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Effect of Skin Pigmentation on Near Infrared Spectroscopy

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Abstract

The purpose of this study was to determine the effects of skin pigmentation regarding Near Infrared Spectroscopy (NIRS) tissue oxygen saturation values (StO_2). The study examined NIRS values in individuals with varying skin pigmentation on the anterior compartment of the lower leg and volar forearm to determine if correlation exists among three NIRS devices, the EQUANOX, Casmed, and INVOS. Skin pigmentation was measured on the anterior lower leg (AL) and volar forearm (VF) of participants using a noninvasive colorimeter that employed reflective spectroscopy to produce a quantitative value for erythema (skin "redness") and melanin (skin pigment). Muscle oxygenation was measured using three oximetry devices with sensors placed in the same areas. The EQUANOX device showed no significant correlation with skin pigmentation, while the Casmed and INVOS devices showed moderate and significant correlation with skin pigmentation, respectively. Different devices have different abilities to remove confounding variables, such as skin pigmentation and erythema, which may affect clinical decision-making, and affect the use of NIRS technology.

Keywords

Near Infrared Spectroscopy, Skin Chromophores, Confounding Factors, Variability between Manufacturers

1. Introduction

Near-Infrared Spectroscopy (NIRS) is a useful technology that allows for noninvasive measurement of percentage of oxygenated hemoglobin as well as local blood flow and oxygen consumption [1] [2]. NIRS devices have

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three primary components: 1) A light source; 2) An optode to detect unabsorbed light; 3) A computer to perform calculations related to absorption based on diffusion theory (Beer-Lambert Law). This theory correlates absorbance to the extinction coefficient, path length, and concentration of light absorbers in the sample. Devices used in medicine typically consist of a sensor pad, containing both the light source and optode, connected by wire to a nearby computer. The sensor pad is typically coated with an adhesive and may be placed superficially on the skin. Devices utilize two or more wavelengths of light with sensors in the pad to detect the absorption of each. The depth of penetration of the light is roughly half of the distance between the light source and the sensor. Melanin has also been shown to impair light penetration and reported rSO_2 values [3]-[5].

The values reported by NIRS indicate the relative oxygenation of hemoglobin under the sensor and is mostly confined to the microcirculation as larger vessels absorb the light completely. The microcirculation consists of arterioles, capillaries, and venules. Because roughly sixty percent of blood volume is found in the venous system, values tend to be lower and reflect hemoglobin that has off-loaded it's oxygen to tissues in contrast to pulse-ox monitoring which reflects the saturation of arterial blood.

NIRS has found application in medicine and several NIRS devices are currently FDA approved for monitoring cerebral perfusion. Typical clinical settings where this could prove useful include those undergoing cardiac surgery, or who are at risk of systemic shock and resulting cerebral hypoperfusion. An additional utilization of the technology is its application in the detection and diagnosis of acute compartment syndrome.

Gianotti *et al*. found that NIRS StO_2 values were significantly lower than control values in limb compartments of trauma patients with compartment syndrome [6]. Shuler *et al*. have demonstrated that NIRS values decrease significantly with decreasing lower limb perfusion pressures in patients with lower limb trauma [7]. Studies have also shown differences in NIRS values between injured vs. non-injured limbs. A non-injured contralateral limb may serve as a control in evaluating and detecting a possible compartment syndrome [3]. Because skin pigmentation is a factor known to confound NIRS values, it is vital to understand its effects on device measurements. Wassenaar & Van den Brand demonstrated a relationship between dark skin color and loss of signal in NIRS devices in 2005 [5].

This study seeks to determine skin pigmentation's effects on NIRS readings. NIRS has the potential to provide non-invasive, real time data to the clinician to aid them in the diagnosis and subsequent treatment of compartment syndrome. Because skin pigmentation varies so widely among individuals, it is vital to understand and to account for these differences as well as determine differences between technologies before the data can be integrated into the decision making process. The hypothesis is that there are no differences between technologies for skin pigment.

2. Materials and Methods

2.1. Study Participants

Approval for the study was received from the local Institutional Review Board. Enrollment came from a clinical patient population between the dates of May 20, 2013 and May 28, 2014. Participants were otherwise healthy and excluded if they were under the age of 18, over 65, or pregnant.

Participants were patients, screened and recruited during regular clinical visits. Eligible subjects were males and non-pregnant females between the ages of 18 and 65 who were able and willing to participate. Data on age, race, body mass index (BMI), and gender were collected.

2.2. Measuring Skin Color

Once patients were deemed eligible and went through the informed consent process, their skin pigmentation was measured on the anterior compartment of the lower leg (AL) and volar forearm (VF) using the Cortex Industries DSM-II (Cortex Technology ApS, Denmark). The DSM_II is a noninvasive colorimeter that employs reflective spectroscopy to produce a quantitative value for erythema (skin redness) and melanin (skin pigment). Participants were in the seated position as measurements were recorded. Three measurements were obtained over each compartment and averaged for each subject.

2.3. Measuring Muscle Oxygenation

Following determination of pigmentation, muscle oxygenation was measured using three oximetry devices with

sensors placed in the same position. This study employed the INVOS5100C (Somanetics, Troy, MI), EQUANOXTM Model 7600 (Nonin Medical Inc., Plymouth, MN), and the CASMED MC-2030C (CASMED, Branford, CT). Sensors were placed over the same area where pigmentation was measured. Data was recorded following 4 cycles of a stable value. The INVOS cycles every 6 seconds, versus every 1.5 seconds for the EQUANOXTM and CASMED machines. Oxygenation values were obtained after approximately 60 seconds with each machine. Again, subjects were in the seated position.

2.4. Data Analysis

Final skin color measures for each patient were the average of the three recorded measurements for each variable (melanin, erythema, red, green, and blue). Correlations were calculated using Pearson's correlation coefficients and associated p-values. Means testing was conducted using ANOVA. All calculations were performed using STATA statistical software.

3. Results

Over a two-month period, 196 subjects agreed to participate in the study. The characteristics of the study population can be seen in **Table 1**.

The colorimeter was able to detect differences in mean skin color measures (mealanin, erythema, red, blue and green colors) by race for both the anterior leg and volar forearm compartments as seen in **Table 2**. The correlations between mean skin pigmentation measures (melanin and erythema) were analyzed by ethnicity and anatomical location in **Table 3**. In both the anterior leg and volar forearm compartments there was a clear trend

Table 1. Subject demographic characteristics.

Characteristic	N = 196	
	Mean (SD)	Range
Age (years)	45.70 (14.10)	18 - 65
BMI (kg/m^2)	30.14 (6.94)	17.85 - 50.21
Gender	Males (%)	Females (%)
	94 (47.96)	102 (52.04)
Race/Ethnicity	Frequency	Percent
Caucasian	139	70.92
African-American	42	21.43
Hispanic	12	6.12
Asian	2	1.02
Native American	1	0.51

Table 2. Differences in skin color between races.

	Hispanic (12)	Caucasian	African-American	Asian
Caucasian (140)	a, b, c, d, e, f, g, h, i, j			
African-American (41)	a, b, e, f, h, j	a, b, c, d, e, f, g, h, i, j		
Asian (2)	-	-	*b, f, h	
Native American (1)	*c, e, g, h, i, j	-	*a, b, c, d, e, f, g, h, i, j	-

Significant differences are indicated by letters in each cell. Each letter corresponds to a different measure as follows: [a]Melanin (Anterior), [b]Melanin (Volar), [c]Erythema (Anterior), [d]Erythema (Volar), [e]Red (Anterior), [f]Red (Volar), [g]Green (Anterior), [h]Green (Volar), [i]Blue (Anterior), [j]Blue (Volar). A dash line indicates that no significant differences were found. Numbers in parentheses represent sample size for each race. Sample sizes for Asian and Native American participants are too small for definitive conclusions (*).

Table 3. (a) Summary statistics of skin color by race (anterior leg compartment); (b) Summary statistics of skin color by race (volar forearm compartment).

(a)

Race/Ethnicity [N]	Melanin	Erythema	Red	Green	Blue
Caucasian [139]					
Mean (SD)	41.87 (7.05)	12.78 (3.09)	98.49 (15.49)	74.18 (15.88)	70.83 (17.83)
Range	29.31 - 61.02	7.51 - 19.85	62.67 - 130.00	40.33 - 108.33	36.67 - 111.00
African-American [42]					
Mean (sd)	68.31 (13.38)	17.35 (1.44)	55.00 (15.78)	37.36 (11.40)	34.31 (15.26)
Range	47.36 - 95.53	14.72 - 20.14	28.33 - 85.67	19.33 - 61.33	18.00 - 106.33
Hispanic [12]					
Mean (sd)	56.33 (7.28)	15.94 (2.20)	71.97 (12.21)	50.17 (10.72)	44.58 (12.15)
Range	42.00 - 67.60	11.37 - 18.44	54.00 - 97.00	35.33 - 74.67	30.67 - 72.00

(b)

Race/Ethnicity [N]	Melanin	Erythema	Red	Green	Blue
Caucasian [139]					
Mean (SD)	42.15 (5.38)	14.73 (3.03)	97.78 (10.98)	70.35 (12.12)	65.51 (13.36)
Range	30.07 - 59.77	6.88 - 22.28	65.67 - 127.67	39.67 - 109.00	35.00 - 108.00
African-American [42]					
Mean (sd)	67.72 (10.44)	19.28 (1.92)	55.18 (13.17)	35.69 (9.99)	29.47 (8.67)
Range	48.59 - 90.21	14.34 - 22.55	30.67 - 83.67	19.33 - 60.00	16.67 - 50.33
Hispanic [12]					
Mean (sd)	52.10 (8.57)	17.35 (2.86)	78.14 (14.30)	52.94 (12.40)	46.06 (12.02)
Range	41.61 - 69.88	13.49 - 22.55	50.67 - 97.66	32.00 - 71.67	26.00 - 65.00

in both melanin and erythema with changes in skin color. Caucasians had the lowest values followed by Hispanic and African American participants.

Oximetry values (rSO_2) were recorded for each device and correlated against the five measures of skin color (**Table 4(a)**, **Table 4(b)**). The EQUANOXTM device showed no significant correlation with skin pigmentation, while the Casmed and INVOS devices showed moderate and significant correlation with skin pigmentation, respectively. **Table 5** shows correlation of rSO_2 between devices by location. There was a moderate degree of correlation seen, with the highest being between the INVOS and Casmed readings over the anterior leg compartment ($r = 0.6948$).

4. Discussion

NIRS has potential application in a variety of clinical settings. Broadly, oximetry monitoring could be utilized to detect patients who are deteriorating rapidly. Such states could include systemic shock, neurologic problems, or the development of a compartment syndrome.

In each of these examples, NIRS provides the clinician a means to monitor the patient in a continuous, non-invasive manner that also has the value of being in real time. However, there are several variables that have potential to affect the accuracy of reported values. Trauma, subcutaneous adipose tissue, and skin pigmentation are three factors that vary among patients [3] [8] [9]. In addition, manufacturers of NIRS devices use proprietary algorithms and different wavelengths of light in determining stO_2 values. This study sought to determine if skin

Table 4. (a) Correlation of rSO_2 values and skin color by device (anterior leg compartment); (b) Correlation of rSO_2 values and skin color by device (volar forearm compartment).

(a)

Device	Melanin	Erythema	Red	Green	Blue
INVOS	−0.4281**	−0.3647**	0.4262**	0.4230**	0.3970**
EQUANOX	−0.0574	0.0092	0.0259	0.0114	−0.0011
CASMED	−0.3514**	−0.2010**	0.3075**	0.2866**	0.2458**

(b)

Device	Melanin	Erythema	Red	Green	Blue
INVOS	−0.4900**	−0.4446**	0.5044**	0.5079**	0.4971**
EQUANOX	−0.1342	−0.0645	0.1576	0.1406	0.1348
CASMED	−0.1376	−0.1456*	0.1329	0.1489*	0.1323

*significant at $\alpha = 0.05$; **significant at $\alpha = 0.01$.

Table 5. (a) Correlation of rSO_2 values between devices (anterior leg compartment); (b) Correlation of rSO_2 values between devices (volar forearm compartment).

(a)

	INVOS	EQUANOX
EQUANOX	0.6727	
CASMED	0.6948	0.5210

(b)

	INVOS	EQUANOX
EQUANOX	0.5865	
CASMED	0.6107	0.4280

pigmentation correlated with reported values between devices made by three different manufacturers. This study sought to answer this question by quantitatively measuring skin pigmentation and erythema prior to measuring stO_2 values with the three devices.

The findings in this study demonstrate that all technologies are not created equally. Different technologies have different algorithms which have different capabilities to remove pigment and erythema from a reading. In this study, the Equinox device was least affected by variations in pigment or erythema. Of note, all devices were moderately well correlated and indicated all were reading a similar variable (tissue oxygenation).

There were several limitations in this study. A broad spectrum of ethnicities was sought to reflect differences in skin pigmentation. In actuality however, there was an under representation of intermediate skin tones. Roughly 25% of our population sample was non-Caucasian. Future studies could include more participants with intermediate skin tones. Additionally, volunteers were not traumatized and these findings may not completely translate to a traumatized setting. Erythema especially may or may not affect values of NIRS in a traumatized setting.

In summary, this study shows that NIRS manufacturers all show reasonable correlation to tissue perfusion; however, some devices are more capable of removing confounding variables such as skin pigmentation. If controls on the same subject are used, this variability should cancel each other out assuming a similar pigmentation profile at the two sites. In cases where small variations or no control is used, these differences may have significant effects on clinical decision-making.

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