Accepted: 21 June 2017

DOI: 10.1111/srt.12396

ORIGINAL ARTICLE

WILEY

SpectraCam®: A new polarized hyperspectral imaging system for repeatable and reproducible in vivo skin quantification of melanin, total hemoglobin, and oxygen saturation

A. Nkengne[1] | J. Robic[1] | P. Seroul[2] | S. Gueheunneux[1] | M. Jomier[2] | K. Vie[1]

[1]Laboratoires Clarins, Pontoise, France

[2]Newtone Technologies, Lyon, France

Correspondence
Alex Nkengne, Laboratoires Clarins, Pontoise, France.
Email: alex.nkengne@clarins.com

Abstract

Background: An accurate way to determine skin pigmentation is to acquire the spectral reflectance of a skin sample and to quantify chromophores by reverse calculation from physical models of light propagation. Therefore, we tested a new hyperspectral imaging device and software suite, the SpectraCam® system, and evaluated its accuracy to quantify skin chromophores.

Methods: Validation of the SpectraCam® system was performed by, firstly, comparing the known and the acquired reflectance spectra of color phantoms. Repeatability and reproducibility were then evaluated by two operators who performed acquisitions at different time points and compared the acquired reflectance spectra. The specificity of the system was tested by quantitative analysis of single chromophore variation models: lentigo and pressure relief. Finally, we tested the ability of the SpectraCam® system to detect variations in chromophore in the eye region due to the daily application of a new anti-dark circle cosmetic product.

Results: The SpectraCam® system faithfully acquires the reflectance spectra of color phantoms (r^2>0.90). The skin reflectance spectra acquired by different operators at different times are highly repeatable (r^2>0.94) and reproducible (r^2>0.99). The SpectraCam® system can also produce qualitative maps that reveal local variations in skin chromophore or underlying structures such as blood vessels. The system is precise enough to detect melanin variation in lentigo or total hemoglobin and oxygen saturation variations upon pressure relief. It is also sensitive enough to detect a decrease in melanin in the eye region due to the application of an anti-dark circle cosmetic product.

Conclusion: The SpectraCam® system proves to be rapid and produces high-resolution data encompassing a large field of view. It is a robust hyperspectral imaging system that quantifies melanin, total hemoglobin, and oxygen saturation and is well adapted to cosmetic research.

KEYWORDS

hemoglobin, hyperspectral, imaging, in vivo, melanin, quantification

1 | INTRODUCTION

Human eyes ability to detect subtle variations in skin color changes has been a key driver of social interactions.[1] Nowadays, dermatologists still rely on naked eyes to diagnose several pigmentation-related disorders. In these diagnostics, color plays a major role despite being a subjective and nonlinear[2] sensory perception. Indeed, human eyes sensitivity to visible light depends on its wavelength[3] and varies between individuals.

The need for objective, noninvasive techniques for the measurement of skin pigmentation led to the very first attempts of setting-up quantitative approaches as early as 1920s-1930s when it was shown that pigment quantification could be achieved by measuring attenuation of the light intensity remitted by the skin.[4,5] If the light scattered by a skin sample depends on the structure of its surface, it further depends on the concentration of several chromophores that will absorb light in deeper layers.

Two chromophores are assumed to play a major role in healthy human skin color: melanin and hemoglobin. Melanin is located in the epidermis and its concentration varies according to the skin type and their response to sun exposure, from very low in light, never tanning, Caucasian skin type I to very high in black African skin type VI.[6] Its absorption spectrum has no characteristic maximum in the visible range but shows a monotonic decrease toward longer wavelengths. Hemoglobin that is found in the microvascular network of the dermis exists in two forms: oxy-hemoglobin and deoxy-hemoglobin. Oxy-hemoglobin exhibits maxima of absorbance at 542 and 577 nm, and its extinction coefficient decreases sharply over 600 nm.[7] Deoxy-hemoglobin absorbance displays a single pic of absorbance at 555 nm and low, but higher than oxy-hemoglobin, values over 600 nm.[7]

An accurate way to determine skin pigmentation is to quantify the spectral reflectance of a skin sample. One of the most widespread methods is optical spectroscopy. It uses a visible light source that is used to irradiate the skin in the visible range. A spectrometer allows to estimate the reflected skin spectrum that can be used to compute the color L*,a*,b* information or to calculate chromophores concentration.[8] Even if the results are accurate, they do not provide any visual map of skin chromophores distribution.

Another option for determining skin chromophores distribution is to use several narrow spectral bands as in the multispectral imaging system.[9] This approach presents the advantage of offering spatial information allowing to visualize chromophore distribution. A key point is then to accurately compute pigment concentration from reflectance images. For this, various light propagation models have been used: Monte Carlo simulations,[10,11] modified Beer-Lambert law,[12] the Kubelka-Munk model,[13-16] or the model proposed by Stamatas et al.[17]

Several multispectral and hyperspectral systems exist.[18-20] Most of these systems were developed to diagnose malign melanoma, and their field of view, spatial resolution, or acquisition speed were not, therefore, compatible with study of larger skin areas for documenting normal skin conditions. We tested a new hyperspectral system, SpectraCam®, that allows both skin spectrum and optical image acquisition within seconds and that quantifies skin chromophores within a few minutes. We evaluated its sensitivity on optical ghosts as well as its in vivo repeatability and reproducibility. We also tested its sensitivity to detect stimuli and cosmetic product-induced changes in skin chromophore.

2 | MATERIALS AND METHODS

2.1 | The SpectraCam® hyperspectral imaging system

SpectraCam® (Newtone Technologies, Lyon, France) is a portable camera that collects in vivo reflectance data from human skin (Figure 1)[21]. In its standard mode, it captures 10-nm narrow band wavelengths images every 10 nm in the visible spectrum (400-700 nm). Thus, it collects 31 images from a scene illuminated by white and blue light-emitting diodes. The camera is equipped with polarization filters that reduce specular light from the skin surface: one for polarizing the incident light and one, orthogonal, to filter the reflected light. Acquired images are 5 cm width and 4 cm height with a resolution of 1×10^6 pixels, therefore producing pixels that correspond to 0.002 mm^2 of skin surface. Acquisition of the 31 images takes approximately 2 seconds and data integration is almost instantaneous.

Spectral calibration is performed by comparing the acquired image with ones from a Spectralon and a light trap according to the following formulae:

$$\text{Calibrated image} = \frac{\text{original image} - \text{light trap image}}{\text{Spectralon image} - \text{light trap image}}$$

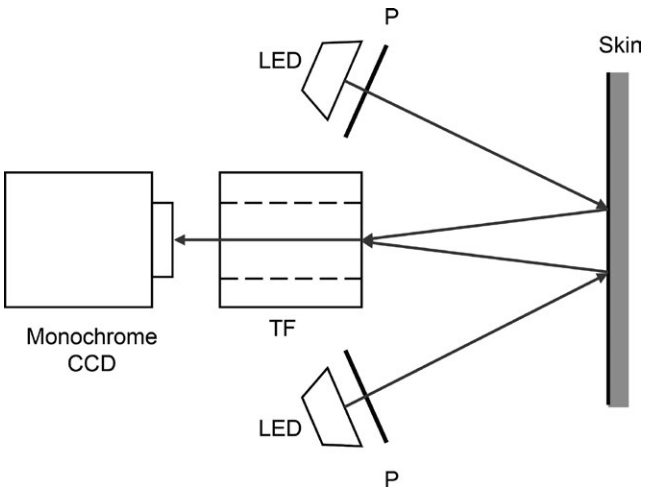

FIGURE 1 Schematic principle of the SpectraCam®.[21] Light emitted by LEDs is transmitted through the polarizers (P) and reflected by the skin. A tunable filter (TF) let pass a specific wavelength and is used as analyzer. The resulting image is captured by a monochromatic camera

Data processing uses the Kubelka-Munk model, to which Saunderson correction is applied to guarantee better accuracy.[16] This processing enables quantification of melanin volume fraction, total hemoglobin volume fractions, and its oxygen saturation. Calculations can be performed on the entire acquired region, on selected zones, or for every single pixel. Therefore, maps of the various parameters can be displayed to observe the underlying structures: blood vessels, pigmented spots, pores, hematoma … or can be superimposed to a "classical" image that highlights the general structure/shape of the acquired skin zone.

2.2 | Validation of the SpectraCam® imaging system on optical phantoms

In a first experimental series, the reliability of SpectraCam® data was tested on optical phantoms. Reflectance spectra of the 24-color cubes of the ColorCheker® (X-Rite, MI, USA) were acquired, and each spectrum was compared to its known reference. The coefficient of determination (r^2) was calculated to give the proportion of variance.

2.3 | In vivo validation of the repeatability and reproducibility of the SpectraCam® imaging system

Repeatability and reproducibility tests were performed on 20 phototype II, III, and IV women. All measures were performed after 30 minutes of rest in a controlled environment (21±1°C and 45%±5% relative humidity). The reflectance spectra of 4 skin zones were acquired using SpectraCam®: outer side of the forearm, inner face of the arm, cheek, and the eye region. A single operator performed different measures to evaluate intra-operator repeatability: two acquisitions in a row the same day and an additional acquisition the following day. Inter-operator reproducibility was evaluated by two sets of measures performed by two different operators the same day. For both studies, analysis was performed on average data from the entire zone acquired focusing on the full reflectance spectra. Volume fractions are expressed as percentages of a theoretical model of a skin containing no chromophore (0%) or 100% chromophore.

2.4 | Detection of variations in chromophores

Qualitative analysis was performed on acquired skin region from the repeatability/reproducibility study using the ability of the SpectraCam® software to produce maps of chromophores from their quantification at the level of every single pixel.

2.5 | In vivo validation of the accuracy of the SpectraCam® imaging system

In order to evaluate the accuracy of the system, two experimental series were performed to induce controlled variations of specific chromophore (melanin or total hemoglobin and oxygen saturation) and to assess if these changes were recorded by the system. These studies were performed on a group of 22 phototype II, III, and IV women.

First, melanin variation was studied by acquisition of a region of the forearm presenting lentigos. Second, variations in total hemoglobin volume fractions and in oxygen saturation were studied by applying three different pressures (3.52, 10.57, and 14.09 kPa) on the inner side of the forearm for 90 seconds and acquiring the region with the SpectraCam® 4–6 seconds after the pressure was released. A recovery period of 3 minutes was allowed in between pressure applications. The pressures—3.52, 10.57, and 14.09 kPa—were produced by the mean of 1.08, 3.6, and 4.6 kg weights, each with a section of $2.784\times10^{-3}m^2$. For both studies, the SpectraCam® software was used to quantify chromophores variations, comparing the region of interest and average data from the rest of the acquired image. We also computed chromophore variations using Stamatas et al. method.[17]

2.6 | Monitoring of the effect of an anti-dark circle cosmetic product

Fifty-three women of an age ranging between 26 and 55 years old were recruited: 27 women of phototypes II and III and 26 women of phototypes IV and V. At the beginning of the study, all of them had moderate to severe dark circles under the eyes. Every morning, during 56 days, they used a new anti-dark circle cosmetic product. At days 0 and 56, chromophores were quantified using the SpectraCam® system. Measures focused on the upper eyelid and the dark circle to avoid interference with eyelashes. At the same time points, trained cosmetic evaluators rated surface and intensity of the dark circle (both on a 10-grade scale). They also used a CM700d spectrocolorimeter (Konica Minolta) to perform color measurements (L*, a*, b*) of the dark circle and of an adjacent control zone.

2.7 | Statistical analysis

Values are expressed as mean±standard error of the mean (SEM). Results showing normal distribution according to Shapiro-Wilk test at $P<1\%$ were compared using two-tailed paired Student's t test; otherwise, results were compared using Wilcoxon's signed-rank test. For the pressure release experiment, data were analyzed using ANOVA followed by Turkey or Duncan comparisons of results pairs. Results were also compared using the coefficient of determination (r^2), the square of the correlation coefficient, that estimates the proportion of the variance in the dependent variable that is predictable from the independent variable(s).

3 | RESULTS

3.1 | Validation of the SpectraCam® system on optical phantoms

Reliability of the SpectraCam® system was first tested on optical phantoms. For most of the 24 reference color cubes, comparison of the acquired spectra with the known reflectance spectra shows excellent coefficient of determination ($0.90<r^2<0.99$) all along the spectra (Table 1). Only two colors of 24 are not faithfully acquired: pure gray scale colors and very dark colors.

TABLE 1 Coefficient of determination (r^2) between the reflectance spectra acquired by the SpectraCam® and the known ColorCheker® reflectance spectra

Reference name	Coefficient of determination
Dark skin	0.942
Light skin	0.992
Blue sky	0.980
Foliage	0.961
Blue flower	0.970
Bluish green	0.992
Orange	0.999
Purplish blue	0.995
Moderate red	0.999
Purple	0.906
Yellow green	0.992
Orange yellow	0.998
Blue	0.983
Green	0.994
Red	0.998
Yellow	0.991
Magenta	0.990
Cyan	0.998
White 9.5	0.995
Neutral 8	0.957
Neutral 6.5	0.958
Neutral 5	0.828
Neutral 3.5	0.381
Black 2	0.056

3.2 | Repeatability and reproducibility of the SpectraCam® system

Comparisons of the reflectance spectra of a defined skin region obtained by one operator upon repeated measures show a coefficient of determination of 0.99 (Table 2). This 0.99 r^2 value is obtained when considering acquisitions performed in a row but also for data acquired with 24-hour interval. It indicates almost no variance and therefore an excellent intra-operator repeatability of the measures.

To have an insight on the inter-operator reproducibility of the SpectraCam® system, we also compared the reflectance spectra obtained by two operators. Depending on the region scanned, the coefficients of determination range from 0.94 to 0.99 (Table 2). Similar values are obtained when comparing spectra from the two operators at different times. Taken together, these data indicate that there is a very good reproducibility of the measures.

3.3 | Detection of skin's chromophores variations

We tested the ability of the SpectraCam® system to retrieve qualitative data for every single pixel acquired and to produce maps of chromophores' variations. Some characteristic pictures, shown in Figure 2, clearly enable to detect variations in melanin and/or hemoglobin. They also reveal underlying structures such as nonobvious skin color alterations or blood vessels.

TABLE 2 Coefficient of determination (r^2) between reflectance spectra for intra-operator repeatability and inter-operator reproducibility

Acquisition zone	Operator 1		Operator 1 vs operator 2
	t1 vs t2 vs t3	t1 vs t4	
Inner side of the forearm	0.99	0.96	0.99
Outer face of the arm	0.99	0.94	0.99
Cheek	0.99	0.99	0.99
Eye region	0.99	0.99	0.99

To gain more insight in the ability of the SpectraCam® system to quantify fine variations of a single chromophore, we first focused on skin regions presenting lentigos. Quantification of chromophores in the lentigo and in the surrounding region by the SpectraCam® system (Table 3, Figure 3A) shows significant accumulation of melanin in lentigos compared with the surrounding region, while there are no variations in total hemoglobin and oxygen saturation. We also analyzed the lentigos spectrum with Stamatas et al.[17] algorithm. Results (Table 3, Figure 3B) show that, compared with the surrounding region, lentigos present no significant variation in melanin, an increase in total hemoglobin and no variation in oxygen saturation.

Hemoglobin variation was studied by applying local pressure to the skin surface. An ANOVA statistical analysis of chromophores' quantification (Table 4, Figure 4) shows no significant variation in amounts of melanin (P=0.54) between the different pressure. Only the total concentration of hemoglobin (up to +33%, P=0.04) and oxygen saturation (up to +37%, P<0.0001) significantly increase between 3.52 and 10.57 kPa and then remain stable (14.09 kPa). Quantification of chromophores from the spectra acquired by the SpectraCam® using the method by Stamatas et al.[17] shows no variation in melanin (P=0.65) or oxygen saturation (P=0.92). It shows variation in total hemoglobin (P<0.0001) between no weight and any weight.

3.4 | Monitoring of the effect of an anti-dark circle cosmetic product

Melanin accumulation being a factor of severity for the clinical signs associated with dark circles eye,[22] we studied the impact of the daily application of a new cosmetic product on chromophores variations after 56 days. For the entire panel, the phototype II-III subgroup, and the phototype IV-V subgroup, results of chromophores' evolution by the SpectraCam® system (Table 5, Figure 5) show a significant decrease in melanin. It occurs mainly in the eyelid region (−5.5%, P=0.026, for the phototype II-III subgroup and −25.6%, P<0.0001, for the phototype IV-V subgroup) and is at the limit of significance in the region of the dark circle (−3%, P=0.075, for the phototype II-III

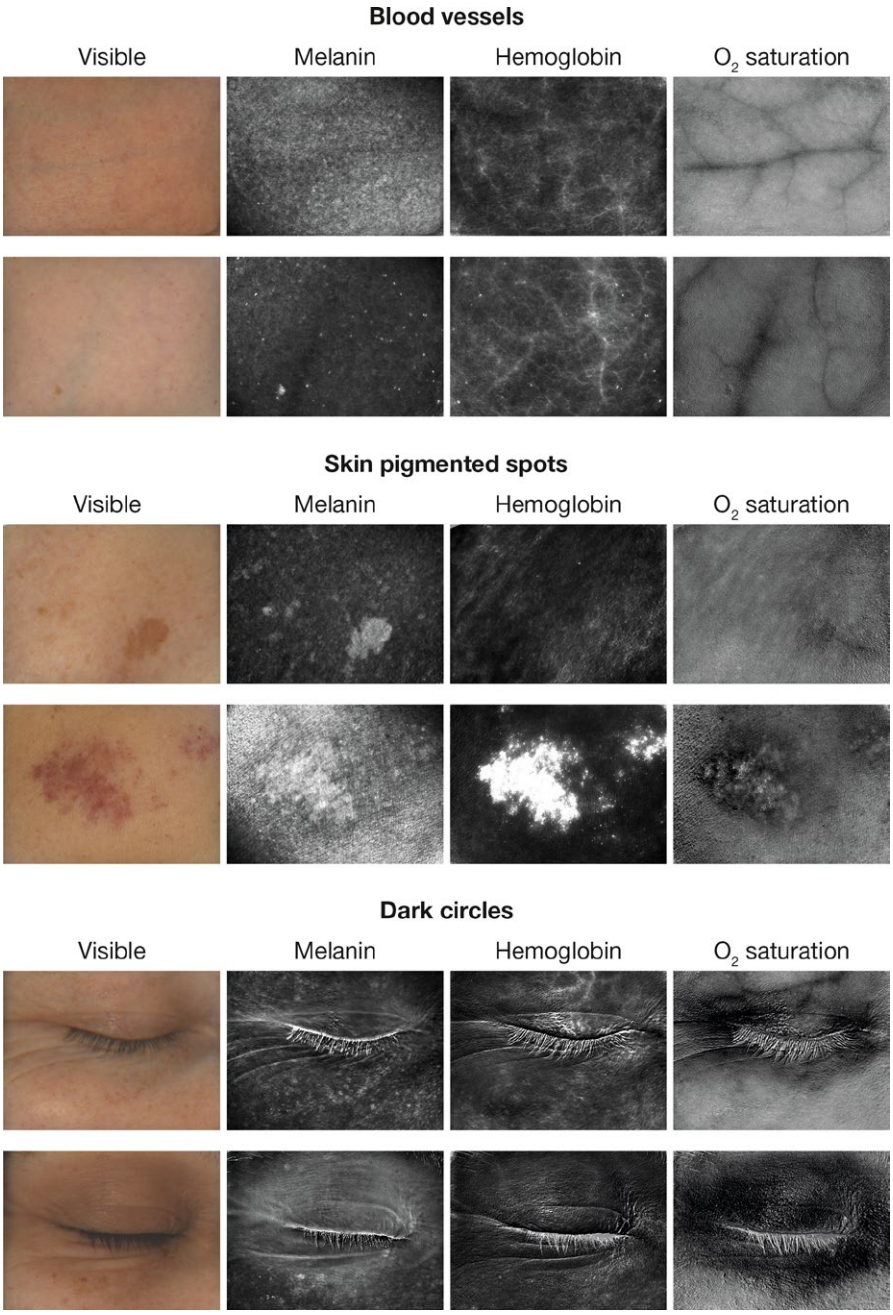

FIGURE 2 Characteristic pictures obtained on acquisition and data analysis by the SpectraCam® system. For SpectraCam® images, dark colors represent low melanin/total hemoglobin content or low oxygen saturation values (venous system). Lighter colors represent higher melanin/total hemoglobin content (melanin/hemoglobin pigmented areas or arterial system) or higher oxygen saturation values

TABLE 3 Quantification of chromophores in lentigos and in the surrounding region according to the SpectraCam® software or using Stamatas et al. method.[17] Results are expressed as mean±SEM, and the probability is the probability of difference according to paired Student's *t* test. For the SpectraCam® system, melanin and total hemoglobin values are volume fractions. For results according to Stamatas et al., results are expressed in arbitrary units. For both, oxygen saturation is expressed as the percentage of oxy-hemoglobin over total hemoglobin

	Chromophore	No lentigo	Outside lentigo	Probability
SpectraCam®	Melanin	0.697±0.013	0.567±0.012	<0.0001
	Total hemoglobin	0.055±0.003	0.052±0.002	0.09
	Oxygen saturation	57.9±1.29	59.0±1.21	0.43
Stamatas et al.	Melanin	84.9±2.0	85.6±1.8	0.14
	Total hemoglobin	225.4±23.4	215.1±21.0	0.0009
	Oxygen saturation	53.7±2.2	54.3±4.5	0.41

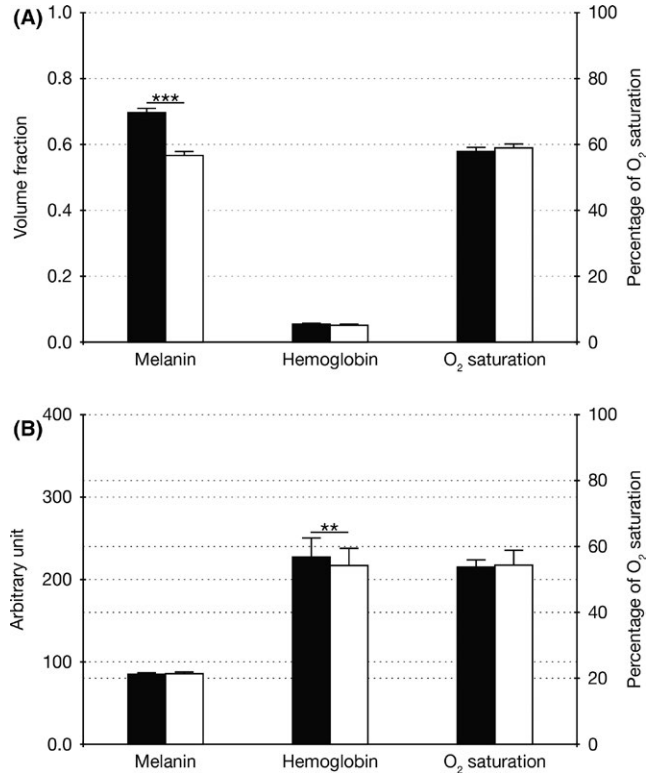

FIGURE 3 Quantification of chromophores in lentigos (in black) and in the surrounding region (in white) according to (A) the SpectraCam® software or (B) using Stamatas et al. method[10]. Results are expressed as mean±SEM. Significance is the results of paired Student's *t* test with ***P*<0.001 and ****P*<0.0001

subgroup and −21.9%, *P*=0.064, for the phototype IV-V subgroup). In addition, in the phototype II-III subgroup, detailed analysis of the different regions of the eyes reveals a possible decrease in total hemoglobin that is limited to the dark circle region (−31.8%, *P*=0.097).

The changes detected by the SpectraCam® system are confirmed by clinical quotations of dark circle surface (−4%, *P*=0.008, for the phototype II-III group and −5%, *P*=0.016, for the phototype IV-V group), its color intensity (−12%, *P*<0.001, for the phototype II-III group and −15%, *P*<0.001, for the phototype IV-V group), and skin luminosity (+15%, *P*<0.001, for the phototype II-III group and +18%, *P*<0.001, for the phototype IV-V group). They are also confirmed by a spectrocolorimetric approach that shows an increased luminosity (L) of the skin (+3%, *P*<0.001, for the phototype II-III group and +4%, *P*<0.001, for the phototype IV-V group) and, for the phototype IV-V group, an increased Individual Typology Angle (+83%, *P*<0.001) that represent the intensity of skin pigmentation. These variations are observed only in the dark circle region, while the color (L, a*, b*) of the adjacent control region remains constant.

4 | DISCUSSION

To circumvent the limitations of visual skin quantitative grading and in order to improve current technologies, we tested a new hyperspectral imaging system that, within seconds, acquires repeatable and reproducible data allowing to detect skin chromophores: melanin, total hemoglobin, and oxygen saturation. This system produces high-resolution images that are useful to detect tiny local variations in chromophores or underlying structures. It also produces highly specific data for each chromophore, data that are sensitive enough to detect existing or induced variations in melanin or total hemoglobin and oxygen saturation.

Our initial tests with ColorChecker® optical phantoms demonstrate high correlation for 22 colors out of 24. Despite pure gray colors scale and darkest colors are recognized less faithfully, the skin color range does not usually exhibit reflectance characteristics that compares to these two colors. In the case of skin's chromophores analysis, the quality of the data we obtained shows that these limitations do not interfere, even in the case of the phototype IV subjects we tested.

In fact, the SpectraCam® system is reliable and sensitive enough to reveal the mid-term effect of a cosmetic product on dark circles, an important cosmetic concern caused by melanin accumulation and/or hemodynamic congestion in the infraorbital region of the eyelids.[23] Results show that the cosmetic product induces a decrease in melanin leading to a decrease in the severity of the dark circle symptoms, data that are confirmed by expert evaluators and spectrocolorimetric analysis. The measured color changes are limited to the dark circle area, while the surrounding skin remains unchanged.

Stamatas[8,17] approach estimates skin concentration of melanin, oxy-hemoglobin, and desoxy-hemoglobin by analyzing a few spectral bands reflected by the skin. These bands are selected because they

TABLE 4 Quantification of chromophores after release of local pressure according to the SpectraCam® software or using Stamatas et al. method.[17] Results are expressed as mean±SEM and the probability is the probability of difference according to paired Student's *t* test. For the SpectraCam® system, melanin and total hemoglobin values are volume fractions. For results according to Stamatas et al., results are expressed in arbitrary units. For both, oxygen saturation is expressed as the percentage of oxy-hemoglobin over total hemoglobin

	Chromophore	No pressure	3.52 kPa	10.57 kPa	14.09 kPa
SpectraCam®	Melanin	0.276±0.002	0.291±0.002	0.307±0.002	0.301±0.002
	Total blood	0.031±0.001	0.037±0.001	0.043±0.001	0.042±0.001
	Oxygen saturation	62.6±0.6	76.6±0.5	83.3±0.5	81.9±0.5
Stamatas et al.	Melanin	91.2±0.4	91.2±0.3	90.0±1.3	89.9±1.3
	Total blood	184.1±14.6	179.2±15.4	186.2±14.2	184.8±14.0
	Oxygen saturation	52.4±2.7	58.8±2.4	62.7±2.6	61.2±2.5

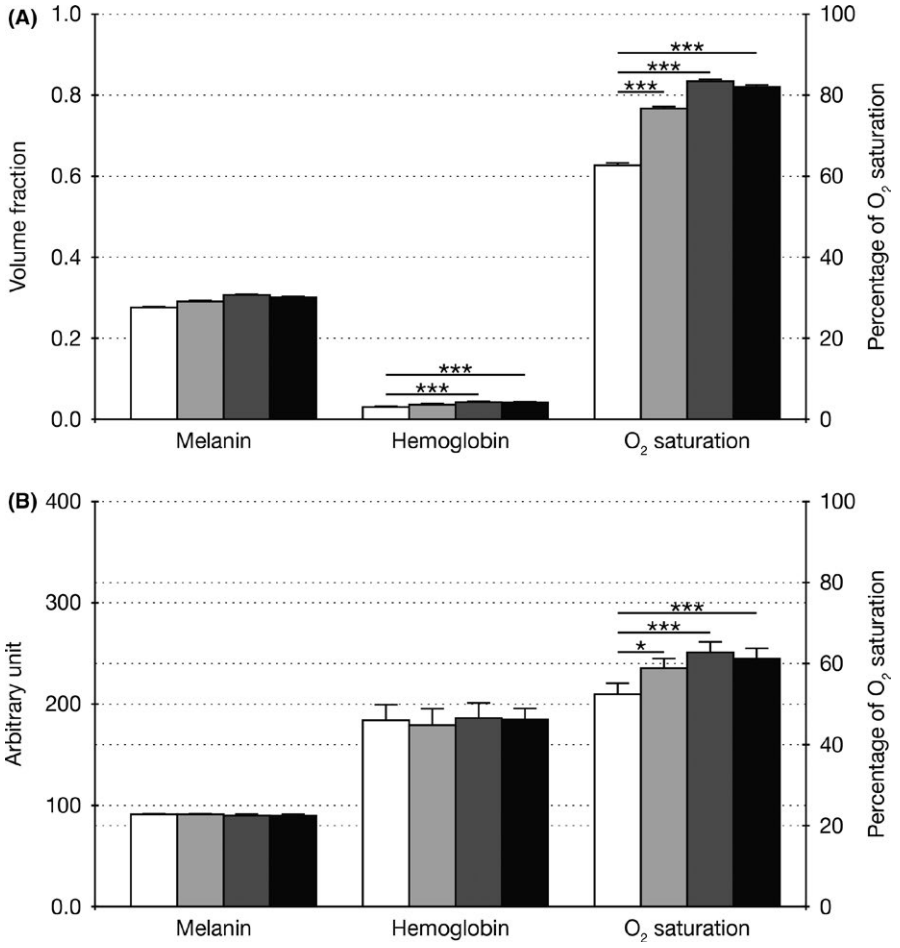

FIGURE 4 Quantification of chromophores after release of local pressure according to (A) the SpectraCam® software or (B) using Stamatas et al.'s method.[17] Results are expressed as mean±SEM. Significance is the results of an ANOVA analysis followed by Turkey or Duncan comparison of results pairs with *P<0.01 and ***P<0.0001. White: no pressure, light gray: 3.52 kPa, dark gray: 10.57 kPa, and black: 14.09 kPa

TABLE 5 Variations of chromophores upon application of a new cosmetic product on the entire panel, the phototype II-III, and the phototype IV-V subgroups. Results are expressed as mean±SEM. Melanin and total hemoglobin values are volume fractions. Oxygen saturation is expressed as the percentage of oxy-hemoglobin over total hemoglobin

Chromophore	Group/Subgroup	Day 0	Day 56
Melanin	Entire panel	0.395±0.015	0.370±0.014
	Phototypes II-III	0.345±0.019	0.331±0.017
	Phototypes IV-V	0.436±0.020	0.414±0.021
Total blood	Entire panel	0.106±0.005	0.105±0.006
	Phototypes II-III	0.123±0.006	0.121±0.009
	Phototypes IV-V	0.089±0.006	0.088±0.006
Oxygen saturation	Entire panel	49.5±1.3	48.3±1.5
	Phototypes II-III	51.4±1.7	51.2±1.8
	Phototypes IV-V	47.6±2.0	45.0±2.5

correspond to the absorption peaks of the chromophores, regardless of the light interaction with other skin structures.[17] In our case, we use the Kubelka-Munk method that resolves the full radiative transfer function of the light into the skin by considering it a multilayer medium.[16] This different approach most probably explains the discrepancy we observed when measuring chromophores' variations in lentigos. Indeed, melanin presents no maximum of absorption and can, therefore, be difficult to accurately measure using a spectral band. Therefore, we believe our approach provides a more consistent approximation of the concentration of each skin chromophores.

5 | CONCLUSION

Most existing hyperspectral imaging systems have been developed to detect melanoma. If they do perform well for the diagnosis of malign pigmented spots, they are only poorly adapted to cosmetology studies because of their slow acquisition, low-resolution, limited field of view, and their lack of quantitative data. For these reasons, we developed and tested the SpectraCam® and our data show the interest of this new system. Acquisition and integration of data are rapid avoiding recalibration and letting us consider the possibility to

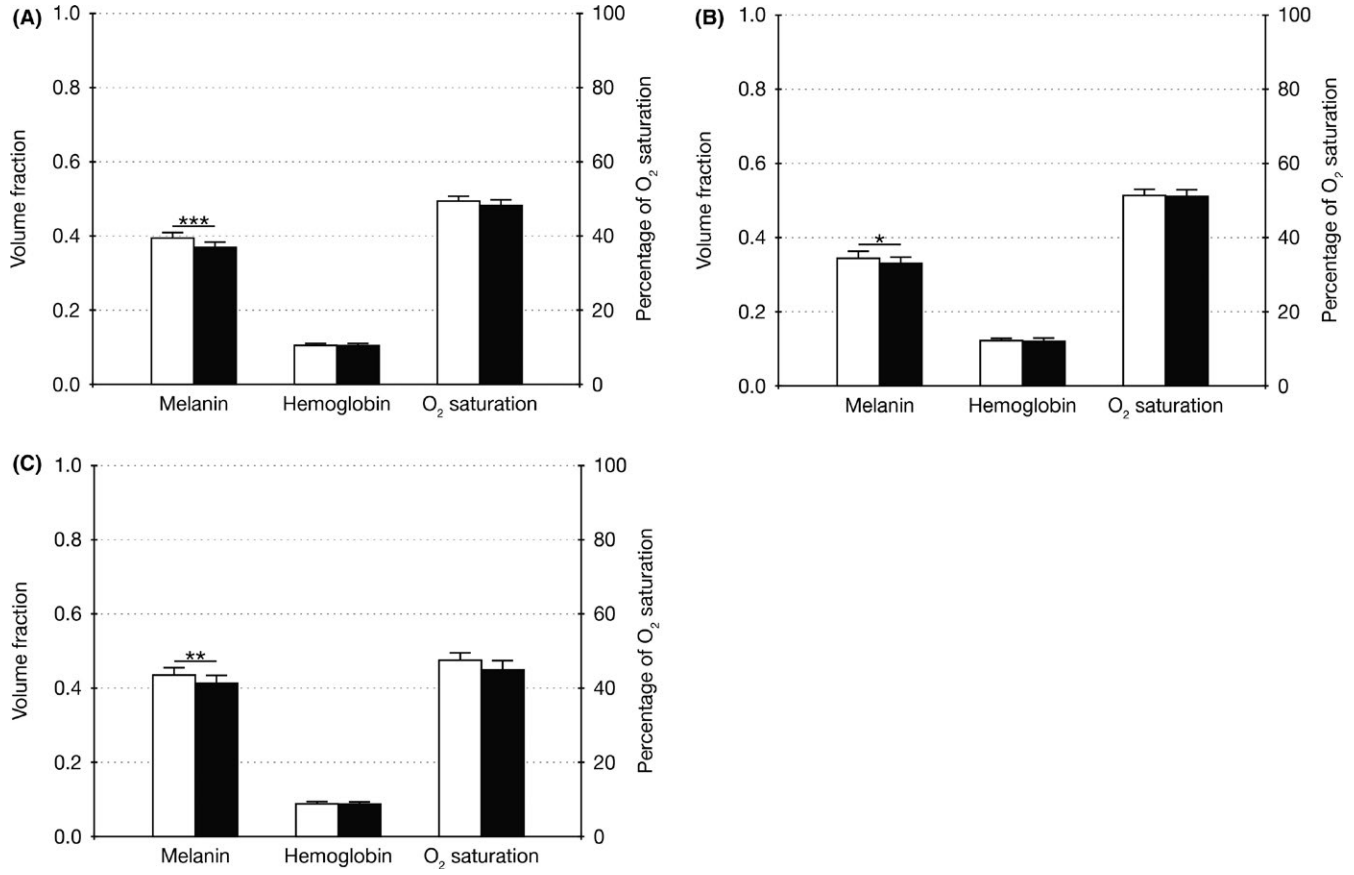

FIGURE 5 Variations of chromophores upon application of a new cosmetic product on (A) the entire panel, (B) the phototypes II-III, and the (C) phototype IV-V subgroups. Results are expressed as mean±SEM. Results are compared using paired Student's *t* test. **P*<0.02, ***P*<0.001, ****P*<0.0001. White: day 0 and black: day 56

study dynamic processes. Data have a very high resolution enabling a precise detection of underlying structures such as venous and arterial network. Field of view is large enough to detect variations in an extended eye region and, with technical adaptations, could even be enlarged to areas as large as the entire face. Finally, our approach provides a consistent approximation of the concentration of each skin component. It also offers a framework in which other skin pigments can be added to the skin model without reformulating the concentration estimation method.

ACKNOWLEDGEMENTS

The authors thank Alexane Ducros, a trainee, who performed most of the SpectraCam® acquisitions. They also thank Dr Philippe Crouzet, Estium-Concept, for scientific writing services.

CONFLICTS OF INTEREST

A. Nkengne, J. Robic, S. Gueheunneux, and K. Vie are full-time employees of Clarins, a major company specialized in the design, manufacturing, and marketing of cosmetic products. P. Seroul and M. Jomier are full-time employees of Newtone Technologies, a company specialized in imaging solutions for life sciences.

REFERENCES

1. Fink B, Grammer K, Matts PJ. Visible skin color distribution plays a role in the perception of age, attractiveness, and health in female faces. *Evol Hum Behav*. 2006;27:433-442.
2. Rosen CF, Jacques SL, Stuart ME, Gange RW. Immediate pigment darkening: visual and reflectance spectrophotometric analysis of action spectrum. *Photochem Photobiol*. 1990;51:583-588.
3. Dowling JE. Retinal processing of vision. In: Greger R, Windhorst U, eds. *Comprehensive Human Physiology*. New York: Springer; 1996:773-788.
4. Brunsting LA, Sheard C. The color of the skin as analyzed by spectrophotometric methods: II. The role of pigmentation. *J Clin Invest*. 1929;7:559-574.
5. Edwards EA, Duntley SQ. The pigments and color of living human skin. *Am J Anatomy*. 1939;65:1-33.
6. Fitzpatrick TB. The validity and practicality of sun-reactive skin types I through VI. *Arch Dermatol*. 1988;124:869-871.
7. Anderson RR, Parrish JA. The optics of human skin. *J Invest Dermatol*. 1981;77:13-19.
8. Stamatas GN, Zmudzka BZ, Kollias N, Beer JZ. Non-invasive measurements of skin pigmentation *in situ*. *Pigment Cell Res*. 2004;17:618-626.
9. Elbaum M. Computer-aided melanoma diagnosis. *Dermatol Clin*. 2002;20:735-747.
10. Meglinski IV, Matcher SJ. Computer simulation of the skin reflectance spectra. *Comput Methods Programs Biomed*. 2003;70:179-86.
11. Shi T, DiMarzio CA. Multispectral method for skin imaging development and validation. *Appl Opt*. 2007;46:8619-26.

12. Shimada M, Yamada Y, Itoh M, Yatagai T. Melanin and blood concentration in human skin studied by multiple regression analysis: experiments. *Phys Med Biol*. 2001;46:2385-2395.
13. Igarashi T, Nishino K, Nayar SK. The appearance of human skin: a survey. *Found Trends Comput Graphics Vision*. 2007;3:1-95.
14. Krishnaswamy A, Baranoski GVG. A biophysically based spectral model of light interaction with human skin. *Comput Graph Forum*. 2004;23:331-340.
15. Jolivot R, Benezeth Y, Marzani F. Skin parameter map retrieval from a dedicated multispectral imaging system applied to dermatology/cosmetology. *Int J Biomed Imag*. 2013;2013:978289.
16. Seroul P, Hébert M, Jomier M. Hyperspectral imaging system for *in-vivo* quantification of skin pigments. *Proc 28th IFSCC Congress, Paris, France*. 2014;123:132
17. Stamatas GN, Balas CJ, Kollias N. Hyperspectral image acquisition and analysis of skin. *SPIE*. 2003;4959:77-82.
18. Gutkowicz-Krusin D, Elbaum M, Jacobs A, et al. Precision of automatic measurements of pigmented skin lesion parameters with a MelaFind™ multispectral digital dermoscope. *Melanoma Res*. 2000;10:5635570.
19. Michalska M, Chodorowska G, Krasowska D. SIAscopy—A new non-invasive technique of melanoma diagnosis. *Ann Univ Mariae Curie Sklodowska Med*. 2004;59:421-431.
20. Vasefi F, MacKinnon N, Saager RB, et al. Polarization-sensitive hyperspectral imaging *in vivo*: a multimode dermoscope for skin analysis. *Sci Rep*. 2014;12:4924.
21. Seroul P, Hébert M, Cherel M, Vernet R, Clerc R, Jomier M. Model-based skin pigment cartography by high-resolution hyperspectral imaging. *IS&T Int Symp Electron Imag*. 2017;60:108-114.
22. Freitag FM, Cestari TF. What causes dark circles under the eyes? *J Cosmet Dermatol*. 2007;6:211-215.
23. Kikuchi K, Masuda Y, Hirao T. Imaging of hemoglobin oxygen saturation ratio in the face by spectral camera and its application to evaluate dark circles. *Skin Res Technol*. 2013;19:499-507.

How to cite this article: Nkengne A, Robic J, Seroul P, Gueheunneux S, Jomier M, Vie K. SpectraCam®: A new polarized hyperspectral imaging system for repeatable and reproducible in vivo skin quantification of melanin, total hemoglobin, and oxygen saturation. *Skin Res Technol*. 2017;00:1–9. https://doi.org/10.1111/srt.12396