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Depigmented Skin and Phantom Color Measurements for Realistic Prostheses

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Abstract

Purpose—The purpose of this study was to test the hypothesis that regardless of human skin phototype, areas of depigmented skin, as seen in vitiligo, are optically indistinguishable among skin phototypes. The average of the depigmented skin measurements can be used to develop the base color of realistic prostheses.

Methods and Materials—Data from 20 of 32 recruited vitiligo study participants. Diffuse reflectance spectroscopy measurements were made from depigmented skin and adjacent pigmented skin, then compared to 66 pigmented polydimethylsiloxane phantoms to determine pigment concentrations in turbid media for making realistic facial prostheses.

Results—The Area Under spectral intensity Curve (AUC) was calculated for average spectroscopy measurements of pigmented sites in relation to skin phototype ($p=0.0505$) and depigmented skin in relation to skin phototype ($p=0.59$). No significant relationship exists between skin phototypes and depigmented skin spectroscopy measurements. The average of the depigmented skin measurements (AUC 19,129) was the closest match to phantom 6.4 (AUC 19,162)

Conclusions—Areas of depigmented skin are visibly indistinguishable per skin phototype, yet spectrometry shows that depigmented skin measurements varied and were unrelated to skin phototype. Possible sources of optical variation of depigmented skin include age, body site, blood flow, quantity/quality of collagen, and other chromophores. The average of all depigmented skin measurements can be used to derive the pigment composition and concentration for realistic facial prostheses.

Keywords

diffuse reflectance spectrometry; anaplastology; facial prosthetics; skin phantom; vitiligo

Purpose

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Translucent Skin Color

As photons emit from a light source, matter of any size absorbs or scatters photons. (1) After interacting with the atmosphere, light interacts with the skin and 4–7% of incident photons are reflected from the tissue surface.(2) Human skin is heterogeneous, and reflects, absorbs, or transmits photons in different proportions in each tissue. Intracellular fluids, extracellular fluids, and globular proteins are among those that disperse photons(Figure 1). The predominant chromophores in human skin are melanin, oxyhemoglobin, deoxyhemoglobin, beta carotene, and bilirubin and consist of varying optics due to their irregular size, shape, and density. Other photon-scattering chromophores of the skin include fibrous collagens, cell membranes, and cell nuclei; these components have not been adequately investigated with respect to their impact on skin color.

The perceived color of skin is a combination of directly reflected photons and remitted photons that penetrate the skin and reflect back. (Figure 2) Diffuse reflectance spectrometry measures the remitted and diffusely reflected photons from textured surfaces; these measurements can be collected and analyzed to quantify the color of the skin and the intensity or quantity (when calibrated) of photons.

A History of Spectrometry in Realistic Prostheses

For centuries, many people missing an ear, eye, nose, or other part of their body have sought realistic prosthetic replacements. The challenge always was and always will be to make prostheses appear alive. One of the best-documented prostheses was a metal nose made by and for the famous Danish alchemist and astronomer Tycho Brahe in 1566.(5) Between the sixteenth and twentieth centuries, papier-mâché, vulcanized natural rubber, celluloid, aluminum, gelatin-glycerol, vinyl polymers, and rigid polymers were used to disguise large facial amputations and deformities.(6) In most recent decades, polydimethylsiloxane (PDMS) and dry earth pigments have commonly been used.(7) Despite the realism of prostheses, photons do not have the same interactions in PDMS as in skin due to differences in temperature, pH, size and shape of chromophores and fibers, chromophore-specific density and refraction, and overall density and refraction.(9–11) Human skin and pigmented PDMS are completely different materials and will never be optically equivalent. Phantoms and prostheses will at best be optically similar and give the illusion of realism. Matching the color and turbidity of skin is very difficult, especially when done subjectively.

As early as 1969, prosthetists attempted to measure the color of prosthetic materials in order to replicate human skin.(12) Some used spectrometers to measure the number of photons reflected from the skin.(12–15) Others used colorimeters, which measure the reflected photons typically of densely pigmented “opaque” materials.(7, 16–18) Spectrophotometers objectively measure the turbidity and color of facial prosthetics more accurately than colorimeters (Figure 3).

Methods and Materials

Spectrophotometry

A USB 2000 spectrophotometer (Ocean Optics, Dunedin, FL, USA) was used to measure turbidity and color of each participant's skin and an array of silicone phantoms. Incident light came from an LS-1 tungsten halogen light source (Ocean Optics) and illuminated the skin at a 45° angle. Using a fiber optic probe holder (45° Curved Surface Probe Holder, Ocean Optics) at the angle of incidence omits specular reflectance and allows the one optical fiber in the middle of the six illumination fibers to capture the diffusely reflected photons to the spectrometer. The percent of diffuse reflectance per wavelength is calculated by saturating the sensor inside the spectrophotometer relative to the white reference (WS-1 PTFE Diffuse Reflectance Standard, Ocean Optics) and comparing it to the number of photons gathered by the sensor. The sensitivity of the sensor can be adjusted by the integration time which remained consistent for all participants and phantoms.

Participants

University of Utah's Institutional Review Board approved this study (#29226). Vitiligo patients were recruited for this study because of their depigmented skin. Visually, skin affected by vitiligo appears similar among all skin phototypes. Depigmented skin allows researchers to quantify the underlying optical components of human skin.(20) Approximately 90 people that attended a patient support conference for vitiligo were informed of the study and 23 consented to skin color measurements. Three participants had depigmented skin sites that oversaturated the spectrometer's sensor; we chose to exclude all measurements for those participants to avoid skewed results. Participant recruitment resulted in 20 participants with reportable data.

Phantoms

Following skin color measurements of depigmented skin, PDMS phantoms were fabricated with the Human Coloration System (SiliClone Studio, Valley Forge, PA). The color formula of the PDMS phantoms was chosen subjectively based on clinical outcomes, visual observation of depigmented skin, and histologic specimens of human dermis of various phototypes. A spectra of phantoms, ranging from unpigmented to heavily pigmented in addition to a range of concentrations of red and blue synthetic fibers in PDMS, was created in a matrix (Figure 4).(21) Upon cure, 66 PDMS phantoms were measured in a dark room using the spectrophotometer.

Analysis

A paired test was used to analyze the relationship between normally pigmented and depigmented skin. Linear regression was used to analyze the relationship between AUC and skin phototype. Statistical analysis was performed using R 2.8.0 statistical computing software (R Foundation for Statistical Computing, Vienna, Austria).

The average spectral curve of the depigmented skin measurements was analyzed by calculating the Area Under the spectral intensity Curve (AUC) with the spectral curves of 66 silicone phantoms to determine which phantom most closely resembled the average of depigmented skin measurements. Calculating the AUC allowed for quantifying the overall reflection and turbidity of depigmented skin and silicone phantoms, given the similar color.

Results

Depigmented Skin Measurements

A total of 20 vitiligo patients of various skin types were measured on a depigmented and an adjacent normally pigmented skin site. The average of the depigmented skin sites had an AUC of 19,129 and the average of the pigmented sites had an AUC of 16,303, representing a statistically significant difference ($p=0.0005$) (Figure 5).

Pigmented and depigmented skin measurements were graphed by AUC according to each self-reported skin phototype (Figure 6). Among pigmented sites, the AUC decreases as the skin tone becomes darker according to skin phototype ($p=0.0505$). Among depigmented skin sites, the AUC showed no relation to skin phototype ($p=0.59$). Using simple linear regression to analyze the relationship between the difference in AUC as the response variable and skin phototype as predictor, the estimated AUC increase is 1037 ($p=0.002$) per skin phototype. The difference between the depigmented and pigmented skin for phototype I is not significant ($p=0.33$). The standard deviation for pigmented skin is 2667 and the standard deviation for depigmented skin is 2057. The standard deviations are not statistically significantly different ($p=0.27$, F-test for equality of variances), albeit the expectation for depigmented skin to be much smaller than the adjacent pigmented skin. Collagen composition varying with age and gender, follicular density, and fluid content, could be the variables causing the variation. Based on the study size and data collected, the authors were not able to conclude the likely cause of variability.(22) Further research on the subject will be pursued.

Phantom Measurements

The silicone phantom most similar to the average of the depigmented skin measurements (AUC 19,129) in hue and turbidity was phantom 6.4 (AUC 19,162). The most notable variations of the compared spectral curve were around wavelengths 515 nm and 580 nm and indicate that the phantoms had lower color intensity than the skin (Figure 7).

Conclusions and Clinical/Research Implications

Areas of depigmented skin are visually indistinguishable per skin phototype, yet skin color measurements demonstrated a great deal of variability. The skin phototype cannot be determined by spectroscopy of a depigmented lesion, such as seen in vitiligo..

Regarding prostheses, the composition and concentration of pigments in synthetic materials most closely resembling human skin (phantom 6.4) will now be used clinically as a base color for realistic prostheses. Future research might address the possible sources of optical variation (including age, body site, blood flow, quantity/quality of collagen, and other chromophores) of depigmented skin measurements. This research should allow prosthetists to individualize pigment composition and concentration of prostheses.

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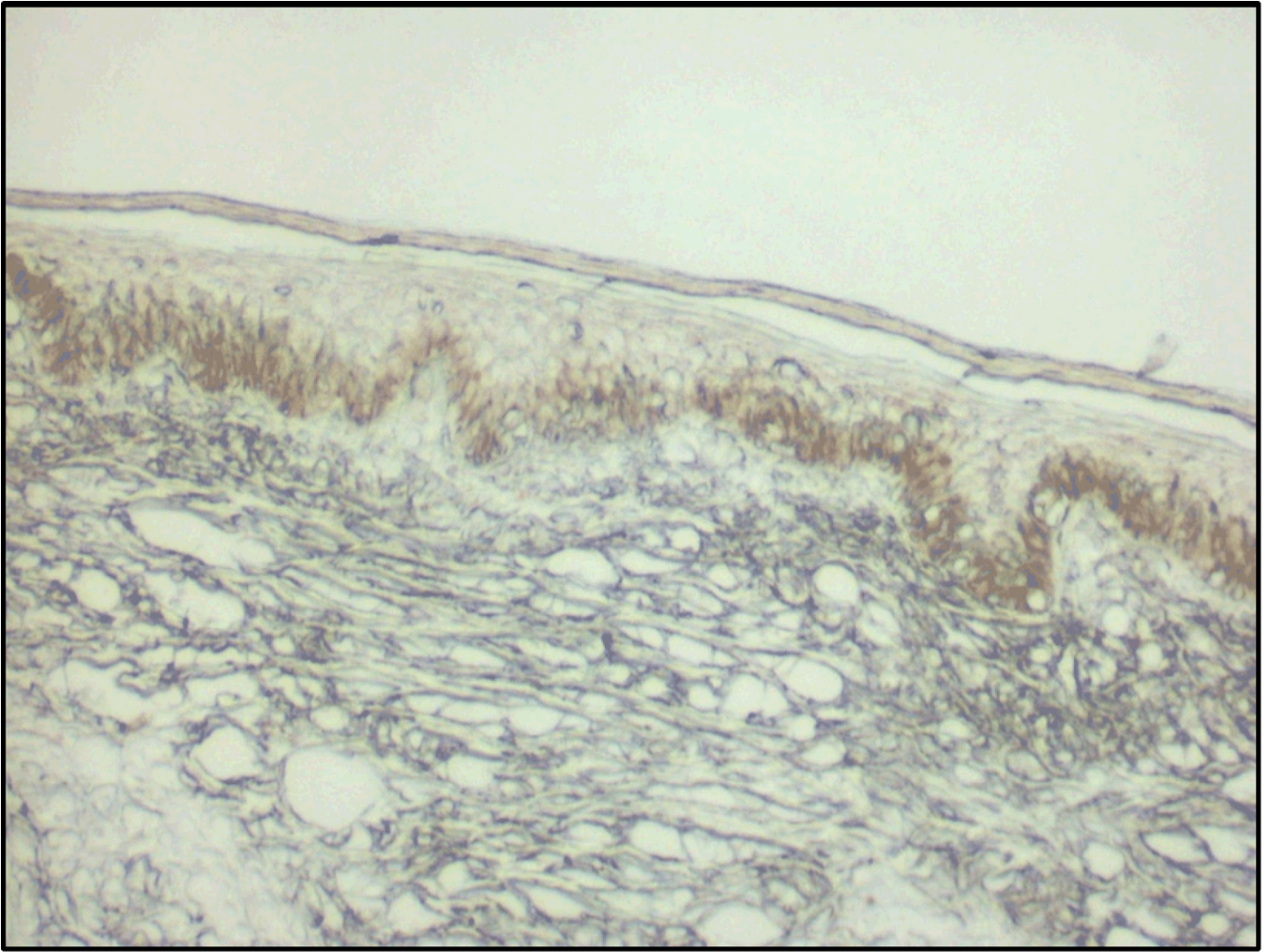


Figure 1. Photograph of an unstained histologic specimen of a skin phototype V individual. Under a microscope, light from beneath the specimen is blocked by the scattering components of the skin.

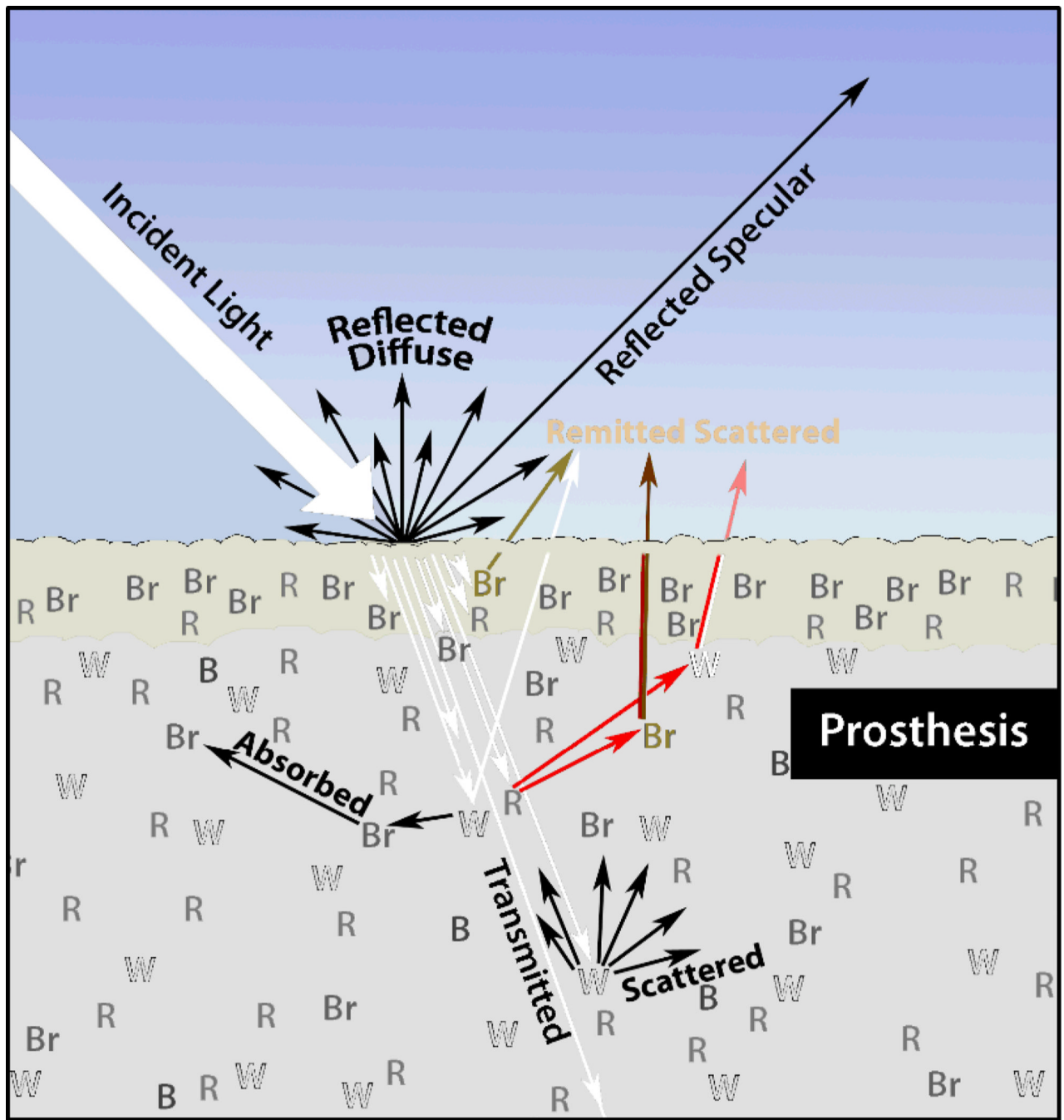


Figure 2. Diagram of photon interaction with turbid media, such as human skin or realistic prostheses.



Figure 1.
Diffuse reflection spectroscopy measurement of auricular prosthesis adjacent to patient's ear.

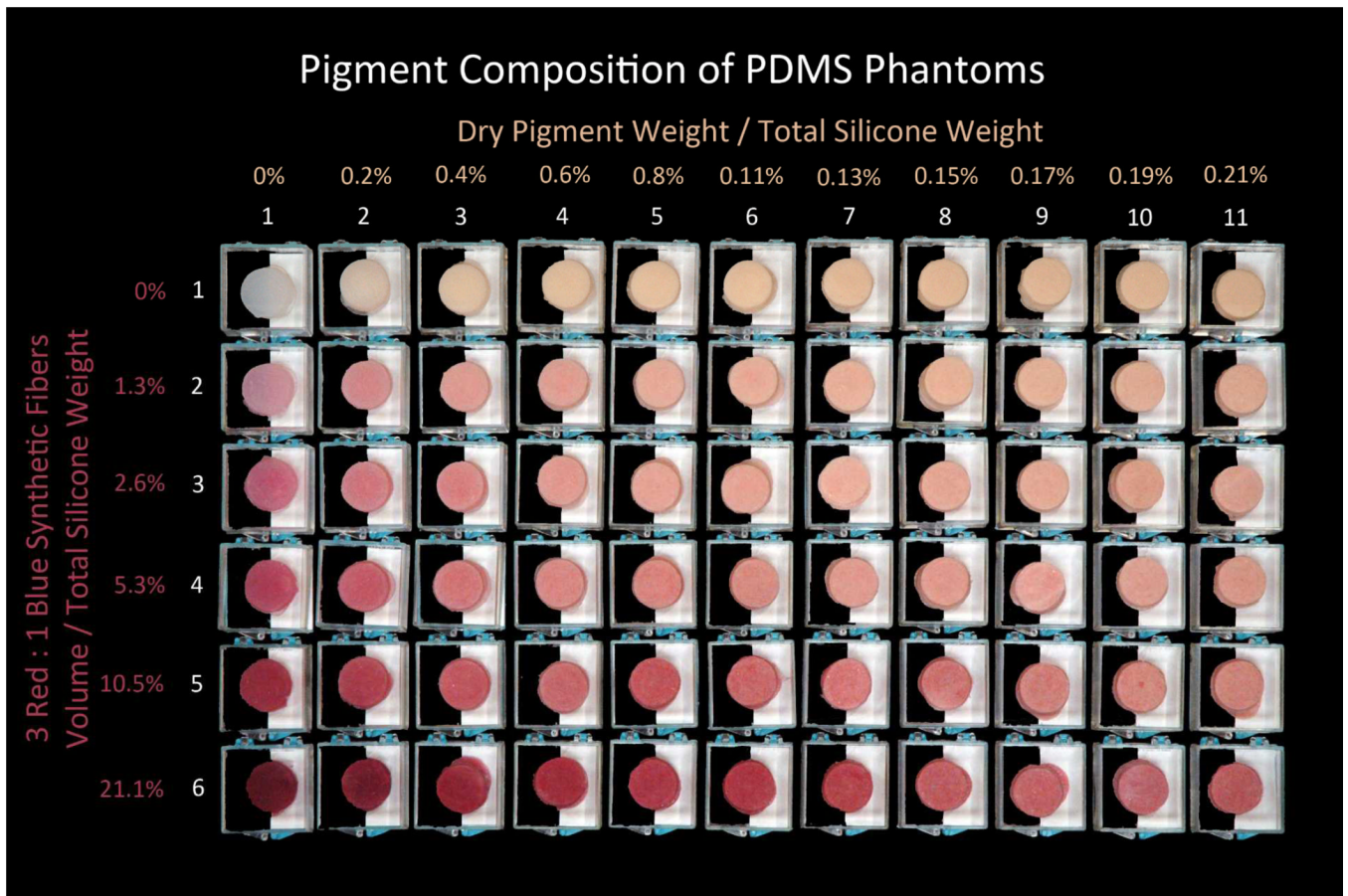


Figure 2.

Each phantom represents a dermis resembling pigment concentration (along the horizontal axis ranging from 1–11) and blood resembling concentration (along the vertical axis ranging from 1–6).

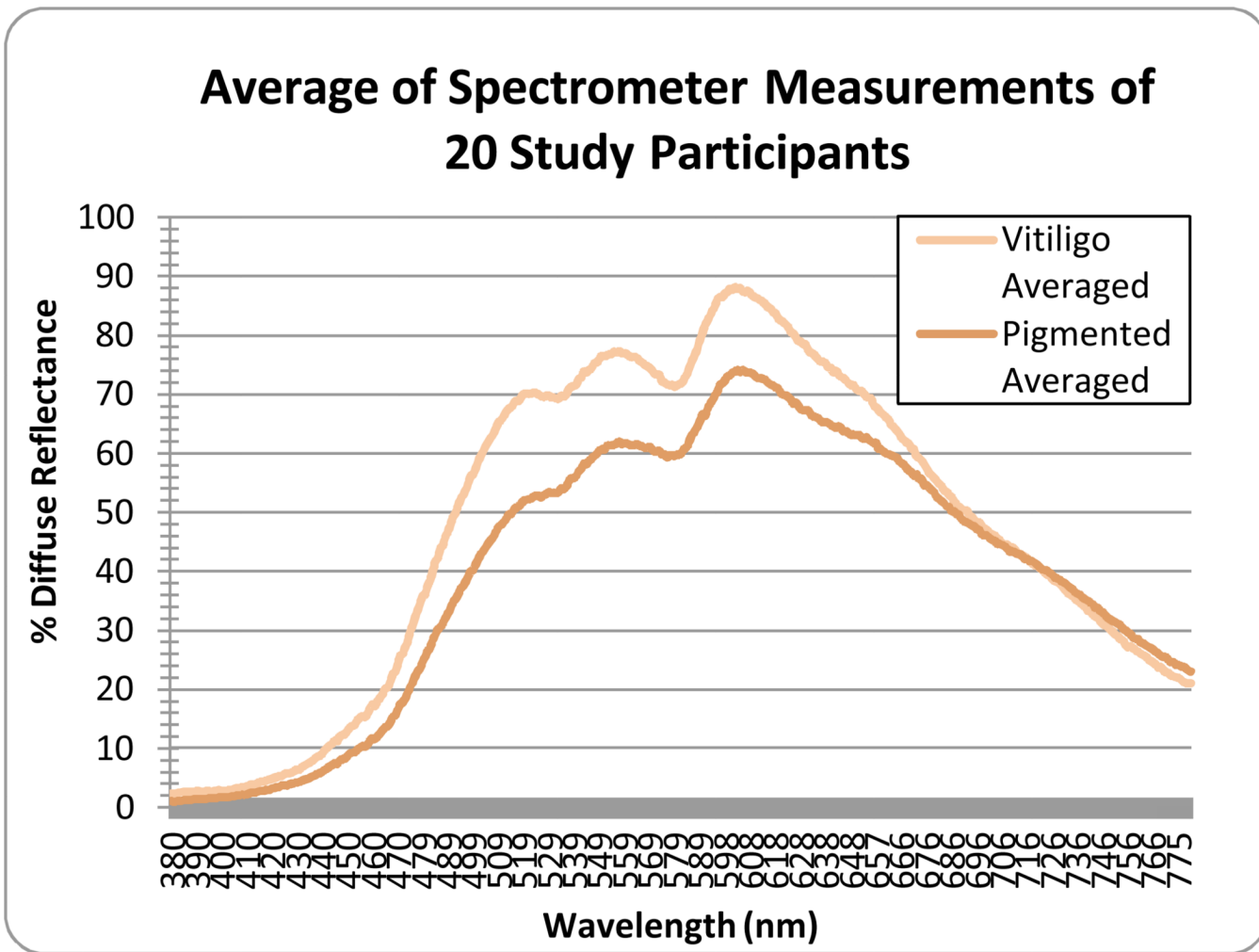


Figure 3. Comparison of the average measurements of depigmented skin sites vs. the average measurements of pigmented skin sites of 20 study participants.

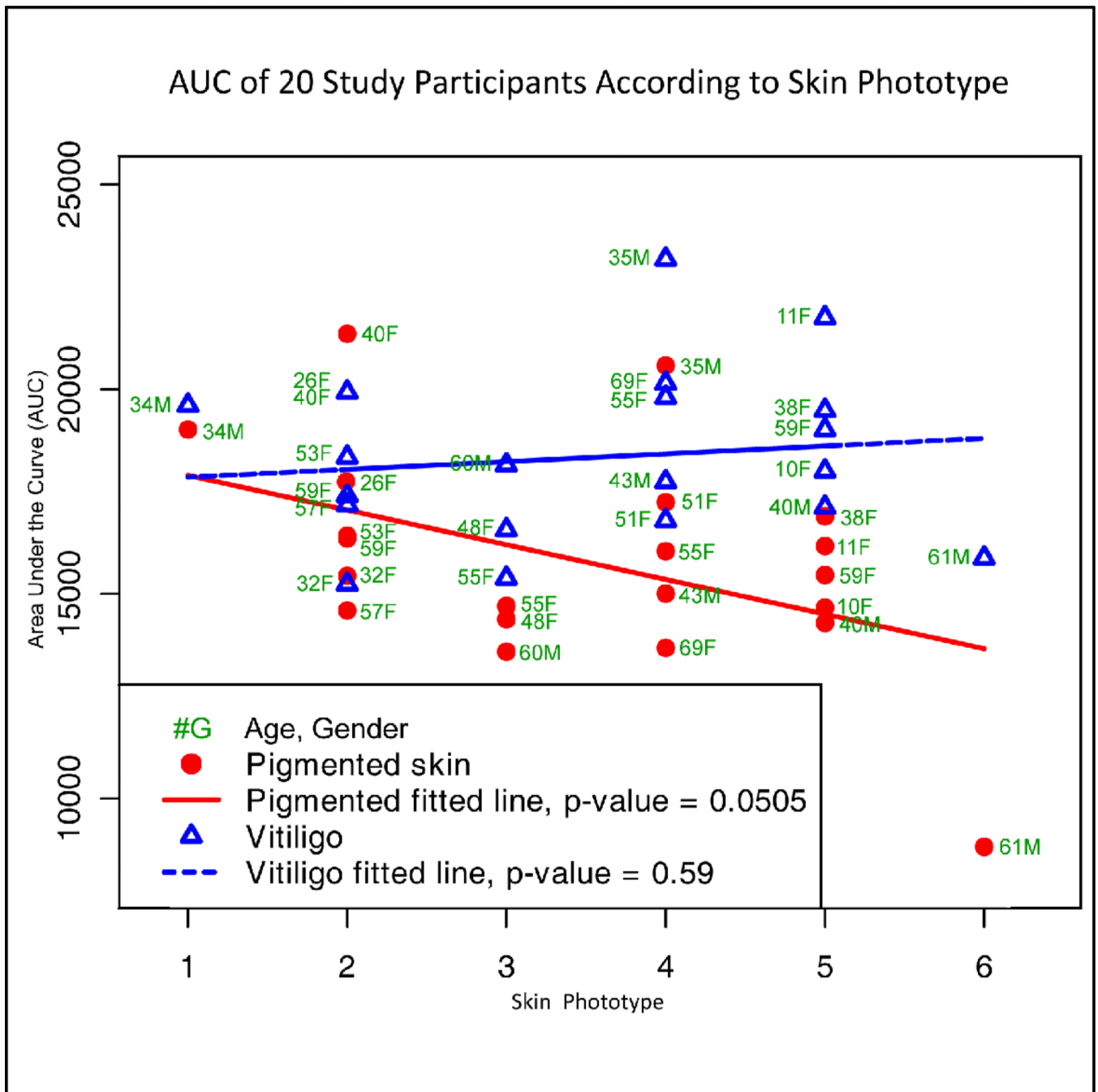


Figure 4. AUC values of pigmented and depigmented skin measurements of 20 study participants according to skin phototype.

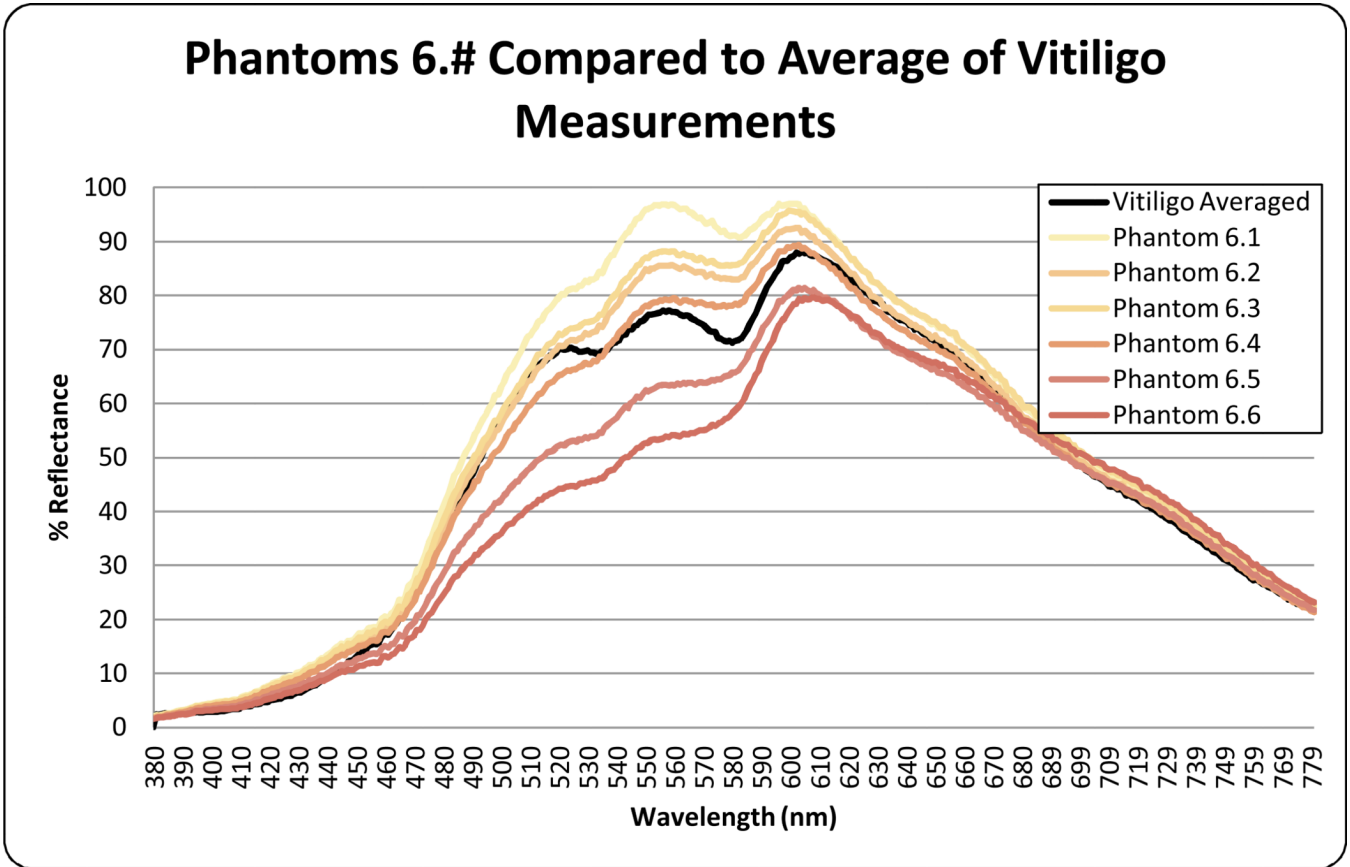


Figure 5. The spectral average of depigmented skin measurements of the 20 study participants compared to the silicone phantoms. In this study, phantom 6.4 was the most similar in hue and pigment turbidity.