gentle pressure value so that negative changes indicated a decrease in concentration

when pressure was applied. The "spectroscopic blanch response" was defined as the change in total hemoglobin (ΔtHb) that occurred when pressure was applied to the skin.

Data used to calculate measurement reliability were obtained from a second data analysis approach. In this paired difference approach, the relative concentrations of Hb and HbO_2 for conditions of light contact and gentle pressure were subtracted within each subject and for each anatomical site. This paired difference approach provided the relative change in the concentrations of HbO_2, and Hb due to the application of pressure on the skin. Calculating a ΔtHb parameter by summing the calculated values of ΔHbO_2, and ΔHb provides a measure of the amount of blood displaced out of the sampling volume of the optical beam during the application of pressure. ΔS_tO_2 was calculated as $[\Delta HbO_2/[\Delta HbO_2 + \Delta Hb]] \times 100\%$.

4.2.5 Statistical Analysis

Dependent samples t-tests were used to compare the light contact and gentle pressure values of each hemodynamic species (tHb, S_tO_2, HbO_2, and Hb) and to compare the magnitude of change in the concentration of these species with pressure application between the two body positions. Dependent samples t-tests were also used to compare the relative concentration of melanin at the sacrum versus the heel within each participant. Independent samples t-tests were used to compare the magnitude of the change in each species between light and dark skinned participants and to compare the relative concentration of melanin (averaged over both positions) for the light skin versus dark skin group. Statistical tests were run in SPSS (v. 11.0.1, SPSS, Inc.) with data split by each unique skin color, body site, and body position combination. An alpha level of 0.05 was selected for all tests.

Intra-rater reliability for the overall sample was quantified using intra-class correlation coefficient (ICC) Model 3.[155,156] This approach is based on a two-way mixed model and calculates ICC values using analysis of variance (ANOVA) for repeated measures. Model 3 was selected because the tested raters were considered the only raters of interest and measurements were repeated within participants. Both average measure (ICC 3,*k*) and single measure (ICC 3,1) outputs were reported. Due to their small magnitude, relative concentration data were multiplied by 10^6 prior to calculating ICCs in SPSS.

Demographic data and Munsell color tile values were compared between the light and dark skin groups. Chi-square analyses were used to assess differences between the light and dark skin groups on nominal variables (gender, race/ethnicity). Independent samples t-tests were used to compare age between the skin color groups. Munsell color tile values were treated as ordinal data and analyzed using the Mann-Whitney U test.

4.3 RESULTS

4.3.1 Participant Characteristics

Demographics and Munsell color tile values are shown in Table 3. The light and dark skin groups were not significantly different from each other in terms of age or gender. As expected, the racial/ethnic makeup of the light and dark skin groups differed (χ^2=26.3, significant at $p<0.001$). The majority of the light skin group members (n=10) described themselves as White, whereas all dark skin group members described themselves as African-American. Munsell color tile values were significantly higher in the light skin group than the dark skin group at both the sacrum and heel ($p<0.001$). The relative concentration of melanin at the both the heel and sacrum was significantly greater in dark-skinned participants than light-skinned participants ($p<0.001$, Table 4). The relative concentration of melanin was significantly greater at the sacrum than the heel for both light and dark-skinned participants ($p\leq0.001$). No discomfort was reported or skin irritation observed in any of the participants participating in the pilot study.

Table 3. Characteristics of light and dark skin groups

Characteristic		**Light Skin** (n = 15)	**Dark Skin** (n = 15)
Name	***Data Format***		
Age in Years	Mean (Standard Deviation)	34.1 (9.9)	33.2 (10.6)
Gender			
Male	Number of Subjects	6	5
Female		9	10
Race/Ethnicity†	Number of Subjects		
African-American		1	15
Asian-Pacific Islander		2	0
Hispanic		1	0
White		10	0
African-American/White		1	0
Munsell Color Tile Value*			
Heel	Median (Range)	7 (6-7)	4 (3-5)
Sacrum		6 (5-7)	3 (2.5-4)

† χ^2=26.3, significant at p<0.001.
* Significant at p<0.001.

Table 4. Relative Concentration of Melanin (μM * cm)

Skin Color	**Heel** *Mean (St. Dev)*	**Sacrum** *Mean (St. Dev)*
Light Skin (n = 15)	167.8 (110.9)	269.0 (154.1)
Dark Skin (n = 15)	638.9 (217.9)	964.6 (222.9)

Note: Melanin data averaged between prone and sidelying measurements.

4.3.2 Heel Spectroscopic Data

4.3.2.1 Hemodynamic Species

Typical light contact and gentle pressure spectra for light and dark skin are shown in Figure 7. The total hemoglobin (tHb) time courses observed during the spectroscopic blanch test are shown in Figure 8. A significant decrease in the relative concentration of tHb, S_tO_2, HbO_2, and Hb was observed with pressure application in both prone and semi-sidelying ($p<0.001$ for all species), as shown in Table 5. The magnitude of the change was not significantly different in prone versus semi-sidelying when data were grouped by skin color, although the magnitude of the change in Hb was greater in semi-sidelying than prone when light and dark skin participant data were combined ($p=0.04$). The magnitude of the decrease in tHb, HbO_2, and Hb with pressure application was not significantly different in light versus dark-skinned participants in either prone or semi-sidelying. The change in S_tO_2 was significantly greater in light skinned participants than dark skinned participants in both prone and sidelying ($p<0.001$ for both positions).

The magnitude of the change in the relative concentrations of each hemodynamic species with pressure application varied considerably between participants. In light-skinned participants, standard deviation values ranged from 39% (tHb in prone) to 62% (Hb in semi-sidelying) of the magnitude of the hemodynamic species' change value. In dark-skinned participants, standard deviation values ranged from 41% (tHb in prone) to 69% (Hb in sidelying) of the change value.

4.3.2.2 Intra-rater Reliability

Single measure ICCs for ΔtHb measurement at the heel (Table 6) were 0.80 or greater, while average measure ICCs (Table 7) exceeded 0.90, indicating good to excellent[156] intra-rater reliability. In general, reliability for ΔS_tO_2, ΔHbO_2, and ΔHb was moderate to good for single measures (most ICCs >0.75) and excellent for average measures (most ICCs >0.90), with the exception of ΔS_tO_2 in sidelying.

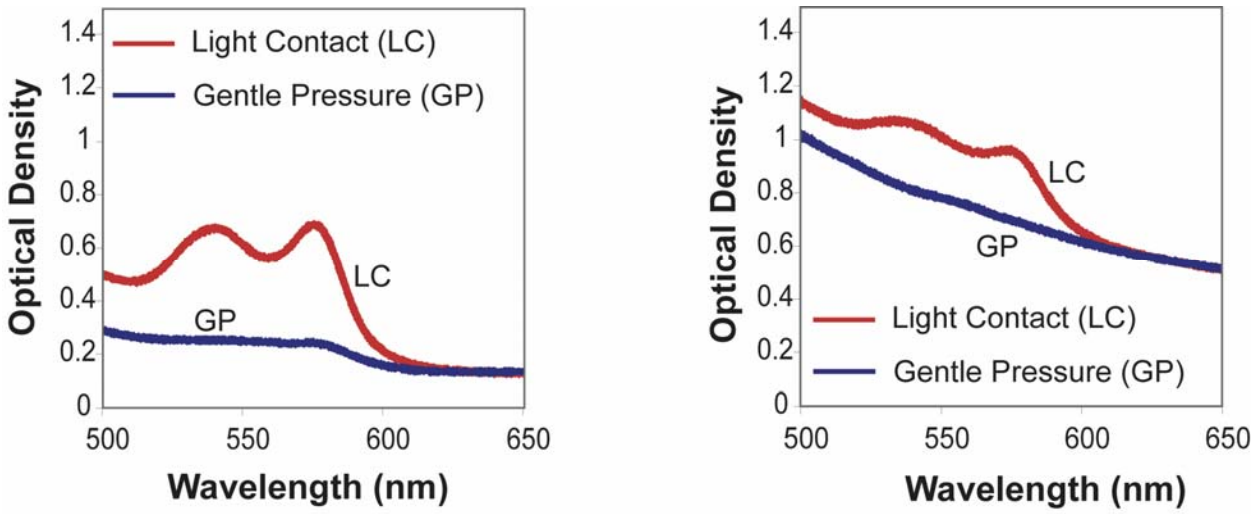

Figure 7. Typical heel spectra observed in participants with light skin (right) and dark skin (left)

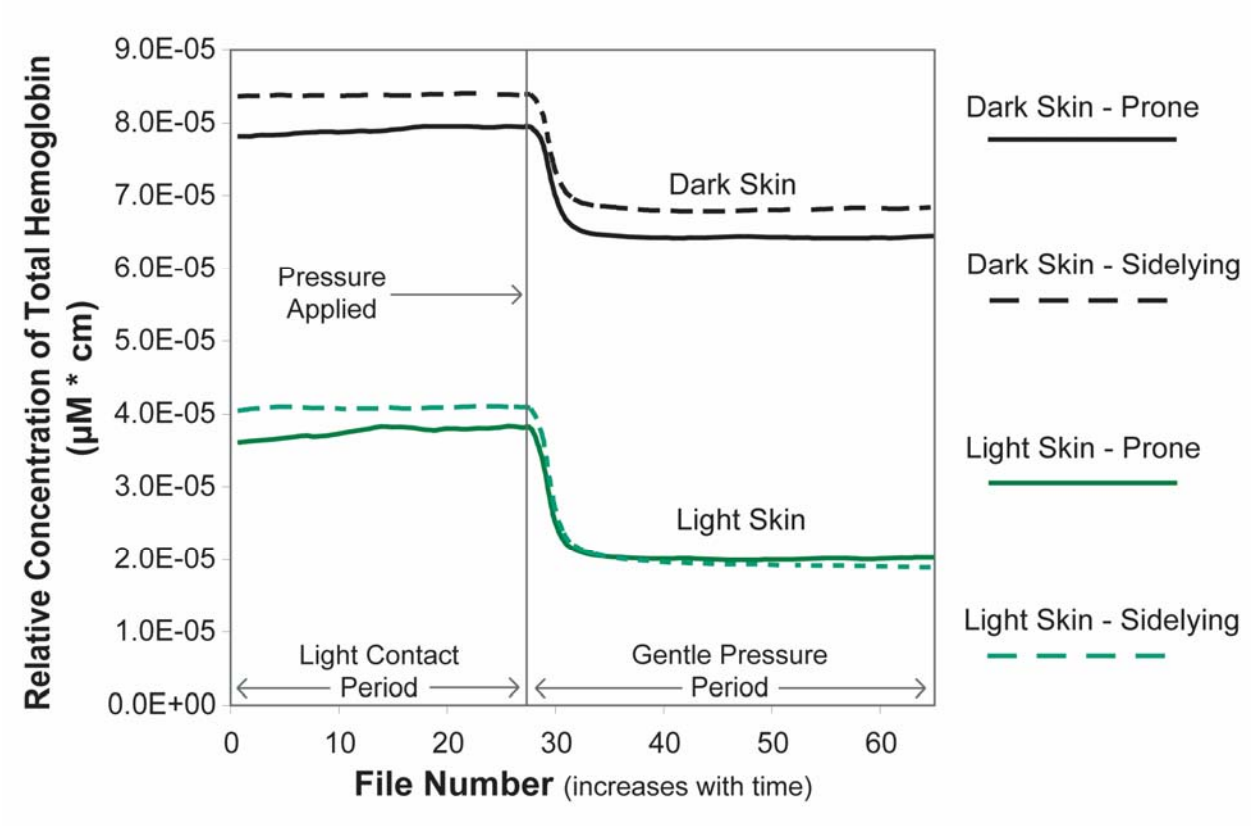

Figure 8. Heel total hemoglobin time courses

Table 5. Mean change in relative concentration of hemodynamic species following pressure application at the heel

Species	**Position**	**Light Skin** (n = 15) *Mean (St. Dev.)*	**Dark Skin** (n = 15) *Mean (St. Dev.)*
ΔtHb (μM * cm)	P	-17.57 (6.83)	-14.66 (6.00)
	SL	-21.64 (10.62)	-15.67 (8.37)
ΔS_tO_2 (%)	P	-18.04 (9.94)	-5.89 (3.51)
	SL	-16.61 (8.17)	-5.48 (3.20)
ΔHb (μM * cm)	P	-7.46 (4.16)	-6.10 (3.29)
	SL	-10.53 (6.56)	-7.03 (4.83)
ΔHbO_2 (μM * cm)	P	-10.11 (4.32)	-8.56 (3.90)
	SL	-11.11 (5.28)	-8.64 (4.45)

P= Prone, SL=Semi-sidelying.

Table 6. Single measure intra-rater ICCs at heel (95% confidence intervals in parentheses)

	Position	
Species	**Prone**	**Semi-Sidelying**
ΔtHb	0.80 (0.67, 0.89)	0.83 (0.71, 0.91)
ΔS_tO_2	0.76 (0.62, 0.87)	0.52 (0.31, 0.71)
ΔHb	0.78 (0.64, 0.89)	0.79 (0.65, 0.88)
ΔHbO_2	0.82 (0.70, 0.90)	0.84 (0.73, 0.91)

Table 7. Average measure intra-rater ICCs at heel (95% confidence intervals in parentheses)

	Position	
Species	**Prone**	**Sidelying**
ΔtHb	0.92 (0.86, 0.96)	0.93 (0.88, 0.97)
ΔS_tO_2	0.91 (0.83, 0.95)	0.76 (0.57, 0.88)
ΔHb	0.91 (0.84, 0.96)	0.92 (0.85, 0.96)
ΔHbO_2	0.93 (0.88, 0.97)	0.94 (0.89, 0.97)

4.3.3 Sacral Spectroscopic Data

4.3.3.1 Hemodynamic Species

Considerable variability was observed in the magnitude and direction of the change in hemodynamic parameters following pressure application at the sacrum. The change in each species was typically positive in dark-skinned participants, with the exception of ΔS_tO_2. In light skinned participants, the change values were typically negative, with the exception of ΔtHb and ΔHb measured in prone.

The magnitude of ΔtHb was not significantly different from zero at the sacrum for either light or dark-skinned participants in either prone or semi-sidelying (Table 8). The magnitude of ΔtHb was not significantly different between the prone and semi-sidelying test positions for data grouped by skin color or for the overall sample. The magnitude of ΔtHb was not significantly different in light versus dark-skinned participants in either prone or semi-sidelying.

Table 8. Mean change in relative concentration of hemodynamic species following pressure application at the sacrum

Species	**Position**	**Light Skin** (n = 15) *Mean (St. Dev.)*	**Dark Skin** (n = 15) *Mean (St. Dev.)*
ΔtHb (μM * cm)	P	0.80 (3.20)	1.08 (3.92)
	SL	-0.73 (2.83)	2.10 (6.60)
ΔS_tO_2 (%)	P	-3.83 (5.19)	-0.23 (0.47)
	SL	-1.93 (3.27)	-0.30 (0.67)
ΔHb (μM * cm)	P	1.38 (1.85)	1.00 (2.36)
	SL	-0.03 (2.12)	1.81 (4.07)
ΔHbO_2 (μM * cm)	P	-0.58 (1.89)	0.08 (1.67)
	SL	-0.69 (1.17)	0.28 (2.63)

P= Prone, SL=Semi-sidelying

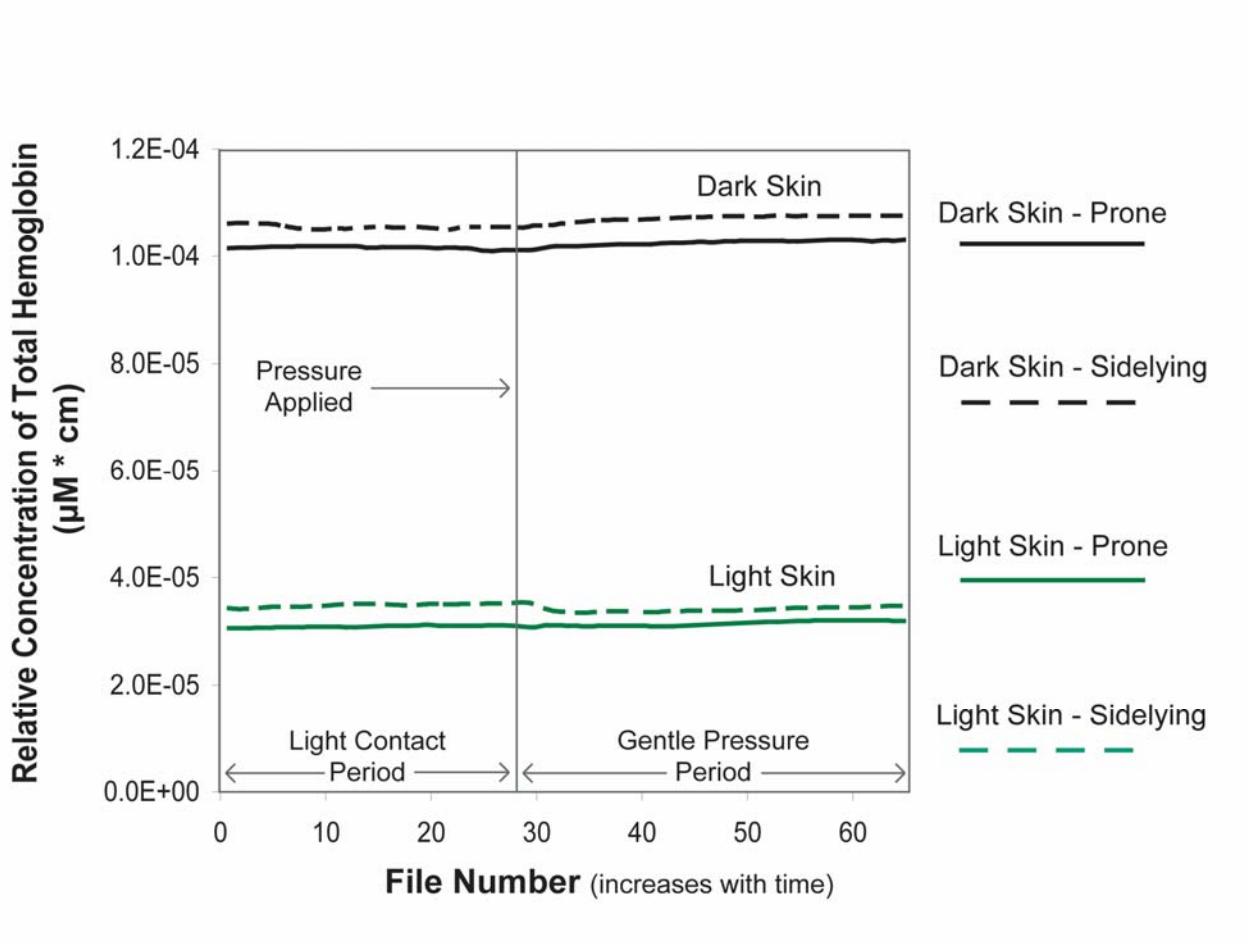

Figure 9. Sacrum total hemoglobin time courses

The total hemoglobin time course data averaged for all participants within each skin color and position combination showed little change after pressure application (Figure 9). Further examination of the time course data acquired for each participant showed that the sacral total hemoglobin time courses fell roughly into three patterns. The first pattern (Figure 10 and Figure 11) shows a sustained decrease in total hemoglobin such that the gentle pressure tHb values were typically less than the light contact tHb values. The second pattern (Figure 12 and Figure 13) showed a relatively flat time course, where tHb varied throughout the light contact and gentle pressure periods but did not show an obvious or sustained decrease in tHb with gentle pressure application. The third pattern (Figure 14 and Figure 15) showed an apparent increase in tHb with pressure application, such that the gentle pressure tHb values typically exceeded the light contact tHb values.

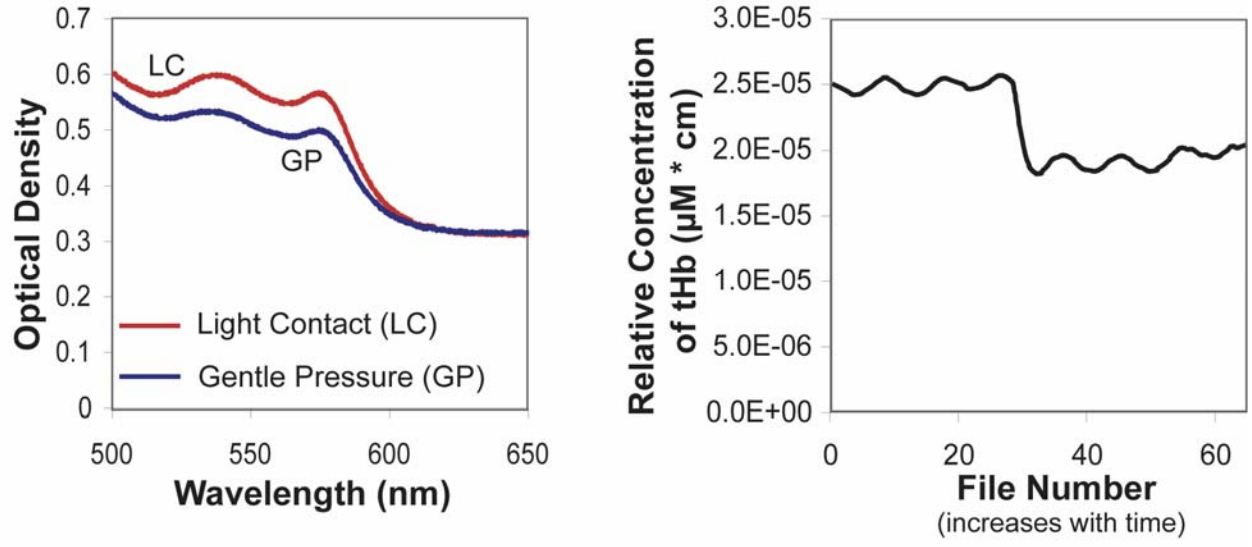

Figure 10. Decreased post-pressure sacral tHb, light skin group participant

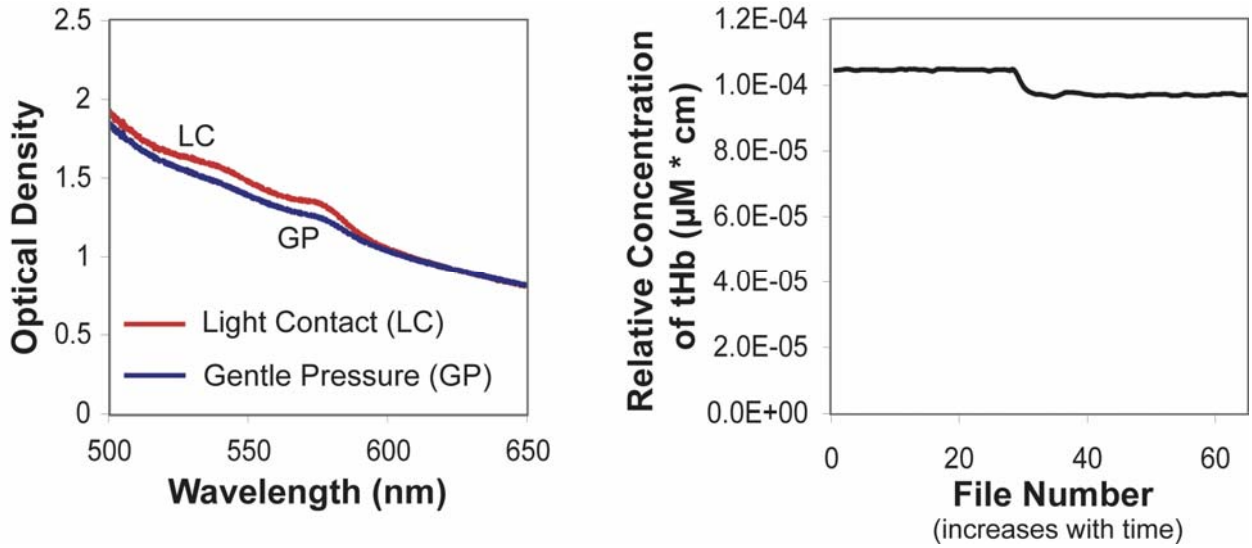

Figure 11. Decreased post-pressure sacral tHb, dark skin group participant

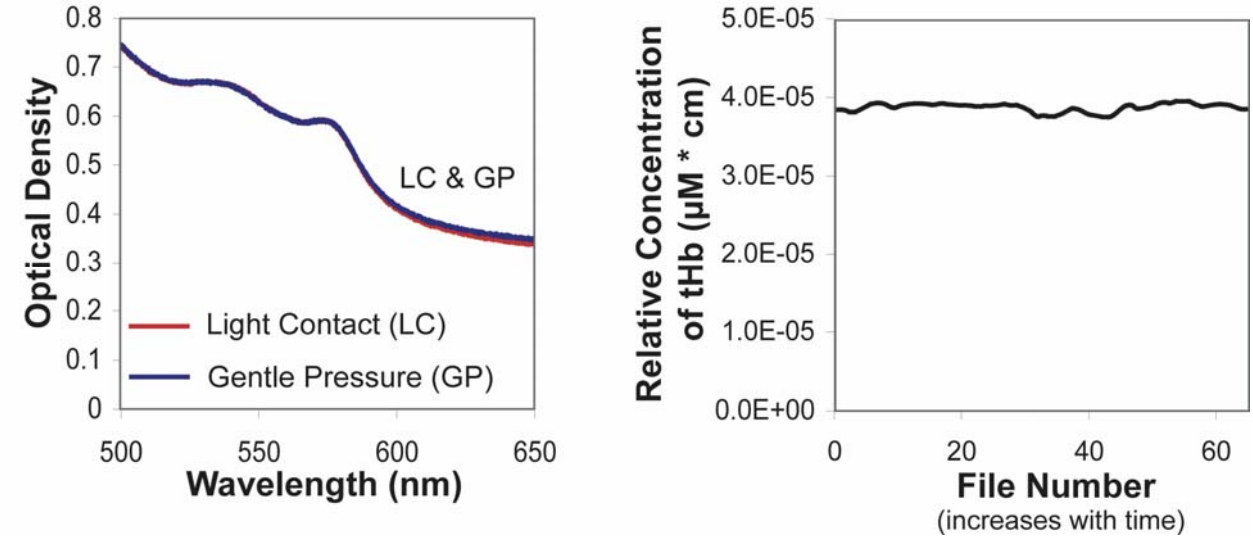

Figure 12. "Flat" post-pressure sacral tHb, light skin group participant

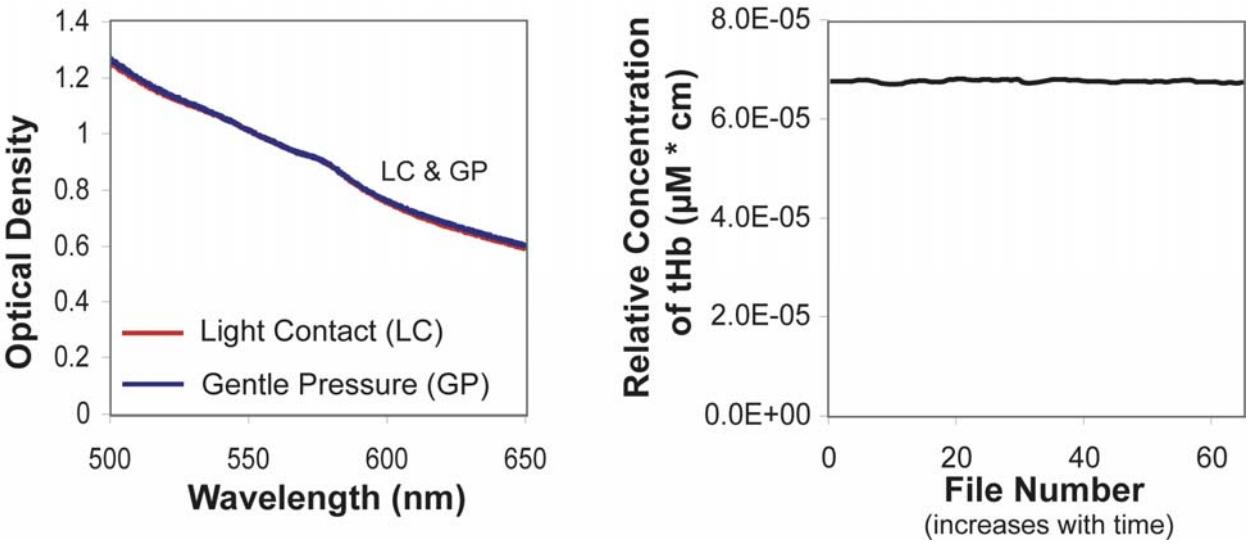

Figure 13. "Flat" post-pressure sacral tHb, dark skin group participant

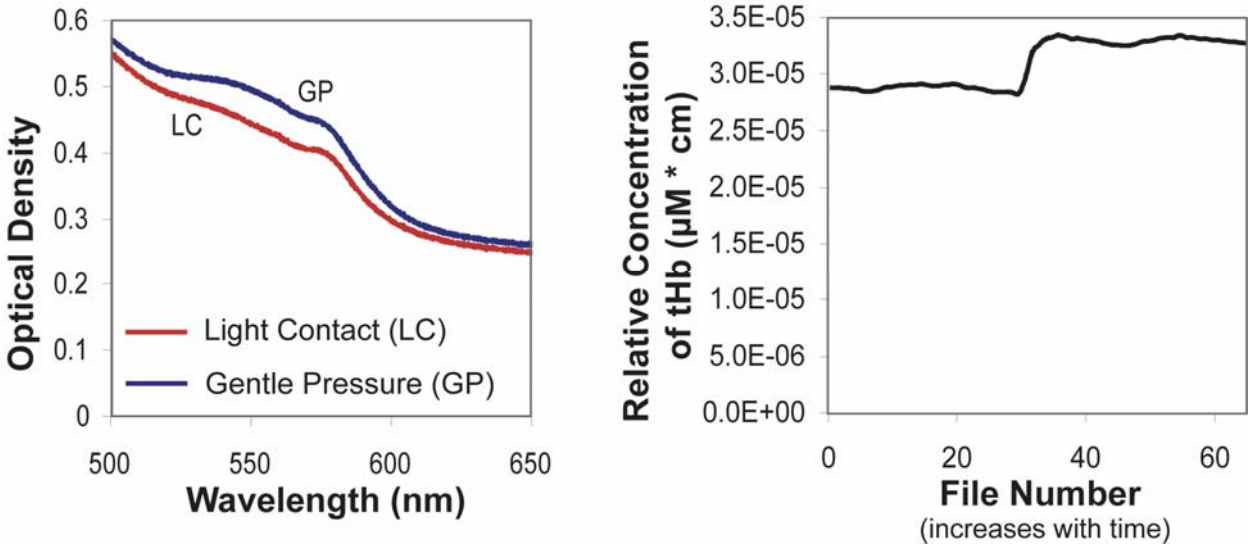

Figure 14. Increased post-pressure sacral tHb, light skin group participant

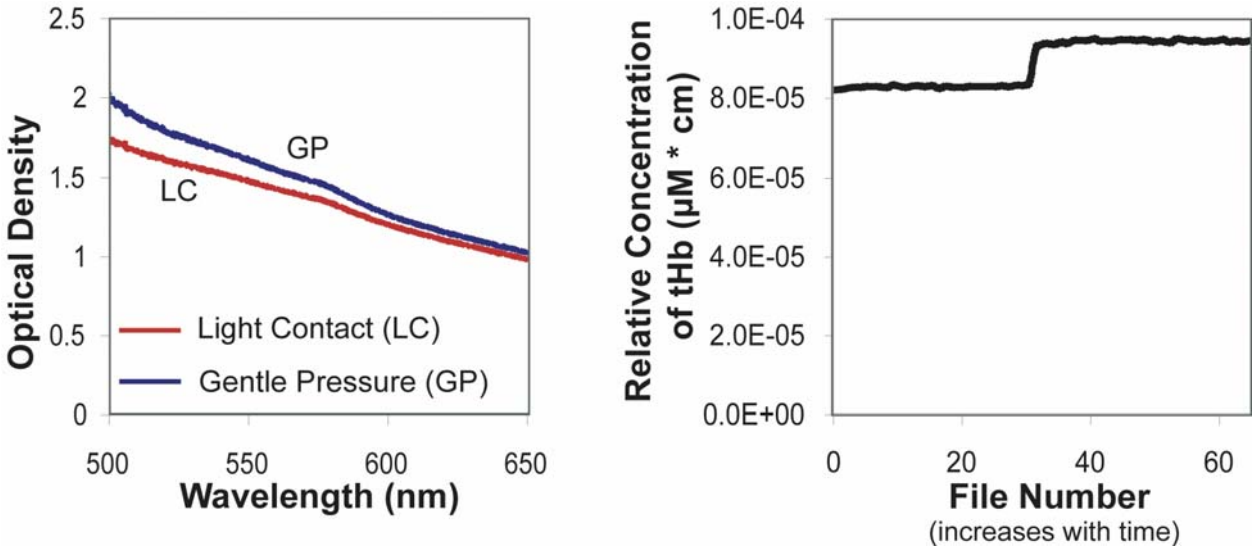

Figure 15. Increased post-pressure sacral tHb, dark skin group participant

The change in S_tO_2, HbO_2, and Hb also varied. A significant decrease in S_tO_2 was observed with pressure application at the sacrum in light-skinned participants in both the prone and sidelying positions ($p=0.013$ and $p=0.038$, respectively). The magnitude of ΔS_tO_2 did not differ between the two test positions for the overall group, but was greater in prone than semi-

sidelying for the light skin group (p=0.048). The magnitude of ΔS_tO_2 was greater in light-skinned participants than dark-skinned participants in prone (p=0.018) but not in semi-sidelying.

A significant decrease in HbO_2 was observed at the sacrum for light-skinned participants in semi-sidelying (p=0.037). The magnitude of ΔHbO_2 was not significantly different from zero for dark-skinned participants in either test position. The magnitude of ΔHbO_2 did not differ significantly between the two test positions for data grouped by skin color or for the overall group. ΔHbO_2 did not differ between the skin color groups in either prone or semi-sidelying.

Contrary to the expected pattern, there was a statistically significant increase in Hb in light skinned participants in prone (p=0.012). The magnitude of ΔHb was not different between the test positions for the overall group, but was significantly higher in prone than semi-sidelying for the light skin group (p=0.024). The magnitude of ΔHb was not significantly different in light versus dark-skinned participants in either prone or semi-sidelying.

The between-participants variability in the magnitude of the change in the relative concentrations of hemodynamic species with pressure application was greater at the sacrum than the heel. In general, the standard deviation values for light skin sacral data ranged between 134% (ΔHb in prone) and 400% (ΔtHb in prone) of the change value. Dark skin sacral data ranged between 204% (ΔS_tO_2 in prone) and 363% (ΔtHb in prone) of the change value. Standard deviation values were extremely high for ΔHbO_2 measured in prone and semi-sidelying in dark skin (2088% and 939% of change values, respectively), and ΔHb measured in semi-sidelying in light skin (7067% of the change value).

4.3.3.2 Intra-rater Reliability

Intra rater reliability for sacral ΔtHb was poor to moderate[156] for single measures (ICC range 0.32-0.69, Table 9) and moderate to good for average measures (ICC range 0.58-0.87, Table 10). Reliability for ΔS_tO_2, ΔHb, and ΔHbO_2 was poor to moderate for single measures (ICC range 0.07-0.74), and poor to excellent for average measures (ICC range 0.18–0.90). ICCs for ΔHb in sidelying were lower than for other species. ICCs for all species were typically higher in prone than in sidelying, particularly for ΔHb.

Table 9. Single measure intra-rater ICCs at sacrum (95% confidence intervals in parentheses)

	Position	
Species	**Prone**	**Sidelying**
ΔtHb	0.69 (0.51, 0.82)	0.32 (0.09, 0.55)
ΔS_tO_2	0.41 (0.18, 0.62)	0.41 (0.19, 0.63)
ΔHb	0.58 (0.37, 0.75)	0.07 (-0.13, 0.32)
ΔHbO_2	0.74 (0.59, 0.86)	0.66 (0.47, 0.80)

Table 10. Average measure intra-rater ICCs at sacrum (95% confidence intervals in parentheses)

	Position	
Species	**Prone**	**Sidelying**
ΔtHb	0.87 (0.76, 0.93)	0.58 (0.24, 0.79)
ΔS_tO_2	0.67 (0.40, 0.83)	0.68 (0.41, 0.84)
ΔHb	0.80 (0.64, 0.90)	0.18 (-0.50, 0.58)
ΔHbO_2	0.90 (0.81, 0.95)	0.85 (0.73, 0.92)

4.4 DISCUSSION

4.4.1 Heel Findings

The findings of this pilot study demonstrated that a blanch response could be detected in light and dark healthy skin at the heel using portable spectroscopy instrumentation. As anticipated, the optical density in the visible region associated with HbO_2 and Hb showed a significant decrease when pressure was applied. This was associated with a drop in the amount of total hemoglobin in the sampled skin area. This change in total hemoglobin (ΔtHb) between the light contact and

gentle pressure states was defined as the spectroscopic blanch response. The spectroscopic blanch response was statistically significant ($p<0.001$), as were changes in HbO_2, Hb, and S_tO_2. These results are consistent with the displacement of blood from vessels in the skin when gentle pressure is applied. The findings at the heel in the current study are consistent with those described at the forearm by Matas and colleagues.[24] In Matas' work, cyclical loads of up to a maximum of 50mmHg were applied to the dorsal forearm via an indenter featuring a stepper motor attached to a benchtop device. A significant change in total hemoglobin between the high and low pressure conditions ($p<0.01$) was observed in both light and dark skinned participants. Despite differences in loading method, pressure magnitude, and body site, the pilot study and Matas' work showed similar results. This observation provides further support for the use of spectroscopy as a tool for assessing the blanch response.

The magnitude of ΔtHb, ΔHbO_2, and ΔHb was not significantly different in light versus dark-skinned participants. Although both groups showed a decrease in S_tO_2, the magnitude of the change in S_tO_2 was significantly higher in light versus dark skinned participants. The difference in oxygenation may indicate real differences in the oxygen carrying capacity of blood in individuals with light and dark skin. There may also be incomplete separation of the melanin and hemoglobin signals in the data analysis algorithm used in the pilot study. The separation of the total hemoglobin time courses between the light and dark skin groups shown in Figure 8 also suggests potential "cross-talk" between melanin and hemoglobin in the data analysis algorithm. The data analysis algorithm continues to be refined to optimize data quality. Despite these issues, the finding that a significant decrease in total hemoglobin occurs in both skin color groups at similar levels of significance suggests that spectroscopy was an effective tool for assessing the blanch response at the heel in both light and dark skin.

When data were grouped by skin color, no significant differences were noted in the magnitude of ΔtHb, ΔHbO_2, ΔHb, and ΔS_tO_2 measured in prone versus semi-sidelying. When data from both skin color groups were pooled, ΔHb was significantly greater when measured in sidelying than in prone. Whether this result occurred by chance or is explained by real physiological differences associated with body position is unknown. The spectroscopic blanch response (ΔtHb) and all other species showed no significant differences between positions for the pooled data. The investigators were able to readily access the heels in both positions, and participants were able to maintain both positions comfortably without movement. These results

indicate that comparable spectroscopic blanch test results may be obtained in different body positions. Individuals at risk for pressure ulcers often have orthopedic or other limitations that prevent them from assuming certain positions, particularly prone. The finding that similar spectroscopic blanch responses can be detected in multiple positions will facilitate the transition of this technology to a clinical environment.

The magnitude of the spectroscopic blanch response (ΔtHb) at the heel was measured with good intra-rater reliability for single measures in both semi-sidelying and prone positions, with ICCs ≥0.80. Average measure ICCs (>0.90, Table 7) exceeded the single measure ICCs, (Table 6) indicating excellent intra-rater reliability when the mean of multiple ratings is the unit of analysis. High intra-rater reliability facilitates the interpretation of spectroscopic blanch response measurements, as it suggests that changes in magnitude of the spectroscopic blanch response from measurement to measurement within a person may be attributed to changes in the blanching of the tissue rather than variability associated with the testing procedure. Intra-rater reliability was likely facilitated by the investigator's ability to view the spectra acquired from the skin during the point spectroscopic blanch test. While this does not allow direct interpretation of the concentration of hemoglobin in the skin, it does provide a general sense of the consistency of the spectra acquired from measurement to measurement. Further work is needed to determine if intra-rater reliability would decrease without this feedback. Inter-rater reliability remains to be examined in future investigations, and must be demonstrated if spectroscopic blanch response measurement is to become a meaningful clinical tool.

Considerable inter-participant variability was observed in the magnitude of the change in each hemodynamic species (see standard deviation values in Table 5). Coefficients of variation for heel data ranged from 39% to 69%. High inter-participant variability has also been reported by other investigators who have used spectroscopy to examine hemoglobin changes associated with tissue loading.[30-32] This is likely the result of a combination of factors. Skin blood flow is likely to vary within and between participants. In addition, each participant will have a unique level of skin pigmentation, therefore inter-participant variability may be attributed in part to real differences in skin pigment and hemoglobin content between individuals. Differences in pressure delivery to the skin may also explain part of the between-participants variability. A portable hand-held indenter was chosen for this study because it would transition to a clinical application more readily than a fixed bench-top device. However, small movements by the

participant or the investigator may have produced variation in the pressure delivered to the skin. Because no force transducer was integrated in the design of the indenter used in the pilot study, it was difficult to verify that the pressure delivered to the skin was at its expected level and was consistent from test to test. Within participants, visual observation of spectral shape provided an indirect indication of the consistency of pressure delivery as changes in the amplitude and shape of the spectrum were readily observed with movement of the hand-held indenter. However, this feedback is not useful in evaluating measurement consistency between participants because the shape of the skin spectrum is unique for each participant. Improving force control of the hand-held indenter may reduce much of the variability seen in the pilot study and increase precision of spectroscopic blanch response measurement. Excessive variability in spectroscopic blanch response measurement may complicate interpretation of findings and the limit diagnostic value of this assessment method, therefore it is beneficial to reduce sources of variability whenever possible. Despite these limitations, the pilot study showed that a blanch response may be measured with good intra-rater reliability in healthy heel skin of both light and dark skin pigmentation.

4.4.2 Sacral Findings

In contrast to the heel, a statistically significant spectroscopic blanch response was not detected in either light or dark sacral skin using our current instrumentation and data analysis methods. The direction of change in total hemoglobin was inconsistent, showing a negative value for light skin in semi-sidelying but positive values for light skin in prone and for dark skin in both test positions. Moreover, a spectroscopic blanch response was not detected even in light skinned individuals where blanching during manual pressure was observed. This suggests that our results do not reflect a true lack of blanching at the sacrum, but rather that adjustments to our instrumentation and data analysis techniques are needed to enable us to measure the blanch response spectroscopically at the sacrum.

The change in total hemoglobin following pressure application did not differ from zero for either the light or dark skin group in either position. Time course data averaged across all participants within each skin color and position combination showed a flat pattern, with little change in tHb occurring after pressure application. When the time courses for individual

participants were examined further, three patterns of tHb time course data emerged. The first pattern showed a drop in tHb following pressure application, but typically showed more variability during the light contact and gentle pressure periods than the heel data. As discussed at the heel, revising the design of our indenter to provide more precise force control would likely improve the variability in the data. In addition, many of these time courses showed an initial drop in tHb after pressure application followed by a gradual increase in tHb. One possible explanation for this pattern is stress relaxation in the viscoelastic soft tissue, which was thicker at the sacrum than at the heel test site. If the amount of stress experienced by the tissue subsided, the compressed blood vessels might have opened slightly, increasing blood content in the area. It may also be possible that exposure to pressure produced a hyperemic response toward the end of the gentle pressure period, increasing blood flow to the area exposed to pressure and attenuating the initial decrease in tHb that occurred when pressure was applied to the skin. In addition, although the examiner attempted to maintain a constant load on the skin via the hand-held probe, it is possible that subtle changes in the examiner's hand position may have allowed the spring to expand, causing a release of pressure and allowing blood to return to the area of skin beneath the probe.

The second pattern showed a relatively flat tHb time course, where there was little difference in the tHb values measured during the light contact and gentle pressure periods. High variability in the data may have made differences in tHb more difficult to detect. Several of the flat tHb time courses were associated with raw spectral data in which the doublet typically associated with hemoglobin was not pronounced, even in light skin in the light contact condition. This might occur if the sampling depth was not appropriate to reach the blood vessels associated with blanching. If data were sampled from a largely avascular layer (epidermis or adipose subcutaneous tissue), that might explain the lack of pronounced doublet in several of the sacral spectra and why there is minimal change in the hemoglobin signal when pressure is applied. Adjustment of the illumination-collection fiber distance may be needed to optimize sampling depth for data acquisition.

The third tHb time course pattern showed an increase in tHb immediately following pressure application—the reverse of the expected pattern. Notably, this pattern was observed even in light skinned participants whose skin visibly blanched with manual pressure application. At this time, it is unclear what factors are contributing to this phenomenon. While hyperemia

may occur following pressure, the immediate nature of the increase in tHb suggests that a physiological upregulation of blood flow is not the most likely explanation for the observed increase in tHb. Sampling depth may have contributed to this phenomenon. Observations made during the pilot study showed that the soft tissue at the sacral site was typically thicker and contained more adipose tissue than that over other bony prominences, such as the heel. If sampling during the light contact condition is occurring at a depth that is above a vascular layer, perhaps compressing the tissue brings the light path closer to the blood vessels, allowing more hemoglobin to be detected than when the tissue was in an uncompressed state.

Percent oxygenation decreased as expected in participants with light skin in both test positions. HbO_2 also decreased as expected in the light skin group, but only in semi-sidelying. In contrast, Hb increased in the light skin group in prone. The increase in Hb may be partially explained by the partial occlusion of blood vessels with pressure, causing oxygen to be consumed, transforming hemoglobin from its oxygenated to deoxygenated state. Any significant changes in hemodynamic species at the sacrum following pressure were found in light skinned participants. Incomplete separation of the melanin signal from the hemoglobin signal may make subtle differences more difficult to detect in dark skinned participants than light skinned participants at the sacrum. More melanin was found at the sacrum compared to the heel in both light and dark-skinned participants, making interference from skin pigment a greater issue at this site. Further optimization of the data analysis algorithm would be beneficial to more accurately characterize the response of hemodynamic species to pressure at the sacrum.

The changes in S_tO_2 and Hb were both found to have higher magnitudes in prone. During the study, the investigators found that it was more difficult to maintain a steady hand position during spectroscopic blanch tests performed in the semi-sidelying position at the sacrum than in prone, particularly during the light contact condition. This was observed even when pillows were used to help support the examiner's arm during the blanch tests. The semi-sidelying test position required that the examiner hold the probe up against gravity while also controlling pressure applied to the skin. Poor reliability values and high standard deviations calculated for sacral data in semi-sidelying are consistent with the examiner's perceived difficulty in controlling the probe. This variability may have made subtle changes in the relative concentration of hemodynamic species more difficult to detect. Participants who are at risk for pressure ulcers may have physical limitations that prevent them from tolerating the prone

position, therefore it is important to improve the quality of data obtained in the semi-sidelying test position. Improving force control of the hand held indenter may help to reduce some of the variability seen in the semi-sidelying measurements.

4.4.3 Summary

The pilot study demonstrated that a blanch response could be detected with good intra-rater reliability at the heel in both light and dark healthy skin using a hand-held indenter and portable spectroscopy instrumentation. The blanch response was not detected consistently at the sacrum. The sacrum's soft tissue composition as well as imprecise force control in the indenter and incomplete separation of the melanin and hemoglobin signals in the data analysis algorithm may all have contributed to the difficulty in detecting the spectroscopic blanch response at the sacrum. Further work is needed to optimize our instrumentation and data processing algorithms to improve our ability to detect the blanch response at the sacrum. Those at risk for pressure ulcers have a variety of age and health-related conditions that may make blanch response detection more difficult than in healthy participants. To evaluate the effectiveness of our instrumentation and data analysis modifications, it would be beneficial to repeat the blanch response assessment protocol at the sacrum in a healthy participant population whose skin is known to show a clinical blanch response.

While our pilot study indicates that a blanch response can be detected in healthy heel skin using spectroscopy, additional information is needed to verify that a blanch response can be detected reliably at the heel in individuals at risk for, but currently without, pressure ulcers. The clinical study discussed in Chapter 6.0 will address this area of uncertainty by using spectroscopy to assess the blanch response in the skin of elderly nursing home residents at risk for pressure ulcers.

5.0 RELIABILITY OF SKIN COLOR ASSESSMENT VIA COLOR TILE MATCHING AND COLORIMETRY

5.1 BACKGROUND AND OBJECTIVE

After the completion of the pilot study discussed in the previous chapter, it was determined that a reliable means of skin color description was needed to aid recruitment in subsequent studies of the spectroscopic blanch response. Munsell color tile matching was used to describe skin color at the sacrum and heel in the pilot study (see section 4.2.1). In the Munsell system, alphanumeric designations are assigned to color samples based on three qualities: hue, value, and chroma.[129,153] Hue is the color quality that is described as red (R), yellow (Y), green (G), etc. Value is the lightness or darkness of a color, ranging from 0 for pure black, to 10 for pure white. Chroma can be described as the vividness or saturation of a color. Sets of color tiles arranged by Munsell hue, value, and chroma are commercially available. By identifying the tile that best matches a material, the color of that material may be described using Munsell color notation.

Munsell color tiles have been used in several studies to describe the color of both healthy and lesioned skin. Munsell color tile matching has been used to describe the lightening of capillary vascular malformations ("port wine stains") exposed to pulsed dye laser treatments[157], assist in the evaluation of glycolic acid peel treatment for melasma in Asian women[158], classify the skin color of participants in a study of erythema detection mechanisms[23], and assess the perception of blue tones in skin overlying veins[159]. The relationship between the Munsell value of subjects' skin and the accuracy of pulse oximetry readings has also been reported in research literature.[152] Munsell color tiles are inexpensive (less than $20 for 1 card), compact and easy to carry, and require virtually no maintenance. However, the color tile matching process requires subjective decision-making on the part of the observer, increasing variability in skin color assessment.

Colorimetry is a technique that provides objective data on skin color. A colorimeter is a device that uses measurements of red, green, and blue light reflected from the skin to calculate descriptive parameters of skin color in a variety of color notation systems.[129] Several investigations have used colorimetry to assess patient responses to topical treatments or irritants applied to the skin[160-168], evaluate the outcomes of dermatologic procedures such as carbon dioxide laser resurfacing[169], and measure skin tanning following ultraviolet radiation exposure or use of tanning agents.[163,170-172] Colorimetry has been used to describe burn scars[173], assess psoriatic plaque severity[174], and evaluate overall illness severity in at-risk newborn infants.[175] The primary advantage to colorimetry is that it provides quantitative data on skin color instantaneously and in a manner that does not involve subjective color perception, reducing measurement variability. However, a colorimeter may cost several thousand dollars, must be properly calibrated and maintained, and—while portable—is more bulky and heavy than a color tile card.

Little is known about the reliability of skin color descriptions obtained using these "low tech" and "high tech" methods. One study by Gitelson reported 83% agreement for skin color descriptions obtained by Munsell color tile matching.[151] No results specific to the assessment of hue, value, or chroma were reported in Gitelson's study, and no other studies examining reliability of Munsell skin color matches were identified. The majority of studies using colorimetry have not reported data on the reliability of colorimetric measurements. Three studies have reported high reliability for colorimetry in healthy skin[163,176] and in burn scars[173], but reproduction of these data are needed.

The objective of this investigation was to examine the intra and inter-rater reliability of skin color assessments performed using Munsell color tile matching and colorimetry in a group of 10 healthy adults. Data obtained in this study were used to determine which method of skin color description was most appropriate for a subsequent study of spectroscopic blanch response assessment in elderly nursing home residents at risk for pressure ulcers.

5.2 METHODS

5.2.1 Participants

A convenience sample of 10 participants was recruited from students, staff, and faculty at the University of Pittsburgh. Recruitment and screening procedures were completed by an investigator who was not involved in performing skin color assessment procedures. Eligible participants were: 1) males or females age 18 years or older, 2) in general good health (per self-report), and 3) free of rashes, scarring, bruising, or pigmentation disorders on the volar aspect of the forearm. Participants of a variety of skin tones were selected from those who expressed interest in the study and met eligibility criteria. All study procedures, risks, and benefits were discussed and informed consent provided prior to the beginning of any study procedures in compliance with the policies of the Institutional Review Board at the University of Pittsburgh.

5.2.2 Instrumentation

5.2.2.1 Munsell Color Tiles

A set of 5YR Munsell color tiles was used to perform skin color matches (Figure 3). The 5YR card consisted of 33 tiles arranged in 7 rows of 2-6 tiles each mounted on neutral grey flexible cardboard. The card included tiles of Munsell value 2.5 and 3 – 8, and Munsell chroma 1-4, 6, and 8. The tiles were perforated to allow close comparison of each tile to the participant's skin. Gitelson (1965) reported fewer matching errors using perforated versus non-perforated tiles both in vitro and in vivo.[151]

5.2.2.2 Colorimeter

Skin color was also assessed using a hand-held colorimeter (Chroma Meter™ model CR-300, Minolta Co., Ltd., Osaka, Japan). The colorimeter system consisted of a hand-held measuring head (Figure 16) with an 8 mm diameter measuring area and an attached data processor that displayed and printed color data. The colorimeter contained a pulsed xenon arc lamp to illuminate the skin and photodetectors to collect reflected light in the red, green, and blue regions

of the visible light spectrum (approximately 600 nm, 560 nm, and 450 nm, respectively). The colorimeter was calibrated immediately prior to the study session using the standard white plate provided by the manufacturer. The colorimeter was set to use the Commission Internationale d'Eclairage (CIE) Standard Illuminant C and "multi measure" mode, in which three readings are automatically taken and averaged when the button on the measuring head is pressed. Skin color measurements were taken by placing the measuring head of the colorimeter perpendicular to and in light contact with the participant's skin (Figure 16) and pressing the measuring button once to trigger acquisition of color data. Data obtained by the colorimeter were expressed in CIE *L*a*b** color notation. In this system, *L** represents the "luminance" or "brightness" of a color, ranging from 0 for black to 100 for white. The *a** descriptor represents where a color falls on a continuum from red (positive *a** values) to green (negative *a** values). The *b** descriptor represents where a color falls on a continuum of yellow (positive *b** values) to blue (negative *b** values). Both the *a** and *b** descriptors have a range of –60 to +60.[129,163,167]

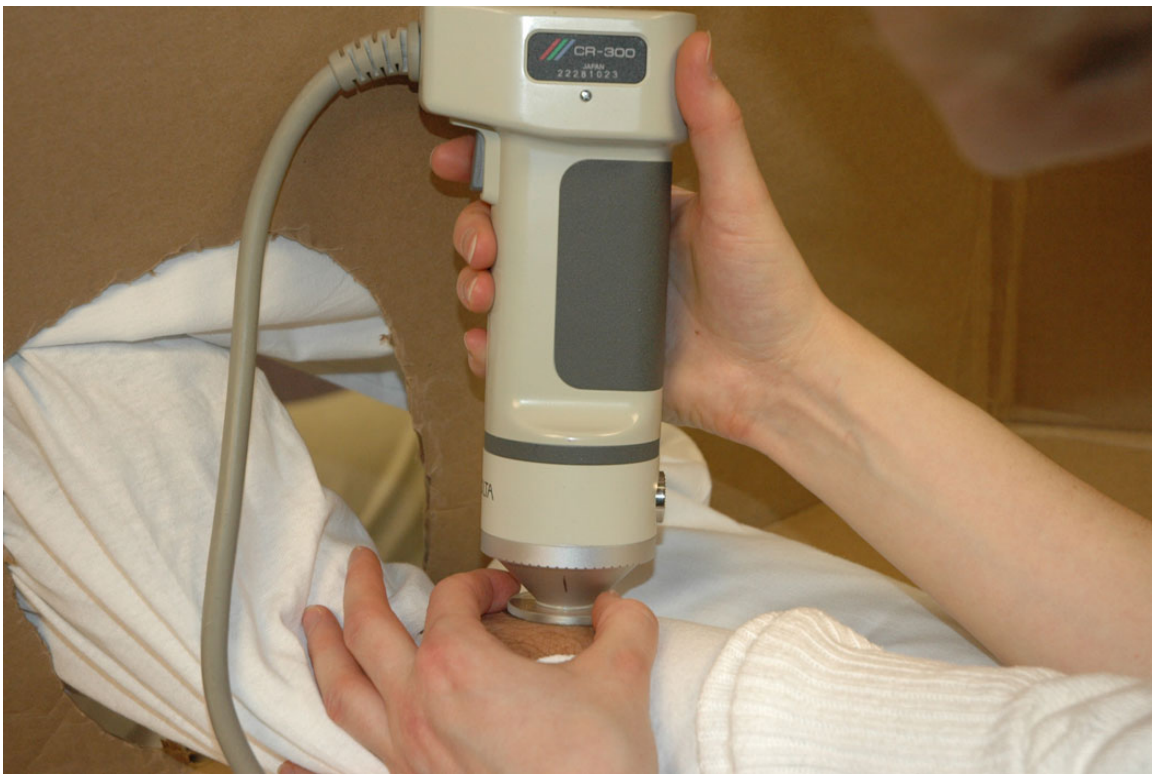

Figure 16. Investigator performing skin color assessment using the Minolta CR-300 colorimeter

5.2.2.3 Assessment Area Setup

An assessment station was created to prevent the investigators performing the skin assessments from viewing any part of the participant other than the forearm site of interest (Figure 17). The station was created by placing a cardboard shield on top of a table draped with a sheet, concealing the seated participant's upper and lower body from the view of the examiners seated on the opposite side of the table. The shield contained a hole into which the participant inserted his/her arm. A cloth flap attached to the front of the shield assisted in preventing the examiners from viewing anything other than the participant's arm through the hole in the shield (Figure 18).

Figure 17. Participant seated in front of assessment station

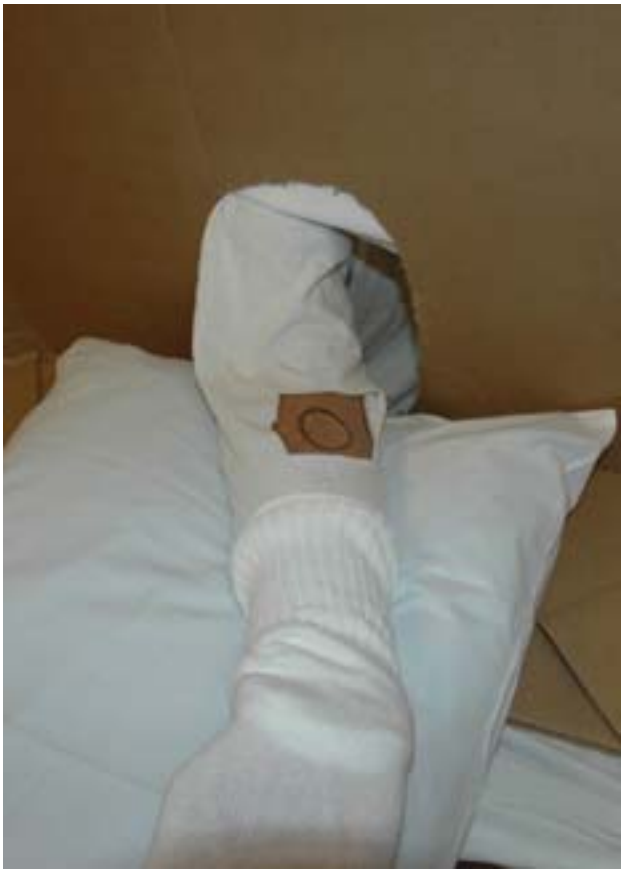

Figure 18. Forearm skin site of interest as viewed by examiners behind assessment station

5.2.3 Protocol

Three investigators, designated Examiners A, B, and C, implemented the research protocol. Examiner A conducted recruitment and screening procedures and assisted in the preparation and guidance of participants through the assessment procedures. Examiners B and C performed the skin color assessments, and were masked to the identity of the study participants and to each other's skin color assessments. All skin color assessments took place under indoor fluorescent light conditions, which were kept constant throughout the procedures described below. All skin assessments were completed on the same testing day during a session lasting approximately 90 minutes.

5.2.3.1 Preparation Steps

In an area outside of the assessment room, each participant provided general demographic information to Examiner A, including age, gender, race, and ethnicity. Examiner A marked a small circular area of the exposed skin on the participant's right volar forearm using a non-toxic washable marker and a cardboard template. The marked area was approximately 1 square inch in area and was located approximately 1 to 2 inches distal to the cubital fossa. Each participant then donned a white long-sleeved shirt with a small patch cut out to expose the marked area of skin, and then donned a white sock on his/her right hand.

5.2.3.2 Skin Color Assessments

The order in which participants were assessed was randomized prior to the start of study procedures. Examiner A assigned each participant a two-digit identification (ID) number (01 – 10). Examiner A then searched a random numbers table for numbers between 01 and 10, recording each number on a list in the order in which it appeared in the table. This process continued until each ID number had been found in the table three times, generating a list of 30 numbers. Participants were presented to Examiners B and C in the order of their ID numbers in the list.

Examiner A escorted the participant to be assessed into the assessment room. Examiners B and C were unable to see the participant entering the room. The participant assumed a seated position in front of the assessment station and inserted his/her right arm into the hole in the cardboard shield.

Examiner B entered the station and placed the Munsell color tile card on or near the marked site on the subject's skin. Examiner B selected the color tile that he/she felt best matched the participant's skin and recorded the Munsell value and chroma of the selected tile on an index card. Examiner B then recorded a reading from the marked site using the colorimeter, and recorded the colorimeter's output in CIE $L^*a^*b^*$ notation on the index card. Examiner B placed the index card in a lidded box, left the station, and sat in a chair in the test room with his/her back to the station. Examiner C then entered the assessment station and completed a Munsell color tile match and colorimeter reading as described for Examiner B above, recording data on a new index card. Examiner C then left the station and sat next to Examiner B with his/her back to the station while Examiner A escorted the participant from the test room. The

process described above was repeated until each participant was presented randomly to Examiners B and C three times, such that a total of 30 Munsell color tile matches and 30 colorimeter readings were completed per examiner.

5.2.4 Data Analysis

Intra and inter-rater reliability for Munsell value and chroma data were described using percent agreement and kappa. To calculate intra-rater percent agreement for each examiner, value or chroma data for each participant were listed for each possible pair of assessments within each examiner (3 pairs/participant). This process generated a list of 30 possible pairs of value or chroma data for each examiner. Percent agreement was calculated by counting the number of absolute agreements within each list, dividing this result by 30, and multiplying that result by 100. To calculate inter-rater percent agreement, value or chroma data for each subject was listed for each possible examiner/assessment combination (9 pairs). This process generated a list of 90 possible pairs of value or chroma data. Percent agreement was calculated by counting the number of absolute agreements within each list, dividing this result by 90, and multiplying that result by 100. As an additional measure of intra-rater agreement, kappas and 95% confidence intervals were calculated for each possible pair of assessments (3 pairs/participant) within each examiner. Inter-rater agreement kappas and 95% confidence intervals (CI) were calculated in two ways. First, kappas were calculated for each possible examiner/assessment combination (9 pairs). Second, the mode of the three Munsell values or chromas recorded for each subject by each examiner was determined (mode B123, mode C123), and kappas describing the agreement between Examiners B and C were calculated using the mode data. Kappas were calculated in SPSS version 11.0.1 for Mac OSX (SPSS, Inc., Chicago, Illinois, USA). To aid data interpretation, the minimum acceptable level of agreement was considered to be 80% for percent agreement and 0.70 for kappa.

Reliability for L^*, a^*, and b^* colorimeter data was described using intra-class correlation coefficients (ICCs). ICC Model 3[155,156] was used to describe intra-rater reliability. This approach is based on a two-way mixed model and calculates ICC values using analysis of variance (ANOVA) for repeated measures. Model 3 was selected because the tested raters were considered the only raters of interest and measurements were repeated within participants.

Single measure ICCs (ICC 3,1) were reported. ICCs and 95% confidence intervals were calculated using data from: (1) each possible pair of assessments (3 pairs/participant), and (2) all three assessments completed by each examiner for each participant.

Inter-rater reliability was described using ICC Model 2.[155,156] This approach is based on a two-way random model and calculates ICC values using analysis of variance (ANOVA) for repeated measures. Model 2 was selected because it considers the tested raters to be selected from a larger population of raters and examines variance due to differences between the tested raters when measures are repeated within subjects. Inter-rater reliability was calculated in two ways. First, single measure ICCs (ICC 2,1) and 95% confidence intervals were calculated for data from each possible examiner/assessment combination (9 pairs). Second, the investigators calculated the mean of the three L^*, a^*, or b^* values obtained during the three assessments for each participant by each examiner (mean B123, mean C123) and then calculated average measure ICCs (ICC 2,*k*) and 95% confidence intervals using the mean data. To aid data interpretation, the minimum acceptable level of reliability was considered to be 0.70 for the ICC.

5.3 RESULTS

5.3.1 Participant Characteristics

The average age of study participants was 27 years (range 23–44 years). All participants were female and described their ethnicity as Not Hispanic or Latino. Forty percent of the participants described themselves as White, 30% as Asian, and 30% as Black or African-American.

5.3.2 Color Tile Matching Agreement

5.3.2.1 Munsell Value

Both Examiners B and C selected values in the range of 4 –7 during their skin color matches (Table 11). Percent agreement (Table 12) within Examiner B was 93% for Munsell value (28 agreements observed out of 30 possible agreements). The 2 observed disagreements were

between adjacent tiles. Kappas describing agreement within Examiner B for Munsell value ranged from 0.87–1.00 (Table 13). Examiner C showed 80% agreement for value (24 agreements observed out of 30 possible agreements). All 6 observed disagreements involved adjacent tiles. Kappas describing agreement within Examiner C for Munsell value ranged from 0.71-0.73 (Table 13).

Inter-rater agreement (Table 12) was 74% for value (67 agreements observed out of 90 possible agreements) with all 23 disagreements involving adjacent tiles. The inter-rater kappas for Munsell value calculated for the nine examiner/assessment combinations ranged from 0.46-0.86 (Table 14). The inter-rater kappa calculated using mode data for Munsell value was 0.60.

Table 11. Descriptive statistics for Munsell color tile and colorimetric data recorded by each examiner during 30 skin color assessments

	Examiner B		**Examiner C**	
Color Descriptor	**Median† or Mean (St. Dev.)**	**Range Min – Max**	**Median† or Mean (St. Dev.)**	**Range Min – Max**
Munsell Value	6†	4 - 7	6†	4 - 7
Munsell Chroma	3†	3 - 4	3†	2 - 4
L*	56.45 (9.64)	39.87 – 68.77	57.62 (10.16)	40.41 – 72.28
*a**	7.94 (1.34)	5.51 – 10.05	8.19 (1.29)	5.66 – 9.73
*b**	16.48 (3.18)	11.54 – 21.31	16.69 (2.90)	12.15 – 20.48

Table 12. Intra and inter-rater percent agreement for Munsell color tile matches

Munsell Descriptor	**Within Examiner B**	**Within Examiner C**	**Between Examiners B & C**
Value	93%	80%	74%
Chroma	93%	60%	61%

Table 13. Intra-rater kappas and 95% confidence intervals for Munsell color tile data

Munsell Descriptor	Assessment Combinations	Examiner B Kappa (95%CI)	Examiner C Kappa (95%CI)
Value	1 & 2	0.87 (0.62, 1.11)	0.71 (0.38-1.05)
	1 & 3	0.87 (0.62, 1.11)	0.73 (0.43-1.03)
	2 & 3	1.00 (1.00-1.00)	0.71 (0.38-1.05)
Chroma	1 & 2	0.78 (0.39-1.18)	*
	1 & 3	0.78 (0.39-1.18)	*
	2 & 3	1.00 (1.00, 1.00)	*

* Not able to calculate kappa because a symmetric 2-way table in which the values of the first variable matched the values of the second variable could not be constructed with the observed data.

Table 14. Inter-rater kappas and 95% confidence intervals for Munsell color tile data

Examiner/Assessment Combinations	Munsell Value Kappa (95% CI)	Munsell Chroma Kappa (95% CI)
B1 & C1	0.86 (0.60-1.12)	*
B1 & C2	0.60 (0.24-0.95)	*
B1 & C3	0.61 (0.27-0.94)	0.21 (-0.43-0.85)
B2 & C1	0.73 (0.41-1.05)	*
B2 & C2	0.46 (0.09-0.83)	*
B2 & C3	0.73 (0.41-1.05)	0.09 (-0.47-0.66)
B3 & C1	0.73 (0.41-1.05)	*
B3 & C2	0.46 (0.09-0.83)	*
B3 & C3	0.73 (0.41-1.05)	0.09 (-0.47-0.66)
Mode B123 & Mode C123	0.60 (0.23-0.96)	0.09 (-0.47-0.66)

* Not able to calculate kappa because a symmetric 2-way table in which the values of the first variable matched the values of the second variable could not be constructed with the observed data.

5.3.2.2 Munsell Chroma

Examiner B selected chromas of 3-4 for all participants, while Examiner C selected chromas in the range of 2-4 (Table 11). Percent agreement (Table 12) within Examiner B was 93% for Munsell chroma (28 agreements observed out of 30 possible agreements). Two disagreements were observed, both involving adjacent tiles. Kappas describing agreement within Examiner B for Munsell chroma ranged from 0.78–1.00 (Table 13).

Percent agreement (Table 12) within Examiner C was 60% for chroma (18 agreements observed out of 30 possible agreements). Ten disagreements involved adjacent tiles, and 2 disagreements involved non-adjacent tiles. Kappas describing agreement within Examiner C could not be calculated because a symmetric 2-way table in which the values of the first variable matched the values of the second variable could not be constructed with the observed data.

Inter-rater agreement (Table 12) was 61% for chroma (55 observed agreements out of 90 possible agreements). Of the 35 disagreements observed, 32 involved adjacent tiles and 3 involved non-adjacent tiles. Inter-rater kappas for Munsell chroma could be calculated for three of the nine examiner/assessment combinations. These kappas ranged from 0.09-0.21 (Table 14). The inter-rater kappa calculated using mode data for Munsell chroma was 0.09.

5.3.3 Colorimetric Measurement Reliability

5.3.3.1 *L** Descriptor

The range of *L** recorded by each of the examiners during the 30 colorimetric measurements is shown in Table 11. ICCs describing intra-rater reliability were very high for *L**. All ICCs were in the range of 0.99-1.00 for Examiners B and C (Table 15).

Inter-rater reliability (Table 16) was also very high with ICCs in the range of 0.98-1.00 for each possible examiner/assessment combination. The ICC calculated using the mean of assessments 1 –3 for each examiner was 1.00.

Table 15. Intra-rater ICCs and 95% confidence intervals for colorimetric data expressed in CIE *L*a*b** notation

CIE *L*a*b* Descriptor	Assessment Combinations	Examiner B ICC (95% CI)	Examiner C ICC (95% CI)
*L**	1 & 2	0.99 (0.95-1.00)	1.00 (0.99-1.00)
	1 & 3	0.99 (0.98-1.00)	1.00 (0.99-1.00)
	2 & 3	0.99 (0.96-1.00)	1.00 (1.00-1.00)
	1, 2, & 3	0.99 (0.97-1.00)	1.00 (0.99-1.00)
*a**	1 & 2	0.94 (0.77-0.98)	0.85 (0.50-0.96)
	1 & 3	0.92 (0.72-0.98)	0.94 (0.77-0.98)
	2 & 3	0.95 (0.82-0.99)	0.92 (0.71-0.98)
	1, 2, & 3	0.94 (0.83-0.98)	0.90 (0.74-0.97)
*b**	1 & 2	0.99 (0.98-1.00)	1.00 (0.99-1.00)
	1 & 3	0.99 (0.97-1.00)	0.99 (0.96-1.00)
	2 & 3	0.99 (0.97-1.00)	0.99 (0.97-1.00)
	1, 2, & 3	0.99 (0.98-1.00)	0.99 (0.98-1.00)

Table 16. Inter-rater ICCs and 95% confidence intervals for colorimetric data expressed in CIE *L*a*b** notation

Examiner/Assessment Combinations	CIE *L*a*b* Descriptor		
	L*	***a****	***b****
B1 & C1	1.00 (0.98-1.00)	0.93 (0.76-0.98)	0.99 (0.96-1.00)
B1 & C2	0.99 (0.96-1.00)	0.77 (0.32-0.94)	0.99 (0.97-1.00)
B1 & C3	0.99 (0.96-1.00)	0.84 (0.48-0.96)	0.99 (0.95-1.00)
B2 & C1	0.99 (0.94-1.00)	0.93 (0.74-0.98)	0.98 (0.93-1.00)
B2 & C2	0.98 (0.93-1.00)	0.91 (0.67-0.96)	0.99 (0.95-1.00)
B2 & C3	0.98 (0.93-1.00)	0.92 (0.71-0.98)	0.98 (0.93-1.00)
B3 & C1	0.99 (0.97-1.00)	0.93 (0.73-0.98)	0.97 (0.90-0.99)
B3 & C2	0.99 (0.97-1.00)	0.87 (0.57-0.97)	0.98 (0.94-1.00)
B3 & C3	0.99 (0.97-1.00)	0.90 (0.65-0.97)	0.99 (0.95-1.00)
Mean B123 & Mean C123	1.00 (0.99-1.00)	0.97 (0.87-0.99)	1.00 (0.98-1.00)

5.3.3.2 *a** Descriptor

All *a** values recorded during the skin assessments were positive for both Examiners B and C (see range in Table 11). Intra-rater reliability (Table 15) was also high for the *a** descriptor, though not as high as that observed for *L**. ICCs calculated using pairs of assessments for Examiner B ranged from 0.92- 0.95. The ICC calculated using all three assessments for Examiner B was 0.94. ICCs describing intra-rater reliability for pairs of assessments made by Examiner C ranged from 0.85-0.94. The ICC calculated using all three assessments for Examiner C was 0.90.

Inter-rater reliability (Table 16) for *a** was lower than that for *L** with ICCs in the range of 0.77-0.93 for each possible examiner/assessment combination. The ICC calculated using the mean of assessments 1–3 for each examiner was 0.97.

5.3.3.3 *b** Descriptor

All *b** values recorded during the skin assessments were positive for both Examiners B and C (see range in Table 11). Intra-rater reliability (Table 15) for *b** was similar to that of *L**. ICCs calculated using pairs of assessments and all three assessments were 0.99 for Examiner B and 0.99-1.00 for Examiner C.

Inter-rater reliability (Table 16) was also very high with ICCs in the range of 0.97-0.99 for each possible examiner/assessment combination. The ICC calculated using the mean of assessments 1–3 for each examiner was 1.00.

5.4 DISCUSSION

The objective of this investigation was to evaluate the reliability of two methods of skin color assessment: Munsell color tile matching and colorimetry. In the Munsell color tile matching method, color is described based on three qualities: hue (red, yellow, green, etc.), value (lightness), and chroma (color saturation). To describe skin color in Munsell notation, the examiner holds a set of color standards (each associated with a specific Munsell hue, value, and chroma) near the skin and selects the tile that best matches the skin. In colorimetry, a device placed on the surface of the skin measures the amount of red, green, and blue light reflected from

the skin. The reflected light is used to calculate color descriptors in a number of systems of color notation. In this study, colorimetric data were expressed in CIE *L*a*b** color notation, in which *L** describes the color's luminance, *a** describes the color's degree of red or green, and *b** describes the color's degree of yellow or blue.

Reliability was expected to be lower for Munsell color tile matching than colorimetry. In colorimetry, the color assessment was made automatically by the device based on light reflected from the skin. In contrast, Munsell color tile matching required subjective judgment on the part of the examiner, which was expected to introduce greater possibility for variation. The data support these expectations. Reliability was very high for colorimetry, for both examiners and all skin color descriptors. In general, reliability was lower for Munsell color tile matching than colorimetry, particularly for Munsell chroma. In addition, skin color assessments made via colorimetry were similarly reliable for Examiners B and C. Unlike colorimetry, reliability was not comparable between Examiners B and C for value or chroma with the greatest differences noted for chroma.

The following sections will: (1) discuss the Munsell color tile and colorimetry findings and relate them to previous work, (2) identify limitations of this study, and (3) describe factors to be considered when selecting skin color measurement techniques.

5.4.1 Agreement of Skin Color Description via Munsell Color Tile Matching

Measures of agreement for Munsell color tile matching are reported in detail in Tables 12-14. For value, intra-rater agreement for Munsell value was high for Examiner B but was moderate for Examiner C. Inter-rater agreement for value was moderate to poor. For chroma, intra-rater agreement was moderate to high for Examiner B and poor for Examiner C. Inter-rater agreement for chroma was poor. In general, for both value and chroma, confidence intervals calculated around kappa were generally wider than they were for the ICCs calculated for the colorimetric data, particularly for Munsell chroma. This observation further supports the conclusion that colorimetry was more reliable than Munsell color tile matching.

Differences in the reliability for Examiner B compared to Examiner C may be explained by differences in the background and experience of the examiners. Examiner B was a clinician who was involved in in-vivo skin research for several months prior to the conduct of this

experiment, and had used Munsell color tile matching during that period to assess participants' skin color. Examiner C was an engineer working primarily with instrumentation, who practiced using the color tiles briefly during the week prior to the study's implementation. Providing Examiner C with additional training and practice time may have increased his intra-rater reliability, and it is likely that inter-rater reliability would also have been higher had Examiners B and C been similarly experienced in the use of the color tiles.

The relative strength of reliability for Munsell value compared to chroma is consistent with the examiners' comments following the completion of the study. The examiners reported that they could select a value faster and with greater confidence than they could for chroma. This is also reflected in the nature of the disagreements between tiles. All disagreements for Munsell value within and between Examiners B and C were between adjacent tiles, suggesting that examiners could reliably narrow the value to 1 of 2 rows on the card. Disagreements for chroma within Examiner B always involved adjacent tiles, whereas disagreements within Examiner C and between Examiners B and C involved non-adjacent tiles. These findings suggest that it was more difficult to narrow down the choice of chroma. Additional training may have improved Examiner C's ability to narrow down chroma matches to 1 of 2 adjacent tiles in a manner similar to Examiner B.

Little data are available in the literature with which to compare our Munsell color tile matching findings. Gitelson's (1965) data indicate an overall intra-rater percent agreement of 83% for Munsell color tile matching using perforated color tiles.[151] In general, Examiner B's intra-rater agreement exceeded Gitelson's finding and Examiner C's intra-rater percent agreement was lower. However, it is difficult to interpret these differences because Gitelson reported percent agreement based on data from multiple body sites using multiple color tile charts, and did not report reliability data specific to value, and chroma. Gitelson did not report inter-rater agreement data.

Two studies allow comparison of the inter-rater reliability of Munsell color tile matching to that of ordinal or nominal scales used to assess skin color. Draaijers and colleagues (2004), conducted a study in which four independent observers assessed the degree of pigmentation of burn scars at various body sites using a ten point ordinal rating scale, and the pattern of pigmentation using a four point categorical scale (normal, hypopigmentation, mixed pigmentation, hyperpigmention).[173] Draaijers reported moderate to poor inter-rater reliability

for the ordinal rating scale (single-measure ICC of 0.59) and poor inter-rater reliability for categorical description of pigmentation pattern (kappa range 0.176 – 0.349). In a study by Koster and colleagues (1998), 5 observers described the color of portwine stains in patient photographs using a seven point ordinal scale and inter-rater reliability was assessed.[177] The average percent agreement among the ten possible combinations of raters was 47% and the average weighted kappa was 0.46. Direct comparison between our findings and Draaijers' findings for the ordinal rating scale is difficult due to the use of different statistics in the two studies. However, inter-rater reliability for Munsell value in our investigation was similar to, or slightly higher than, that reported by Draaijers for both the ordinal and categorical scales. Munsell value inter-rater reliability also exceeded that reported by Koster. Munsell chroma inter-rater reliability was similar to or slightly lower than that reported by Draaijers for the ordinal rating scale and comparably poor for the categorical scale. Our inter-rater percent agreement for chroma exceeds the agreement reported by Koster, but our kappas are lower. More data are needed to determine if Munsell color tile matching, particularly for Munsell value, has higher inter-rater reliability than color descriptions using ordinal or categorical rating scales.

5.4.2 Reliability of Skin Color Description via Colorimetry

Reliability data for colorimetry are reported in detail in Tables 15 and 16. Reliability was excellent for the L^* and b^* color descriptors, where all intra and inter-rater ICCs exceeded 0.97. Reliability was still high, but slightly less so for a^*, where intra-rater ICCs typically exceeded 0.90 and inter-rater ICCs typically exceeded 0.84. ICC confidence intervals were typically wider for a^* than for L^* and b^*, suggesting greater variability in a^*.

The a^* color descriptor relates to the degree of redness in the skin, which depends on the presence of hemoglobin-rich blood. Several factors in this experiment may have affected skin blood content and may explain part of the variation observed in a^*. The end of the colorimeter measuring head is shaped like a hollow cone with a hole at its peak, such that there is no direct contact between the measuring head and the small circular area of skin from which reflected light is measured. However, pressure along the periphery of the sampling area may influence blood flow. Contact pressure of the colorimeter on the skin compresses blood vessels, decreasing the amount of blood flow in the area and causing "blanching" or whitening of the

skin. While care was taken to keep pressure on the skin at a minimal level, some variation in contact pressure was expected because the device was held in contact with the skin by hand. In addition, the protocol did not include an equilibration period prior to data collection as has been used by some investigators.[163,176] Colorimetric measurements were taken immediately after the participant was positioned at the assessment station. The lack of equilibration period may have permitted variations in blood flow due to uncontrolled conditions present just prior to skin assessment (i.e. skin temperature, limb position relative to the heart) and subsequently increased variation in *a**.

Our results for colorimetry are generally similar to those reported by Van den Kerckhove and colleagues (2001), who evaluated intra and inter-rater reliability using the same model of colorimeter (Minolta CR-300) and the same forearm body site in subjects with healthy skin.[176] The mean *L**, *a**, and *b** observed at the forearm by Van den Kerckhove fall within the range of data in our investigation (Table 11). The standard deviations reported in our experiment (Table 11) fall at the low end of the range of standard deviations reported by Van den Kerckhove for *a** (1.30–2.43) and fall within the range reported for *b** (2.07–3.25). Our standard deviation for *L**, the color descriptor for luminance, is higher than the range reported by Van den Kerckhove (2.42–4.86). Van den Kerckhove did not report skin color as a consideration in recruitment, therefore it is possible that we have more variation in *L** because we specifically made efforts to include participants with light, moderate, and dark skin in our sample. Our reliability results are also similar to those of Van den Kerckhove. Both investigations report very high intra and inter-rater reliability for L and b with ICCs exceeding 0.97. Our observed intra-rater ICCs (range 0.85-0.95) for *a** were slightly lower than that reported by Van den Kerckhove (0.98) but still fall in a range that suggests high intra-rater reliability for the measurement of *a**. The inter-rater ICC of 0.92 reported by Van den Kerckhove falls within the range of inter-rater ICCs observed in our investigation (0.77-0.97) suggesting comparably high inter-rater reliability.

A second study of colorimetric assessment reliability in healthy adults was conducted by Clarys and colleagues (2000), who examined intra-subject repeatability of ten *L**, *a**, *b** measurements conducted at the dorsal forearm, volar forearm, belly, and forehead of healthy adults using an earlier colorimeter model (Minolta CR-200).[163] Clarys reported low coefficients of variation at all sites (<5%) for *L** and *b**, with higher variation in *a** (range 4–12%). These

results are consistent with our finding that reliability of colorimetry results, while high, were slightly lower for *a** than for *L** and *b**.

Draaijers and colleagues (2004) examined inter-rater reliability of skin color assessment in lesioned skin.[173] Four independent observers assessed the color of burn scars at various body sites using a Minolta Chromameter (Model CR221-R). The single measure inter-rater ICCs for *L**, *a**, and *b** based on data from all 4 observers were 0.73, 0.75, and 0.89, respectively. These inter-rater ICCs are lower than those observed in our experiment (Table 16), particularly for *L** and *b**. This difference may be explained in part by irregularities in pigmentation, blood flow, and texture in scarred skin that are absent in healthy skin. The average-measure inter-rater ICCs reported by Draaijers for *L**, *a**, and *b** (0.91, 0.92, 0.97, respectively) are similar to the single-measure ICCs observed in our investigation (Table 16). Draaijers did not report intra-rater reliability data.

5.4.3 Limitations

Several limitations of this study must be considered when interpreting its results and establishing recommendations. As has been previously discussed, Examiner C had less experience in skin color assessment than Examiner B, and it is likely that this portrayed a poorer picture of Munsell color tile reliability than might have been observed with similarly experienced examiners. In future investigations, it would be of benefit to either ensure similar training of examiners or include level of training as a variable of interest in the study so that the effects of experience can be examined specifically. In addition, while attempts were made to create as diverse a skin color sample as possible, the range of skin color descriptors was small. There were no participants with very dark skin (Munsell value 2.5 – 3) and the range of chromas observed included only the middle three of the six chromas represented on the card. This should be considered when interpreting the data, as the variance due to error may appear exaggerated due to the small overall variability possible with the observed data. In future investigations it will be desirable to ensure the inclusion of individuals who fall at the light and dark skin color extremes. One must also consider that this protocol attempted to create a "best case scenario" for reliability assessment. The investigators controlled ambient light conditions, selected participants whose skin was free of irregularities in skin color or texture, and allowed the examiners to view only the

skin site of interest, rather than sitting face to face with the person being evaluated, as would be typical in a clinical context. While this design helped to reduce the effect of external factors on the skin color assessment results, several issues remain unaddressed by this investigation. Additional data are needed to determine how skin color assessment reliability is affected when assessments are completed under daylight conditions, under low light conditions, or when ambient light cannot be controlled. In addition, in clinical practice, patients' skin may be irregular in color due to irritation, birthmarks, pigmentation disorders, circulatory impairments, or other factors, all of which may make skin color more difficult to assess reliably. Further studies are also needed to determine how reliability results differ, if at all, when examiners are not masked to the identity of the person being examined. The choice to use only the 5YR Munsell color tile card may also have been problematic. The 5YR card was selected because it had been used in previous studies to describe skin color.[23,151,152] However, the examiners reported that participants with olive or yellow-toned skin often did not match well with the available tiles on the card. The inclusion of other tiles in the yellow-red hue might have improved the examiners' ability to find a skin color match. In addition, because only one Munsell hue is represented on the card, the reliability of Munsell hue matches could not be assessed.

5.4.4 Skin Color Measurement Considerations

In addition to reliability, there are several other factors that should be considered when selecting a system of skin color measurement for a particular application, including cost, portability, measurement time, maintenance, and the nature of the color output. The color tiles used in this investigation are extremely inexpensive, whereas the colorimeter system costs hundreds of dollars/month to lease and thousands of dollars to purchase. The colorimeter system is small enough to be considered portable, with all components fitting into a small suitcase-sized container. However, the colorimeter is much bulkier than the color tile card and requires a power source for its operation. Measurements obtained by the colorimeter appear as output within seconds of initiating the reading. Color matches may take up to a minute or more, particularly with the examiner is trying to decide which of two adjacent tiles is the most appropriate color. The color tiles require appropriate storage and handling to prevent staining or

tearing of the card, but require no other maintenance. The colorimeter must be calibrated properly and, as with any device, may be subject to breakage or malfunction. Colorimetry provides numerically precise readings, however the meaning of these numerical outputs is not necessarily intuitive. Color tile matching provides data that are more qualitative than colorimetric data, but does provide an intuitively meaningful way of describing color. Those interested in skin color measurement must examine their own resources and needs when determining which method of color assessment is the best match for their particular setting.

5.4.5 Summary

The results of this investigation indicate that colorimetry was generally more reliable than Munsell color tile matching. However, a colorimeter would have been very costly to purchase or rent for the duration needed for the planned spectroscopic blanch response study in nursing home residents (discussed in Chapter 6). Although Munsell color tile matching showed moderate to poor intra-rater reliability for Examiner C and moderate to poor inter-rater reliability, Munsell value descriptions were highly reliable within Examiner B, who would be solely responsible for all subject enrollment and data collection in the planned study. Therefore, it was determined that Munsell color tile matching was sufficiently reliable to stratify participants in light, moderate, and dark skin color groups for subsequent research.

6.0 SPECTROSCOPIC ASSESSMENT OF THE BLANCH RESPONSE IN ELDERLY NURSING HOME RESIDENTS AT RISK FOR PRESSURE ULCERS

6.1 HYPOTHESES/OBJECTIVES

The pilot study discussed in Chapter 4 demonstrated that a blanch response could be detected reliably in light and dark healthy heel skin using tissue reflectance spectroscopy (TRS). Unlike the participants in the pilot study, individuals at risk for pressure ulcers frequently are of advanced age, and may have a variety of medical conditions that affect skin structure or tissue oxygenation. Such conditions may affect the magnitude or reliability of the spectroscopic blanch response. In addition, clinical environments are more difficult to control than laboratory settings, and it is necessary to demonstrate that spectroscopic blanch response assessments are feasible and well tolerated in "real world" settings where clinical devices will eventually be applied.

A study was conducted to verify that the spectroscopic blanch response could be detected reliably in the skin of individuals at risk for, but currently without, pressure ulcers. Spectroscopic assessments were performed at the heels of elderly long-term care residents at risk for pressure ulcers to address two objectives: (1) to test the hypothesis that total hemoglobin will decrease significantly when pressure is applied to the skin, regardless of skin color, and (2) to assess the intra-rater reliability of spectroscopic blanch response measurement.

6.2 METHODS

6.2.1 Participants

Fifteen long-term care residents were recruited from six long-term care facilities in the Greater Pittsburgh area. Residents were considered eligible to participate if they met the following criteria: (1) age 65 or older, (2) at risk for pressure ulcer development, (3) limited mobility, (4) free of pressure ulcers on one or both heels. Risk for pressure ulcer development and mobility status were defined by the Braden Scale. The Braden Scale contains six subscales for sensory perception, activity level, mobility, moisture, friction, and nutrition.[45] Studies have shown the Braden scale to be reliable and valid in light and dark-skinned populations.[2,58] A Braden Scale score of ≤18 indicated risk for pressure ulcer development. Limited mobility was defined as a combined activity and mobility subscale score of ≤5. Skin inspections to determine pressure ulcer status were conducted according to current Agency for Healthcare, Research, and Quality (AHRQ) practice guidelines and pressure ulcers (if present) were staged according to NPUAP staging definitions (Table 1). Residents were excluded from the study if they had scarring, bruising, rashes, or abnormal pigmentation of the skin over the posterior aspect of both heels that would prevent accurate assessment of pressure ulcer status.

Participants were recruited in light, moderate, and dark skin color subgroups (5 subjects/subgroup) to ensure a variety of levels of skin pigmentation in the sample. Skin color classifications were determined by matching the skin on the outer forearm of each participant to perforated Munsell color tiles (Figure 3), which have been previously described in section 4.2.1. Skin that matched Munsell 5YR (yellow-red) color tiles of value 7-8 was considered light, 5-6 moderate, and 2.5-4 dark. Munsell color tile matching by the investigator was shown to be highly reliable in the study described in Chapter 5 (93% agreement, kappa range 0.87-1.00).

All study procedures, risks, and benefits were discussed and informed consent provided prior to the beginning of any study procedures in compliance with the policies of the Institutional Review Board at the University of Pittsburgh. In cases where a resident was considered by his/her facility to be decisionally-impaired with regard to consenting to participation in research, informed consent was obtained from a representative authorized to make health care decisions on his/her behalf.

6.2.2 Instrumentation

Skin reflectance data were acquired using the spectroscopy system described previously for the pilot study (see section 4.2.2). The hand-held indenter was modified slightly to include a flexible filament attached to the side of the indenter head (Figure 19). This filament served as an indicator of appropriate spring displacement. The plunger of the spring assembly and filament were placed such that compression of the spring by 20 mm (resulting in 120 mmHg pressure on the skin) would bring the plunger in contact with the filament. The investigator was made aware of excessive pressure application by observation of filament bending, and of insufficient pressure application by a lack of contact between the plunger and the filament.

The light source was allowed to warm up for approximately 5 minutes prior to spectroscopic assessment of the skin. Reference and dark spectra were recorded in a darkened environment prior to data collection to allow calculation of optical density. Reference spectra were recorded from a white reflectance standard made of Halon (≥97% reflectivity). Spectra were recorded using an integration time of 60 msec with averaging set at 50. Spectral data were saved automatically by the software at a rate of 1 spectrum approximately every 3 seconds.

6.2.3 Data Collection Procedures

Medical and demographic information were obtained for each participant via medical chart review and consultation with nursing staff. Medical diagnoses were categorized based on the Cumulative Illness Rating Scale for Geriatrics.[178,179]

The assessment site was identified as the most prominent aspect of the calcaneus on the hand-dominant side heel. In preparation for assessment, the participant was positioned comfortably in bed in a manner that allowed access to the assessment site. Most participants preferred a semi-sidelying position with hips and knees slightly flexed. Others were most comfortable in supine with the lower extremity of interest externally rotated and slightly flexed. Pillows and draping were used as needed to maintain comfort and stability. Footwear and socks were removed to allow access to the assessment site. Each participant's heel skin was matched to Munsell color tiles and a digital photograph of the assessment site was taken. Participants

rested in their preferred position with the assessment site exposed for up to 10 minutes prior to spectroscopic assessment to allow skin temperature to stabilize.

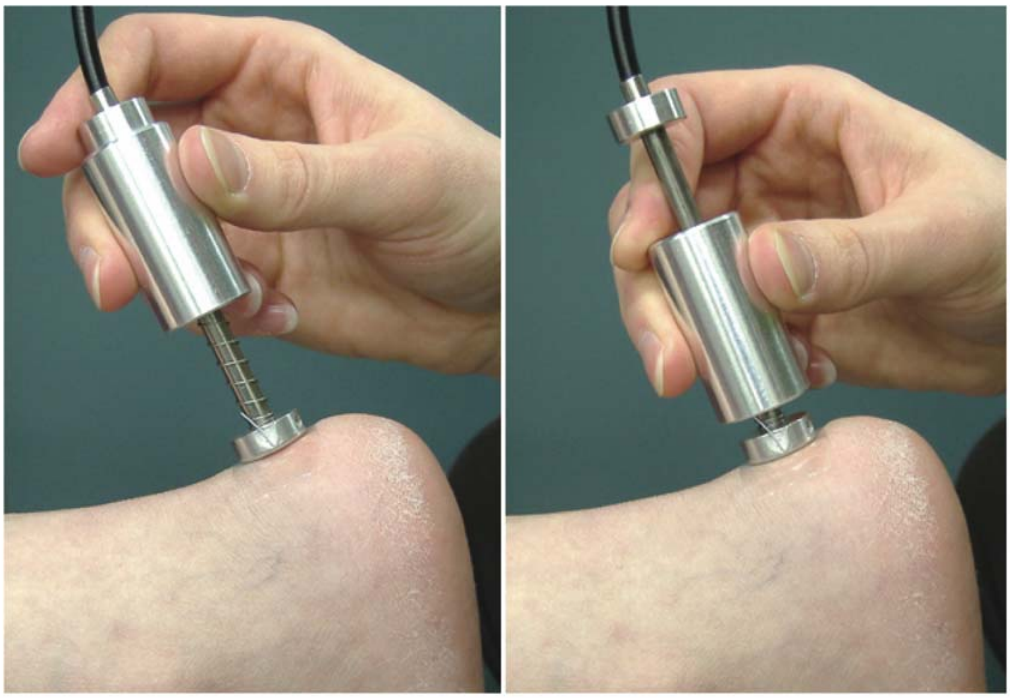

Figure 19. Hand-held indenter with filament in light contact condition (left) and gentle pressure condition (right)

Three point spectroscopic blanch tests (PSBTs) were performed at the heel of interest. A sterile, transparent dressing (Tegaderm™, 3M) was applied to the assessment site. A piece of transparent double-sided tape was applied over the dressing in order to minimize movement of the fiber optic probe during data acquisition. The fiber optic probe was placed in light contact (<5 mmHg) with the tape (Figure 19). The probe was positioned such that incident light was directed perpendicular to the skin surface. The probe was held in this position for 45 seconds while reflectance data were collected by the spectrophotometer. Without lifting the probe from the tape, the investigator gently increased the pressure delivered to the skin to 120 mmHg by depressing the plunger on the probe and compressing the spring until contact was made with the tip of the filament. This gentle pressure was maintained for 45 seconds while reflectance data was collected by the spectrophotometer. The probe was lifted gently off the tape and a two-

minute washout period took place. This process was repeated until three PSBTs at the heel of interest were completed. If a condition arose during a PSBT that would negatively the quality of data collected (i.e. subject movement), that PSBT was repeated to ensure that three data sets suitable for analysis were acquired.

6.2.4 Spectroscopic Data Processing

Reflectance data were converted to optical density units by the OOIBase32 software using the formula $\log_{10}$(reference – dark) – $\log_{10}$(skin reflectance – dark). Spectral data files saved during the light contact and gentle pressure conditions were identified, and spectral data within each of these conditions were averaged to produce a single light contact and gentle pressure spectrum for each PSBT. A difference spectrum for each PSBT was calculated by subtracting the gentle pressure spectrum from the light contact spectrum.

A semiparametric fitting approach, described by Sowa and colleagues[180], was used to estimate the change in the relative concentrations of HbO_2 and Hb that occurred when pressure was applied to the skin. This approach is based on the principles of non-negative least squares estimation, and includes parametric terms which model the contributions of HbO_2 and Hb to the skin spectrum as well as a non-parametric term which accounts for the contributions of melanin, light scattering, and unknown tissue constituents. Difference spectra were regressed against the extinction coefficients for oxyhemoglobin (HbO_2) and deoxyhemoglobin (Hb) using data in the 510-610 nm range. The magnitude of the spectroscopic blanch response (ΔtHb) was determined by summing the calculated values of ΔHbO_2 and ΔHb. Optical density data were analyzed in Matlab (v.6.5, Mathworks, Inc., Natick, MA).

6.2.5 Statistical Analysis

Statistical analyses were performed in SPSS version 11.0.1 for Mac OSX (SPSS, Inc., Chicago, Illinois, USA). A one-way analysis of variance (ANOVA) was performed to explore differences in the magnitude of ΔtHb, ΔHb, and ΔHbO_2 between skin color subgroups prior to pooling these data. Tukey post-hoc tests were performed as needed. A dependent samples t-test was performed

on the pooled data set and Wilcoxon signed ranks tests were performed on data in each of the skin color subgroups to determine if a significant decrease in tHb, Hb, or HbO_2 occurred when pressure was applied to the skin. The non-parametric Wilcoxon signed ranks test was chosen for subgroup analyses due to the small subgroup sample size (n=5).

Reliability of ΔtHb, ΔHb, and ΔHbO_2 measurement was described by the intra-class correlation coefficient (ICC), Model $3^{155,156}$, using data obtained during the three PSBTs at the heel of interest for each participant. ICC Model 3 is based on a two-way mixed model and calculates ICC values using analysis of variance (ANOVA) for repeated measures. Model 3 was selected because the tested raters were considered the only raters of interest and measurements were repeated within participants. ICCs were calculated for the overall group and within each skin color subgroup. Both single measure (ICC 3,1) and average measure ICCs (ICC 3,*k*) were reported. Due to their small magnitude, relative concentration data were multiplied by 10^6 prior to calculating ICCs in SPSS.

One-way ANOVA was used to explore differences among skin color subgroups for continuous medical and demographic variables (age, length of stay, number of diagnosis types, number of medications, Braden Scale scores) with Tukey post-hoc tests performed as needed. Chi-square analyses were used to explore differences between skin color subgroups for nominal variables (gender, race/ethnicity, types of diagnoses, incontinence status, PU history, PU sites, means of mobility, hand dominance), with post-hoc chi-square tests performed as needed. Munsell color tile values were treated as ordinal data and analyzed using the Kruskal-Wallis test. Post-hoc testing was performed using the Mann-Whitney U statistic (exact significance reported). Due to the exploratory nature of this preliminary study, the Bonferroni correction was not used for multiple comparisons tests.

6.3 RESULTS

6.3.1 Participant Characteristics

Participants' demographic and skin color characteristics are shown in Table 17. The average age of study participants was 81.2 years (range 67.1-90.4). Most participants were female (73%). No significant differences were found among the skin color subgroups with regard to age or gender. Race differed significantly between the light versus moderate and dark subgroups ($p<0.01$), with all moderate and dark-skinned participants described as Black or African-American and all light skin participants described as Caucasian or White. As expected based on the study's design, the forearm Munsell value differed significantly among the skin color subgroups with a median value of 7 for light skin, 5 for moderate skin, and 4 for dark skin ($p<0.01$ for all post-hoc comparisons). Heel Munsell values were significantly higher for the light skin group compared to the moderate ($p<0.05$) and dark ($p<0.01$) skin color subgroups, with no significant difference between moderate and dark-skinned participants (median heel Munsell value 7 for light skin, 6 for moderate skin, and 5 for dark skin).

Health-related characteristics of study participants are shown in Table 18. The majority of study participants had a length of stay between 0.9 and 56.2 months, with one subject having a much longer length of stay of 136.9 months. The median number of diagnosis types present per participant was 8 (range 5-13). The most frequently reported diagnosis types were genitourinary (principally incontinence), musculoskeletal/integument, psychiatric illness (principally Alzheimer's dementia), and vascular (Table 19). "Other" diagnoses were reported only in dark skin subgroup participants ($p<0.05$ for comparison to light and moderate subgroups). No other statistically significant differences for length of stay, number of diagnoses, or type of diagnoses were found among the skin color subgroups. The median number of medications prescribed for study participants was 12 (range 8-21), with no significant differences among the subgroups.

The median Braden Scale total score for study participants was 16 (range 13-18) with all subjects having activity/mobility subscale scores of 4 or 5 (Table 18). Braden Scale total or activity/mobility subscale scores did not differ significantly among the skin color subgroups. Seven of the 15 participants had a documented prior history of pressure ulcers, with most ulcers documented at the heel (5 participants) followed by the ischial tuberosities (2 participants), and

greater trochanters (1 participant). Of those participants with a history of heel pressure ulcers, 2 had pressures ulcers on the non-dominant side, 2 on the dominant side, and 1 on both sides. No significant differences were noted among the subgroups with regard to pressure ulcer history or location.

The skin color subgroups did not differ significantly with regard to incontinence status, means of mobility, or handedness (Table 18). Nearly all study participants were incontinent of urine and/or feces (14 of 15 participants). The majority of participants (80%) used manual wheelchairs as their primary means of mobility. Most participants were right-handed (87%).

Table 17. Demographic and skin color characteristics of participants

Variable [*Data Format*]	**All Skin Colors** (n = 15)	**Light Skin** (n = 5)	**Moderate Skin** (n = 5)	**Dark Skin** (n = 5)
Age in Years				
[*Mean (St. Dev.)*]	81.2 (7.5)	85.0 (6.7)	75.9 (7.3)	82.9 (6.7)
[*Median (Range)*]	82.9 (67.1-90.4)	86.9 (73.1-89.2)	75.7 (67.1-84.7)	82.9 (74.5-90.4)
Gender [*n*]				
Male	4	1	1	2
Female	11	4	4	3
Race/Ethnicity [*n*][a]				
White or Caucasian	5	5	0	0
Black or African-American	10	0	5	5
Forearm Munsell Value[b]				
[*Median (Range)*]	5 (3-7)	7 (7-7)	5 (5-6)	4 (3-4)
Heel Munsell Value[c]				
[*Median (Range)*]	6 (4-7)	7 (7-7)	6 (5-7)	5 (4-6)

[a] χ^2=15.0, p=0.001; Light vs. Dark χ^2=10.0, p=0.002, Light vs. Moderate χ^2=10.0, p=0.002, Moderate vs. Dark – not significant

[b] χ^2=13.462, p=0.001; p=0.008 for all skin color subgroup comparisons

[c] χ^2=10.020, p=0.007; Light vs. Moderate p=0.032, Light vs. Dark p=0.008, Moderate vs. Dark – not significant

Table 18. Health-related characteristics of participants

Variable	Data Format	All Skin Colors (n = 15)	Light Skin (n = 5)	Moderate Skin (n = 5)	Dark Skin (n = 5)
Length of Facility Stay in Months	*Mean (St. Dev.)*	28.6 (34.7)	22.8 (22.2)	22.2 (18.1)	40.9 (55.8)
	Median (Range)	13.3 (0.90-136.9)	13.3 (4.6-56.2)	12.3 (11.1-53.6)	14.8 (0.9-136.9)
Number of Diagnosis Types Present	*Mean (St. Dev.)*	8.5 (2.3)	7.4 (1.7)	8.4 (2.2)	9.6 (2.7)
	Median (Range)	8 (5–13)	7 (6–10)	9 (5–11)	10 (6–13)
Number of Medications	*Mean (St. Dev.)*	13.0 (4.0)	12.2 (3.3)	10.6 (2.6)	16.2 (4.3)
	Median (Range)	12 (8–21)	12 (8–17)	9 (9–15)	16 (11–21)
Braden Scale Total Score	*Mean (St. Dev.)*	15.5 (1.8)	14.4 (2.1)	16.4 (1.5)	15.6 (1.5)
	Median (Range)	16 (13–18)	14 (13–18)	16 (15–18)	16 (13–17)
Braden Activity/Mobility Score	*Mean (St. Dev.)*	4.4 (0.5)	4.2 (0.4)	4.6 (0.5)	4.4 (0.5)
	Median (Range)	4 (4–5)	4 (4–5)	5 (4–5)	4 (4–5)
Documented PU History	*n*	7	1	3	3
Incontinence Status	*n*				
Not Incontinent		1	0	1	0
Incontinent of Urine and/or Feces		14	5	4	5
Primary Means of Mobility	*n*				
Manual Wheelchair		12	4	5	3
Recliner		2	1	0	1
Power Wheelchair		1	0	0	1
Hand Dominance	*n*				
Right		13	5	5	3
Left		2	0	0	2

Table 19. Diagnosis types listed by number of participants with each diagnosis

Diagnosis Types	**All Skin Colors** (n = 15)	**Light Skin** (n = 5)	**Moderate Skin** (n = 5)	**Dark Skin** (n = 5)
Genitourinary	15	5	5	5
Musculoskeletal/Integument	14	4	5	5
Psychiatric Illness	13	5	4	4
Vascular	13	5	4	4
Endocrine/Metabolic and Breast	9	4	3	2
Eyes, Ears, Nose, Throat, and Larynx	9	4	2	3
Neurological	9	3	3	3
Heart	8	2	3	3
Respiratory	8	2	4	2
Upper Gastrointestinal	8	1	3	4
Hematopoietic	6	1	3	2
Lower Gastrointestinal	5	1	1	3
Liver	4	0	1	3
Renal	3	0	1	2
Other Diagnosis (es)[a]	3	0	0	3

[a] Overall χ^2 =7.5, p= 0.024; Light vs. Dark χ^2=4.286, p=0.038, Moderate vs. Dark χ^2=4.286, p=0.038

6.3.2 Key Spectral Features

Figure 20 shows examples of light contact, gentle pressure, and difference spectra acquired from participants in each of the skin color subgroups. The shapes of the skin spectra differ between skin color subgroups in a manner consistent with the presence of melanin. Optical density, a measure of light absorption, is highest in dark skin, followed by moderate and light skin. This is expected because the light absorption capacity of darker skin is increased by greater concentrations of light-absorbing melanin compared to light skin. In addition, the skin spectra show a steeper "slope" to their shape with increasing skin pigmentation. Melanin absorbs light in a sloped pattern in the visible region (Figure 2), therefore it is expected that the slope of the overall skin spectrum would increase as the presence of melanin in the skin increases.

The shapes of the skin spectra are also consistent with a decrease in Hb and HbO_2 content with pressure application. Optical density in the visible region decreased with gentle pressure application in all skin color subgroups. The difference spectra for all subgroups show two absorption maxima and one absorption minimum between 500 and 600 nm. This spectral shape is associated with the presence of Hb and HbO_2 in the skin, and indicates that the change in optical density may be attributed to changes in the concentration of Hb and HbO_2 in the sampled tissue.

6.3.3 Change in Hemoglobin Concentration with Pressure Application

The mean change in relative concentrations of tHb, Hb, and HbO_2 following pressure application is shown in Table 20. The relative concentration of tHb decreased significantly with pressure application for the overall group ($p<0.001$) and within each of the skin color subgroups ($p<0.05$) (Figure 21). The relative concentration of Hb (Figure 22) and HbO_2 (Figure 23) also decreased significantly ($p<0.001$ for overall group, $p<0.05$ for subgroups). The magnitude of ΔtHb, ΔHb, and ΔHbO_2 did not differ significantly among the skin color subgroups.

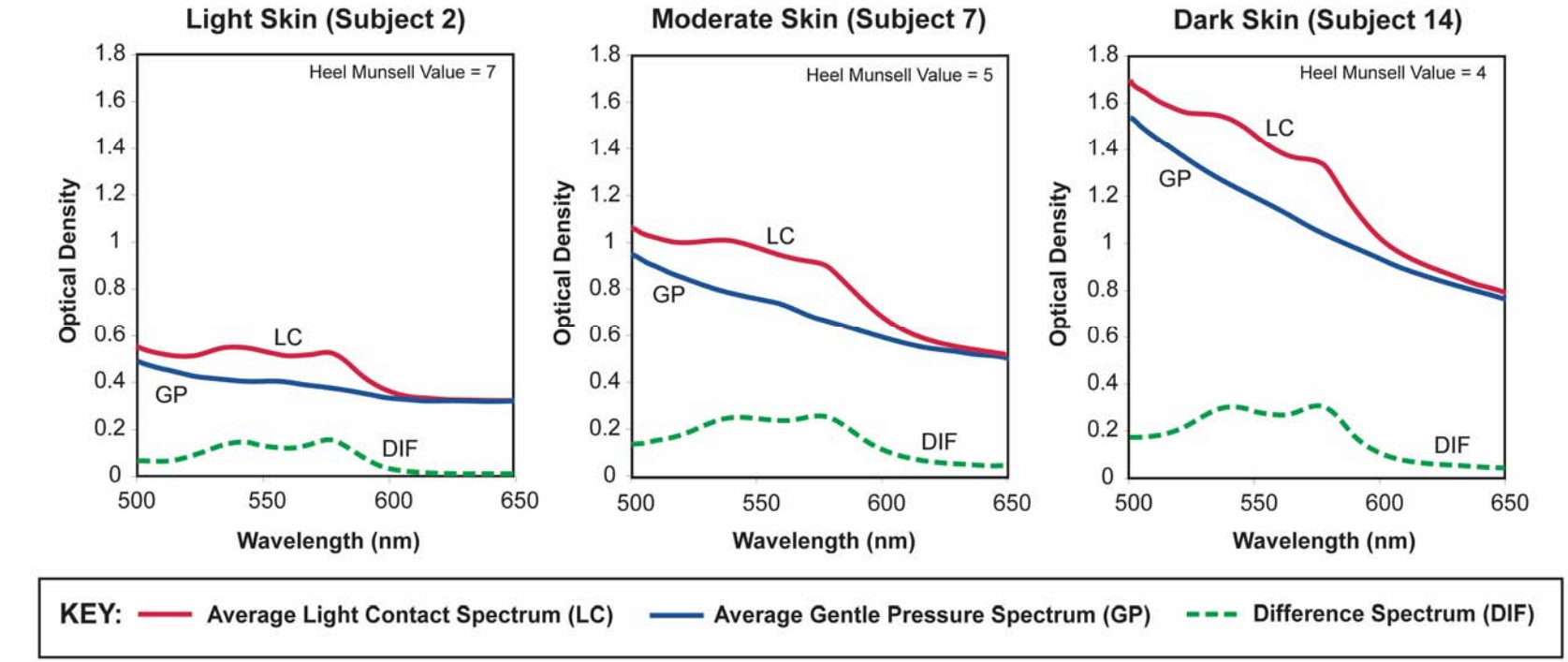

Figure 20. Examples of optical density spectra from participants with light, moderate, and dark skin

Table 20. Magnitude of mean change in relative concentrations of tHb, Hb, HbO_2 with pressure application

Species	**All Skin Colors** (n = 15)	**Light Skin** (n = 5)	**Moderate Skin** (n = 5)	**Dark Skin** (n = 5)
ΔtHb (μM * cm)	15.05 (5.07)	13.29 (4.06)	15.41 (6.91)	16.44 (4.38)
ΔHb (μM * cm)	8.35 (3.09)	7.23 (1.13)	8.83 (4.58)	9.00 (2.95)
ΔHbO_2 (μM * cm)	6.69 (2.78)	6.07 (3.71)	6.58 (2.61)	7.43 (2.30)

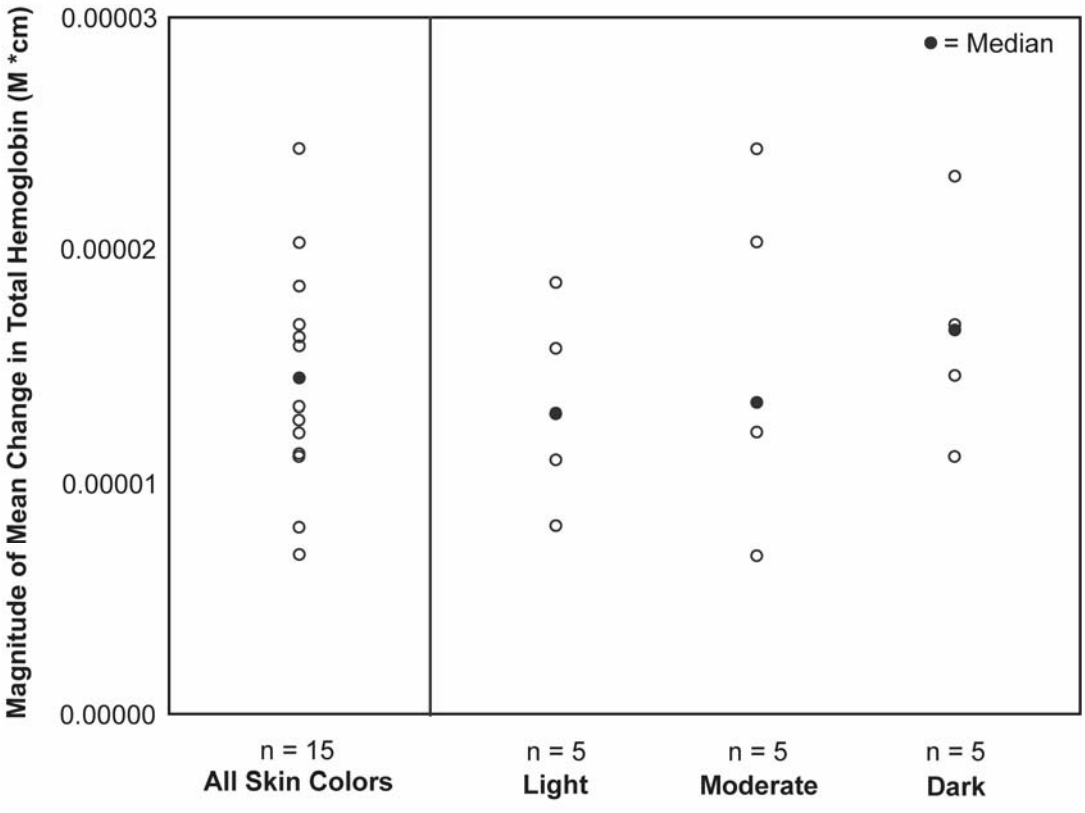

Figure 21. Magnitude of mean change in tHb

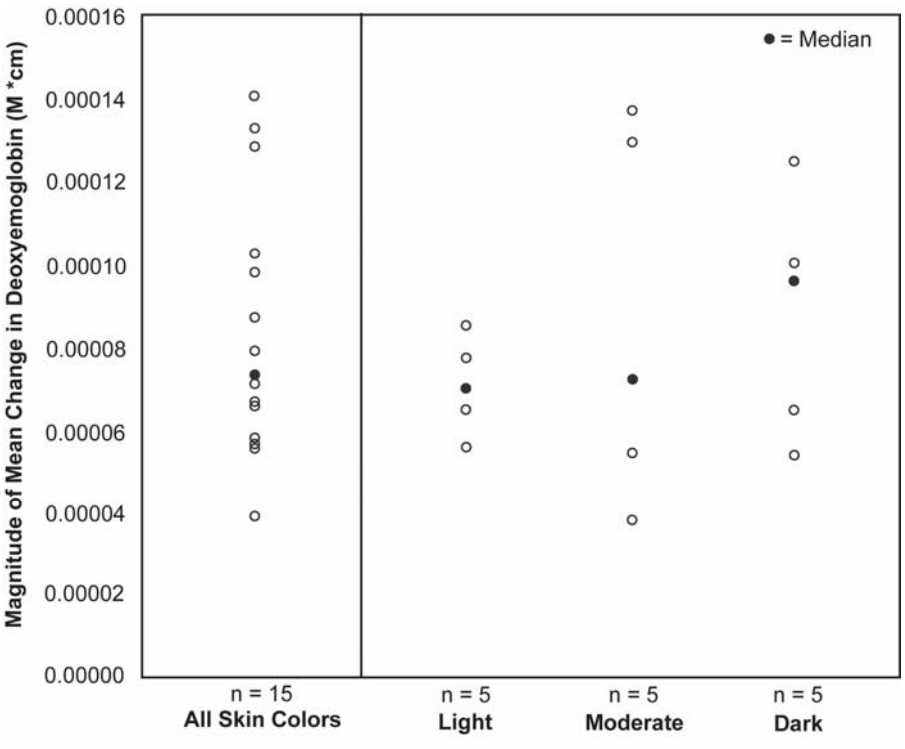

Figure 22. Magnitude of mean change in Hb

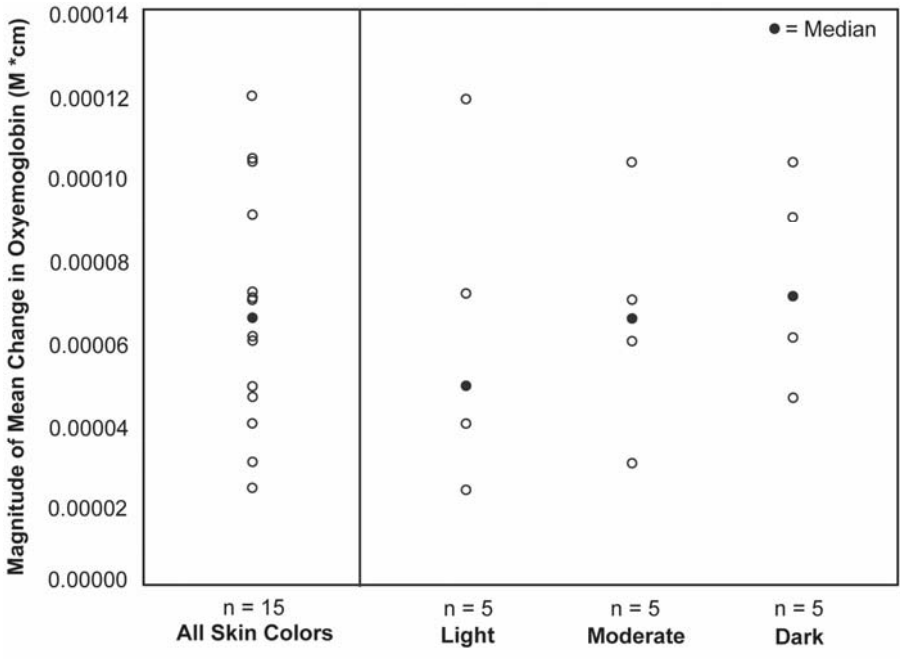

Figure 23. Magnitude of mean change in HbO_2

6.3.4 Reliability of ΔtHb, ΔHb, and ΔHbO_2 Measurement

Intra-rater reliability for the spectroscopic blanch response (ΔtHb) was moderate for single measures (ICC range 0.61-0.77, Table 21), and good to excellent for average measures (ICC range 0.83-0.91, Table 22). Intra-rater reliability for ΔHbO_2 measurement was moderate to good for single measures (ICC range 0.60-0.82) and good to excellent for average measures (ICC range 0.82-0.93). Results for ΔHb measurement reliability were mixed. Intra-rater reliability for ΔHb was generally moderate for single measures (ICC range 0.60-0.76) and good to excellent for average measures (ICC range 0.82-0.90) among the overall sample, moderate skin, and dark skin subgroups, but was very poor in the light skin group for both single and average measures (ICC range 0.05-0.14).

Table 21. Single measure intra-rater ICCs (95% confidence intervals in parentheses)

Species	**All Skin Colors** (n = 15)	**Light Skin** (n = 5)	**Moderate Skin** (n = 5)	**Dark Skin** (n = 5)
ΔtHb	0.61 (0.32, 0.83)	0.65 (0.09, 0.95)	0.67 (0.11, 0.95)	0.77 (0.28, 0.97)
ΔHb	0.60 (0.30, 0.82)	0.05 (-0.34, 0.76)	0.70 (0.16, 0.96)	0.76 (0.26, 0.97)
ΔHbO_2	0.69 (0.43, 0.87)	0.82 (0.38, 0.98)	0.60 (0.03, 0.94)	0.79 (0.33, 0.97)

Table 22. Average measure intra-rater ICCs (95% confidence intervals in parentheses)

Species	**All Skin Colors** (n = 15)	**Light Skin** (n = 5)	**Moderate Skin** (n = 5)	**Dark Skin** (n = 5)
ΔtHb	0.83 (0.59, 0.94)	0.85 (0.23, 0.98)	0.86 (0.27, 0.98)	0.91 (0.54, 0.99)
ΔHb	0.82 (0.57, 0.93)	0.14 (-3.32, 0.90)	0.88 (0.37, 0.99)	0.90 (0.51, 0.99)
ΔHbO_2	0.87 (0.69, 0.95)	0.93 (0.65, 0.99)	0.82 (0.07, 0.98)	0.92 (0.60, 0.99)

6.4 DISCUSSION

6.4.1 Detection of Changes in tHb, Hb, and HbO_2 with Pressure Application

This study demonstrated that a significant spectroscopic blanch response could be detected at the heels of light, moderate, and dark-skinned elderly individuals at risk for pressure ulcers. The spectroscopic blanch response is defined as the change in total hemoglobin (tHb) that occurs when pressure is applied to the skin. In skin that is free of pressure damage, the relative concentration of tHb is expected to decrease with pressure application due to the displacement of blood from the area where pressure is applied. As expected, both the raw spectra and relative concentration data derived from those spectra showed that tHb decreased significantly when pressure was applied to the skin. Visual inspection of skin spectra for all skin color subgroups showed a decrease in optical density between 500-600 nm, a region of high light absorption by Hb and HbO_2. In addition, the presence and location of two maxima and one minimum in the difference spectra indicate that the change in optical density between light contact and gentle pressure conditions can be attributed primarily to a decrease in Hb and HbO_2.

The magnitude of the spectroscopic blanch response (ΔtHb) was statistically significant for both the pooled sample ($p<0.001$) and within each of the skin color subgroups ($p<0.05$), as were changes in Hb and HbO_2. These data indicate that TRS can be used successfully to measure the blanch response at the heels of light, moderate, and dark-skinned elderly individuals at risk for pressure ulcers. Furthermore, these data suggest that age-related skin changes and the presence of cardiovascular and other health conditions does not adversely affect the ability of spectroscopy to measure the blanch response. The PSBT protocol was well-tolerated by participants, with no adverse events, or verbal or non-verbal indications of discomfort during the spectroscopic assessment.

No statistically significant differences in the magnitude of ΔtHb, ΔHb, and ΔHbO_2 were identified between skin color subgroups. However, visual inspection of the data revealed a tendency for the magnitude of change to increase with increasing skin pigmentation, particularly for HbO_2. The small subgroup sample size (n=5) makes it difficult to determine if a true difference in the magnitude of ΔtHb, ΔHb, and ΔHbO_2 exists among subgroups. The power to detect a difference is likely to be low and the distribution of data is greatly influenced by inter-

subject variability in such a small sample. The magnitude of ΔtHb, ΔHb, and ΔHbO_2 is not expected to differ between skin color subgroups, but data from a larger sample is needed to confirm this expectation.

The spectroscopic blanch response findings of the present study are similar to those of the pilot study conducted in healthy, young individuals, discussed in Chapter 4. Differences in the spectral data processing approaches used for these data and those reported for the pilot study preclude direct comparison of the magnitude of ΔtHb in these studies. However, both studies detected a statistically significant spectroscopic blanch response at the heel in individuals with light and dark skin pigmentation. The level of significance for ΔtHb in the subgroups for the current study ($p<0.05$) is somewhat lower than that of the light and dark skin subgroups in the pilot study ($p<0.001$), which may be attributed to the smaller subgroup sample size (n=5 vs. n=15). In combination, the results of the current study and pilot study demonstrate that a significant blanch response may be detected at the heel regardless of age or pressure ulcer risk status.

The findings at the heel in the current study are also consistent with those described at the forearm by Matas and colleagues.[24] In Matas' work, cyclical loads of up to a maximum of 50mmHg were applied to the dorsal forearm via an indenter featuring a stepper motor attached to a benchtop device. A significant change in total hemoglobin between the high and low pressure conditions ($p<0.01$) was observed in both light and dark skinned participants. Despite differences in participant population, loading method, pressure magnitude, and body site, both Matas' investigation and the current study detected a significant blanch response using spectroscopy. The similarity of results between the investigations supports the use of spectroscopy as a tool for assessing the blanch response.

6.4.2 Variability in Measurement of ΔtHb, ΔHb, and ΔHbO_2

The ICC data demonstrate that the spectroscopic blanch response may be detected with moderate or greater intra-rater reliability in individuals of advanced age with health conditions that place them at risk for pressure ulcers. In general, intra-rater reliability for ΔtHb and ΔHbO_2 was moderate for single measures (ICCs ≥ 0.60) and good to excellent for average measures (ICC $\geq$

0.82) for both the pooled sample and all skin color subgroups. As in the pilot study, it is likely that the examiner's ability to view the skin spectrum during data collection may have provided feedback that assisted measurement reliability. There is no obvious physiological explanation for the poor reliability of ΔHb measurement in the light skin subgroup (ICC=0.05-0.14). The variance in ΔHb for the light skin group was lower than that of the other skin color groups, which may have influenced the magnitude of the ICC. Data from a larger sample size may have produced different reliability results. Notably, ΔtHb measurement reliability for the light skin subgroup remained moderate to good despite poor ΔHb measurement reliability. As in the pilot study discussed in Chapter 4, average measure ICCs were higher than single measure ICCs, indicating excellent intra-rater reliability when the mean of multiple ratings is the unit of analysis.

The 95% confidence intervals around the ICCs were very wide, particularly for single measures, with a range as large as 0.09-0.95 for ΔtHb (light skin subgroup). These confidence intervals are wider than those reported for heel data in the pilot study, where the lowest confidence interval boundaries were 0.31 for single measure and 0.57 for average measure ICCs. The small sample size, particularly for the subgroups, likely contributed to the lack of precision in the reliability estimate. Data from a larger sample is needed to quantify intra-rater reliability with greater confidence.

ICC values for ΔtHb in the current study are generally lower than those reported for the pilot study, where ICCs exceeded 0.80 for single measures and 0.92 for average measures. Intra-rater reliability may be lower in the current study for several reasons. First, limitations in participants' range of motion and the setup of residents' rooms made it more difficult for the examiner to position herself in a manner that allowed her to view both the test site and the computer monitor easily. This setup reduced the feedback provided by observation of the skin spectra during data collection. Second, variations in pressure application may have contributed to lower reliability. The examiner found it more challenging to maintain the appropriate amount of spring displacement in the current study than in the pilot. This was due in part to difficulty placing the probe in a manner that allowed full view of the filament and due to difficulty finding a comfortable and stable hand position during the PSBT. Third, residents sometimes moved spontaneously during the PSBT. In several cases, residents' cognitive status prevented them from following directions to keep their feet still during the assessment. In other cases, residents

fell asleep during the PSBT and moved in their sleep or in response to the examiner's contact with the heel site. Others coughed frequently, creating body movement. While PSBTs were repeated in cases where considerable movement occurred, it was not always feasible to obtain 3 PSBT measurements that were unaffected by movement. Finally, participants in the current study frequently had medical conditions that affected circulation, possibly contributing to variability in skin blood content and response to pressure.

Inter-participant variability was high, with coefficients of variation (CV) ranging between 27-45% for ΔtHb, 15-52%, for ΔHb, and 31-61% for ΔHbO_2. These CV are similar to, or slightly lower, than those observed in the pilot study (range 39-69% over all species). High inter-participant variability has also been reported by other investigators who have used spectroscopy to examine hemoglobin changes associated with tissue loading.[30-32] Inter-subject variability may arise from several sources, including variability in the examiner's application of pressure to the skin, subject movement, and variations in skin blood content between individuals due in part to medical conditions affecting circulation.

6.4.3 Summary

This investigation demonstrates that a significant spectroscopic blanch response (ΔtHb) can be detected at the heel in light, moderate, and dark-skinned elderly individuals at risk for pressure ulcers. This finding is similar to that of pilot work conducted in a young, healthy population and to findings at the forearm by other investigators. Findings demonstrate that the spectroscopic blanch response can be measured with moderate or greater intra-rater reliability in those with multiple medical conditions and advanced age. Additional data from a larger sample would be of benefit to determine if there are differences in the magnitude of ΔtHb between skin color groups and to improve the precision of intra-rater reliability estimates. The significance of this work and directions for future research will be discussed further in Chapter 7.

7.0 SUMMARY AND RECOMMENDATIONS

7.1 REVIEW OF OBJECTIVES

Pressure ulcer researchers and clinical experts have frequently reported that pressure damage in intact skin is difficult to detect, particularly in darkly pigmented skin. Tissue reflectance spectroscopy (TRS) has been identified as a possible means of improving pressure damage detection because of its ability to provide information on hemoglobin content regardless of skin pigmentation. Few studies have applied TRS to the problem of pressure damage detection in intact skin.

The goal of this dissertation was to examine the ability of tissue reflectance spectroscopy (TRS) to detect the blanch response, a clinical indicator of pressure damage in intact skin. Three studies were performed to accomplish this goal. Study 1 was a laboratory-based study in which the blanch response was assessed at the heel and sacrum of light and dark-skinned healthy participants using a portable TRS system. Study 1 had two objectives:

1.1 To test the hypothesis that total hemoglobin will decrease significantly when pressure is applied to light and dark healthy skin

1.2 To assess the intra-rater reliability of spectroscopic blanch response measurement in participants with healthy skin

After the completion of Study 1, it was determined that a reliable means of describing participant's skin color was needed to assist subject recruitment for subsequent studies of spectroscopic blanch response assessment. To address this need, a second laboratory-based study (Study 2) was conducted in a population of light, moderate, and dark-skinned healthy participants with the following objective:

2.1 To examine the reliability of skin color assessments performed using Munsell color tile matching and colorimetry

Once a reliable means of skin color description was identified, a third study (Study 3) was conducted to replicate the findings of Study 1 in a population of light, moderate, and dark-skinned elderly nursing home residents at risk for pressure ulcers. Study 3 had two objectives:

3.1 To test the hypothesis that total hemoglobin will decrease significantly when pressure is applied to the skin of elderly nursing home residents at risk for pressure ulcers, regardless of skin color

3.2 To assess the intra-rater reliability of spectroscopic blanch response measurement in elderly nursing home residents at risk for pressure ulcers

Each of these studies has been discussed in detail in Chapters 4-6. The following sections will summarize key findings of each of these studies, their limitations, contributions, and recommendations for future work.

7.2 SUMMARY OF FINDINGS

7.2.1 Study 1 - Pilot Study to Detect the Blanch Response in Lightly and Darkly-Pigmented Skin Using Tissue Reflectance Spectroscopy

Three point spectroscopic blanch tests (PSBTs) were performed at the heel and sacrum of 30 young, healthy participants in two positions: semi-sidelying and prone. Half of the participants had light skin (blanch response visible at the forearm in response to finger pressure) and half had dark skin (blanch response not visible at the forearm). At the heel, a significant decrease in tHb, S_tO_2, HbO_2, and Hb ($p<0.001$) occurred in both the light and dark skin subgroups in both semi-sidelying and prone test positions. The magnitude of the spectroscopic blanch response (ΔtHb) at the heel was not significantly different in light versus dark skinned-participants or between test positions. Single measure ICCs for ΔtHb measurement at the heel were 0.80 or higher, while

average measure ICCs exceeded 0.90, indicating good to excellent intra-rater reliability. Considerable inter-subject variability was observed at the heel with coefficients of variation (CV) for ΔtHb, ΔS_tO_2, ΔHbO_2, or ΔHb measurements ranging from 39-69%.

In contrast to the heel, a significant blanch response was not detected at the sacrum. The magnitude of ΔtHb was not significantly different from zero at the sacrum for either light or dark-skinned participants in either prone or semi-sidelying. Examination of tHb timecourses for individual subjects showed that tHb could decrease, increase, or remain unchanged with pressure application. The magnitude of ΔtHb did not differ significantly between skin color subgroups or test positions. Intra-rater reliability for ΔtHb was typically lower than that at the heel. Intra rater reliability for sacral ΔtHb was poor to moderate for single measures (ICC range 0.32-0.69) and moderate to good for average measures (ICC range 0.58-0.87). Between-subjects variability was much greater than at the heel, with coefficients of variation for ΔtHb, ΔS_tO_2, ΔHbO_2, and ΔHb ranging from 134% to 7067%.

In summary, Study 1 demonstrated that a significant spectroscopic blanch response could be detected with good intra-rater reliability in healthy skin, regardless of skin color or test position, at the heel but not at the sacrum. Based on these results, it was determined that adjustments to the TRS instrumentation would be necessary to improve blanch response detection at the sacrum prior to conducting future studies at this site. However, the results of Study 1 assisted in the design of a subsequent study to examine spectroscopic blanch response measurement at the heels of individuals at risk for pressure ulcers.

7.2.2 Study 2 - Reliability of Skin Color Assessment via Munsell Color Tile Matching and Colorimetry

A reliable means of classifying participants by skin color was needed for subsequent studies of the blanch response. An investigation was conducted to evaluate the reliability of two skin color assessment techniques: Munsell color tile matching and colorimetry. Two examiners (B and C) performed three skin color assessments at the volar forearm of ten healthy participants by matching participants' skin to the 5YR set of Munsell color tiles and performing skin light reflectance measurements with the Minolta Chromameter (CR-300).

Reliability was generally higher for colorimetry than for color tile matching. Reliability was particularly high for the *L** and *b** color descriptors (intra and inter-rater ICCs exceeded 0.97 for *L** and *b**). Intra-rater ICCs for *a** exceeded 0.85 and inter-rater ICCs typically exceeded 0.84. Munsell value assessment was typically more reliable than chroma. Intra-rater agreement for Munsell value was good to excellent for Examiner B (93% agreement, kappa 0.87–1.00) but was moderate for Examiner C (80% agreement, kappa 0.71-0.73). Intra-rater agreement for chroma was moderate to high for Examiner B (93% agreement, kappa 0.78–1.00) and poor for Examiner C (60% agreement, unable to calculate kappa). Inter-rater agreement was moderate to poor for value (74% agreement, kappa typically 0.46-0.73) and poor for chroma (61% agreement, kappa 0.09-0.21).

The results of Study 2 indicated that colorimetry was generally more reliable than Munsell color tile matching. However, a colorimeter would have been very costly to purchase or rent for the duration needed for the planned spectroscopic blanch response study in nursing home residents (Study 3). Although Munsell color tile matching showed moderate to poor intra-rater reliability for Examiner C and moderate to poor inter-rater reliability, Munsell value descriptions were highly reliable within Examiner B, who would be solely responsible for all subject enrollment and data collection in the planned study. Therefore, it was determined that Munsell color tile matching was sufficiently reliable to stratify participants in light, moderate, and dark skin color groups for Study 3.

7.2.3 Study 3 – Spectroscopic Assessment of the Blanch Response in Elderly Nursing Home Residents at Risk for Pressure Ulcers

Study 3 was conducted to verify that the spectroscopic blanch response could be detected reliably in the skin of individuals at risk for, but currently without, pressure ulcers. Fifteen residents age 65 and older who were at risk for pressure ulcers were recruited from six long-term care facilities in the Greater Pittsburgh area. Participants were enrolled in light, moderate, and dark skin color subgroups (n=5 per subgroup) via Munsell color tile matching of each resident's forearm skin. Three point spectroscopic blanch tests were performed at the dominant-side heel of each participant at his/her bedside.

The magnitude of ΔtHb was statistically significant ($p<0.001$) for the overall sample and within each of the skin color strata ($p<0.05$ for all strata). The magnitude of ΔtHb was not statistically different among the skin color subgroups, although visual inspection of the data suggested that the magnitude of change tended to be greater in darker skin. Intra-rater reliability for ΔtHb was moderate for single measures (ICC range 0.61-0.77), and good to excellent for average measures (ICC range 0.83-0.91).

In combination, the results of Study 1 and Study 3 indicate that a significant blanch response may be detected at the heel regardless of age or pressure ulcer risk status. Furthermore, Study 3 demonstrated that the spectroscopic blanch response could be measured with moderate or greater intra-rater reliability in those with multiple medical conditions and advanced age.

7.3 LIMITATIONS

The primary limitation of this work is that it demonstrates successful blanch response detection at only one body site, the heel. The heel is typically less pigmented than other areas of the body, even in very dark-skinned individuals. Therefore, it can be argued that the studies described herein are not a stringent test of spectroscopy's ability to measure a blanch response regardless of skin pigmentation. Furthermore, many body sites at risk for pressure ulcers, such as the greater trochanters and ischial tuberosities, are more similar in structure to the sacrum than to the heel, both in the amount of soft tissue present and the extent of skin pigmentation. Investigators must determine why the expected spectroscopic blanch response was not observed at the sacrum and develop instrumentation that addresses the challenges encountered at this site. Spectroscopy must be able to detect a blanch response at multiple body sites at risk for pressure ulcers if it is to become a useful clinical tool.

One must also consider that the processing techniques used to derive relative concentration data from skin spectra are based on assumptions about the optical properties of skin. The success of spectroscopic blanch response measurement, particularly in those with darkly-pigmented skin, is highly dependent on the accuracy of these assumptions and the ability of data processing algorithms to account for the presence of melanin in the skin. Furthermore,

direct comparison of results from different studies may be difficult depending on the nature of the data processing algorithms used in those studies. The TRS technique described in this dissertation does not provide an absolute or direct measurement of the concentration of a particular chromophore (i.e. hemoglobin) in the sampling area. The data reported are quantities thought to vary with chromophore concentration—measures of "relative" concentration. While relative concentration data are sufficient to address the objectives of this dissertation, the magnitude of these data cannot be directly compared between studies that use different approaches to quantify changes in tissue hemoglobin content. Despite these issues, the non-invasive nature of TRS is highly beneficial from a clinical standpoint, and may counterbalance the lack of absolute information on chromophore concentration.

In addition, hemoglobin data in Studies 1 and 3 are derived using data from the visible region only. However, near-infrared spectroscopy has also been used to examine hemoglobin in tissue[24,27-29,146], and may offer advantages over visible light spectroscopy.[131] Melanin has little light absorbance in the near-infrared region compared to the visible region, reducing the need to account for melanin's contribution to the spectral signal, particularly in those with darkly pigmented skin. Longer wavelength, near-infrared light, although more highly scattered, is absorbed less strongly by tissue compared to visible light and can be used to sample more deeply into tissue. Matas and colleagues demonstrated that a significant blanch response could be detected in both light and dark forearm skin of healthy subjects in both the near-infrared and visible light regions.[24] It would be of benefit to examine both visible and near-infrared data in future investigations when possible to determine which region provides the most useful data for assessing the blanch response.

Another limitation of this work was the method used to control the force applied by the hand-held indenter. In Studies 1 and 3, the force applied to the skin was controlled by manually compressing a spring in the hand-held indenter. The desired spring displacement was determined based on the area of the indenter head and the properties of the spring. A more "high tech" method of force control, including the integration of a force transducer in the hand-held indenter, was considered but was complicated by the small size of the indenter and the configuration of the fiber optic probe. Furthermore, the "low tech" manual spring displacement method of force control did not require additional electronics that would have been costly, would have added bulk to the system, or may have malfunctioned during the testing process. For these

reasons, it was determined that the manual spring displacement method of force control would be most appropriate. However, this method of force control did not provide a means of controlling the rate of force application and was subject to disruption if either the examiner or participant moved during testing. It also did not provide feedback to verify that the force delivered to the skin was at the expected level, or a record of the force applied during testing. Observation of skin spectra during testing showed that the amount of force applied through the indenter had a considerable effect on the shape of the skin spectrum, therefore it is important that force be controlled as precisely as possible. A more precise means of force control in future studies would enhance the reproducibility of blanch response measurement. Furthermore, simultaneous collection of force and blanch response data would allow investigators to examine the relationship between the amount of force and the extent of blanching—data that would be useful in designing clinical devices to assess the blanch response.

Another limitation related to the indenter is the presence of "edge effects". Edge effects occur when there is a high concentration of pressure around the periphery of the indenter. Ideally, pressure should be applied as evenly as possible over the indenter surface. Although the probe edges were rounded to reduce edge effects, visual inspection of the skin immediately after removal of the indenter from the skin surface showed greater blanching (when blanching was visible) around the edges of the area to which pressure was applied. This is problematic because the fiber optics used to measure blanching are located in the center of the indenter. Enhancing the curvature of the probe's edges may be of benefit in order to reduce edge effects in future testing.

The small sample size, particularly in Studies 2 (total n=10) and 3 (total n=15), must also be considered when examining the studies' findings. The precision of reliability estimates for both skin color assessment and ΔtHb measurement would have been enhanced by larger samples of data. In addition, the subgroup sample size in Study 3 was too low to fully explore possible differences in the magnitude of ΔtHb between skin color groups. This limitation is difficult to address, particularly with respect to recruiting larger numbers of individuals with moderate to dark skin. The proportion of residents with dark skin was observed to be low in the facilities participating in Study 3. In addition, residents with moderate to dark skin frequently had legal guardians who were not authorized to enroll them in research. In future investigations, it may be of benefit to consider recruiting participants from other settings (i.e. those receiving care at

home) or geographical areas in which greater racial and ethnic diversity may be found. Future research recruitment may also be improved by outreach efforts to educate individuals with moderate to dark skin and their legal representatives about the benefits of research participation and the legal documentation necessary to allow decisionally impaired individuals to participate in research.

7.4 RECOMMENDATIONS FOR FUTURE WORK

The findings of this dissertation suggest that spectroscopic blanch response measurement may be a useful skin assessment tool. However, further research is needed in a number of areas in order to evaluate the clinical value of spectroscopy in pressure damage detection:

- Successful blanch response detection must be demonstrated at other of body sites at risk for pressure ulcers, particularly those with higher amounts of soft tissue and pigmentation than at the heel.
- Data are needed regarding the inter-rater reliability of spectroscopic blanch response measurement at the heel and other body sites at risk for pressure ulcers.
- Future work is needed to compare the magnitude of the spectroscopic blanch response between sites with and without pressure damage in intact skin. Spectroscopy must be able to differentiate lesioned sites from non-lesioned sites if this technique is to have diagnostic value.
- Additional research is needed to examine whether spectroscopy is capable of identifying signs of pressure damage in intact skin before they are observed clinically.
- Future work should include examination of data from both the visible and near-infrared regions of the spectrum to determine which wavelengths of light provide the most useful data for assessing the blanch response.
- In addition to blanch response detection, the ability of spectroscopy to identify and measure erythema would be of value both in pressure damage assessment and in other wound care applications. Further research on the use of TRS to assess erythema is needed.

- Researchers should also examine the ability of other non-invasive techniques to provide information on pressure damage. Optical techniques such as spectroscopic imaging, which provides information on both the presence and spatial distribution of chromophores in tissue, may be very valuable in pressure ulcer assessment and should be explored further. Temperature measurement, $TCPO_2$, and ultrasound also deserve further study to determine their ability to improve pressure damage detection in both light and dark skin.
- The impact of improved pressure damage detection on clinical outcomes must also be examined.

Additional work is also needed in the area of skin color assessment:

- Additional information is needed on the reliability of skin color assessment in those with medical conditions that create changes in skin color, such as peripheral vascular disease.
- Data are needed regarding the reliability of skin color assessments performed in "real world" clinical environments, where light conditions and other factors are more difficult to control than in laboratory settings.
- The effect of training and experience on skin color assessment requires further study, and may be of particular value in determining if color matching is sufficiently reliable for clinical and research applications.
- Investigators should also examine the reliability of other devices and techniques for skin color measurement such as spectrophotometry.
- Additional information on inter-device reliability would also be useful, particularly for projects involving multiple research centers.
- More data are needed to describe the agreement between subjectively determined skin color descriptors (i.e. Munsell hue, value, and chroma selected through color matching) and those obtained by a device (i.e. Munsell descriptors reported by colorimeter or spectrophotometer).

7.5 CONTRIBUTIONS

The primary contribution of this work is evidence to support the use of TRS as a tool for assessing the blanch response. In combination, the findings of Study 1 and Study 3 demonstrate that a significant blanch response may be observed at a site at risk for pressure ulcers (the heel) regardless of age, skin pigmentation, or the presence of medical conditions that place individuals at risk for pressure ulcers. These data will encourage researchers and manufacturers to develop devices that use spectroscopic technology to assess signs of pressure damage in light and dark intact skin. In addition to raising interest in the use of spectroscopy for pressure damage assessment, the studies' findings provide data to assist in the selection of instrumentation for future studies and the design of clinical devices by manufacturers. Even "negative" results, such as Study 1's finding that the blanch response was difficult to detect at the sacrum, will assist device development by identifying challenges to be considered in instrument designs. Clinical devices capable of detecting pressure damage in intact skin would have considerable clinical impact by reducing disparities in pressure ulcer detection between those with light versus dark skin, facilitating timely intervention to address existing pressure damage or prevent progression, and improving the accuracy of pressure ulcer incidence and prevalence estimates.

A secondary contribution of this work is the data it provides on intra and inter-rater reliability of two methods of skin color assessment, color tile matching and colorimetry. Colorimetry is frequently used in clinical practice and research studies to assess skin color, but few investigators have reported data on its measurement reliability. The results of Study 2 indicate that colorimetry is highly reliable both within and between raters. These data help to validate the use of colorimetry as a skin color assessment tool in clinical and research applications. Study 2 also provides new data regarding the use of Munsell color tiles for skin color description. Prior to Study 2, only one other study was identified that reported data on the agreement of skin color description via color tile matching.[151] However, it did not report agreement data specific to each Munsell color descriptor (hue, value, chroma) and did not assess inter-rater reliability. Study 2 addresses this gap in knowledge by reporting data on both intra and inter-rater reliability for Munsell value and chroma data. These data will assist researchers and clinicians in determining whether Munsell color tile matching will be appropriate for their applications.

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