On the Identification and Interpretation of Human Skin Spectral Responses Under Adverse Environmental Conditions

Gladimir V. G. Baranoski[1], Senior Member, IEEE, and Tenn F. Chen[1], Student Member, IEEE

***Abstract*— The identification and interpretation of skin spectral responses play a central role in a wide range of biomedical engineering applications, from the noninvasive assessment of human health parameters to the location of individuals in distress during search and rescue operations. In this paper, we investigate the sensitivity of these responses to physiological changes triggered by adverse environmental conditions. Our findings, which are supported by predictive computer simulations and experimental observations reported in the scientific literature, indicate that the resulting variations of skin reflectance can be substantial. Accordingly, if not properly taken into account, they may considerably impair the efficacy of systems designed for the detection and analysis of skin signatures within and outside the visible spectral region.**

***Index Terms*— skin, blood flow, water loss, reflectance, spectral sensitivity, simulation.**

I. Introduction

From an optical point of view, the human skin is arguably one the most complex materials found in nature. Light is absorbed and scattered within the various cutaneous tissues resulting in characteristic spectral responses, or signatures, which are central for a wide scope of applications within and outside the visible domain. Noteworthy examples range from the noninvasive assessment of human health parameters [1] and screening of diseases [2] to the tracking of pedestrians in urban settings [3], the remote monitoring of vital signs for sports training purposes [4], and the detection of human targets during search and rescue operations [5]. The effectiveness of these applications is directly connected to the correct identification and interpretation of skin spectral signatures, and these procedures, in turn, may be quantitatively and qualitatively affected by physiological changes triggered by exogenous (environmental) stimuli such as extreme temperatures and overexposure to ultraviolet radiation (UVR)

Under heat stress, a thermoregulatory vasodilation process can lead to a substantial increase in dermal blood flow [6]. This results in noticeable changes in the spectral responses of human skin due to a higher probability of light being absorbed or scattered by blood-borne pigments found in the dermal layers. Similarly, overexposure to ultraviolet light can also lead to a vasodilation process and increased dermal blood flow [7]. In individuals characterized by low levels of melanin pigmentation, it can result in a visible skin reddening at the stimulus site termed erythema [8], commonly referred to as "sunburn". It is worth noting the increased dermal blood flow associated with heat stress and overexposure to UVR can involve the vasodilation of the superficial dermal vessels or the entire cutaneous vascular systems [8]. Similarly, at lower temperatures, the superficial blood vessels become constricted, and the blood flow is directed to the deeper dermal vascular networks [9].

Heat stress, especially when associated with low humidity conditions, can also trigger transepidermal water loss [10]. This process can also affect the spectral signatures of human skin, notably in the near-infrared domain where water is characterized by a strong absorption behaviour [7]. This reduction of skin water content may be accentuated by rapidly flowing wind, a phenomenon known as "windburn" [10].

In many areas, computational, or *in silico*, experimental frameworks are becoming increasingly instrumental in the acceleration of the different cycles of research involving natural processes that cannot be fully studied through traditional laboratory procedures due to practical constraints [11]. Similarly, in this paper, we investigate spectral variations on skin reflectance due to physiological changes triggered by adverse environmental stimuli using controlled computational experiments. This approach allows us to overcome key obstacles normally associated with the execution of actual *in vivo* experiments such as the lack of appropriate logistic conditions to elicit the desired responses in real specimens, and the difficulty to control the large number of biophysical variables and measurement parameters. We believe that our findings should be useful for scientists and engineers working on the development of new systems for the detection and analysis of skin signatures in the hyperspectral domain.

The remainder of this paper is organized as follows. In the next section, we describe our *in silico* experimental framework, including the biophysical data used to characterize the skin specimens considered in our simulations, and the sensitivity measure employed in this investigation. In Section III, we present our results and discuss their practical implications regarding the identification and interpretation human skin spectral signatures employed in different applications. Finally, in Section IV, we close the paper and outline directions for future research in this area.

II. *In Silico* Experimental Framework

The computational experiments depicted in this paper are supported by a predictive hyperspectral light transport model for human skin, henceforth referred to as HyLIoS (*H*yperspectral *L*ight *I*mpingement on *S*kin) [12], and measured data provided in the related scientific literature. The

*This work was supported by NSERC.

[1] Gladimir V. G. Baranoski and Tenn F. Chen are with Natural Phenomena Simulation Group, School of Computer Science, University of Waterloo, 200 University Avenue, Waterloo, Ontario, Canada N2L 3G1. gvgbaran@cs.uwaterloo.ca

978-1-4244-9270-1/15/$31.00 ©2015 IEEE

HyLIoS model employs a first principles simulation approach that takes into account all main light absorbers (keratin, DNA, uranic acid, melanins, functional and disfucntional hemoglobins, beta-carotene, bilirubin, lipids and water) and scatterers (cells, collagen fibers, melanosomes and melanosome complexes) acting within the skin tissues in the ultraviolet (250-400 nm), visible (400-700 nm) and near-infrared (700-2500 nm) regions of the light spectrum.

In order to enable the full reproduction of our investigation results, we made HyLIoS available online [13] via a model distribution system [14] along with the supporting data (*e.g.*, refractive index and extinction coefficient curves) used in our investigation. This system enables researchers to specify experimental conditions (*e.g.*, angle of incidence and spectral range) and material parameters (*e.g.*, pigments and water content), and receive customized simulation results.

Using HyLIoS, we generated modeled directional-hemispherical reflectance curves for skin specimens with different levels of pigmentation considering an angle of incidence of 10°, and employing the specific and general characterization parameters provided in Tables I and II, respectively. We remark that the values assigned to these parameters were selected based on actual biophysical ranges provided by scientific sources which are listed elsewhere for conciseness [12]. These modeled reflectance curves, which closely agree with measured curves obtained for real skin specimens [12], are used as baseline in our *in silico* experiments.

We considered three case studies for which we employed modified versions of the parameter datasets (Tables I and II) used to obtain the baseline curves. In the first case, we simulated the effects of increased dermal blood flow (IDBF) by raising the blood content in the dermal layers to 7% [1], [8], [9]. In the second case, we simulated the effects of transepidermal water loss (TEWL) by reducing the water content of the modeled skin layers by 40% [10]. Finally, in the third case, we simulated the combined action of both physiological processes which may occur when someone is overexposed to sunlight, excessive heat and low humidity conditions [15].

In order to assess the spectral variation patterns more systematically, we performed a differential sensitivity analysis [16] for each of the three case studies across selected spectral ranges: visible (250-700 nm), NIR-A (700-1400 nm), NIR-B (1400-2500 nm) and VNIR (400-2500 nm). This analysis involves the computation of a sensitivity index that provides the ratio of the change in output to the change in a quantity while the other quantities are kept fixed. A ratio equal to 1.0 indicates complete sensitivity (or maximum impact), while a ratio less than 0.01 indicates that the output is insensitive to changes in the selected quantity [17]. Accordingly, we computed the mean sensitivity index (MSI) for the spectral regions of interest to assess the mean ratio of change in reflectance with respect to the change in the selected quantities, namely dermal blood content and cutaneous water content, associated with the first two case studies, as well as with respect to their combined action addressed in the third case study. This index is expressed as

$$MSI = \frac{1}{N}\sum_{i=1}^{N}\frac{|\rho_b(\lambda_i) - \rho_m(\lambda_i)|}{\max\{\rho_b(\lambda_i), \rho_m(\lambda_i)\}}, \qquad (1)$$

where ρ_b and ρ_m correspond to the reflectances associated with the baseline and modified parameter datasets, respectively, and N is the total number of wavelengths sampled with a 5 nm resolution within a selected spectral region.

TABLE I

DATASETS OF SPECIFIC PARAMETERS EMPLOYED IN THE CHARACTERIZATION OF A LIGHTLY (LP) AND A DARKLY (DP) PIGMENTED SKIN SPECIMEN. THE ACRONYMS SC, SG, SS, SB, PD AND RD REFER TO THE SKIN LAYERS CONSIDERED BY HYLIOS, NAMELY, STRATUM CORNEUM, STRATUM GRANULOSUM, STRATUM SPINOSUM, STRATUM BASALE, PAPILLARY DERMIS AND RETICULAR DERMIS, RESPECTIVELY. ALSO, THE ABBREVIATIONS EU. AND PHEO. REFER TO EUMELANIN AND PHEOMELANIN, RESPECTIVELY.

Parameter	LP	DP
Surface Fold Aspect Ratio	0.1	0.45
SC Thickness (cm)	0.0004	0.0002
SG Thickness (cm)	0.0033	0.0007
SS Thickness (cm)	0.0033	0.0007
SB Thickness (cm)	0.0033	0.0007
PD Thickness (cm)	0.02	0.023
RD Thickness (cm)	0.125	0.2
SG Melanosome Content (%)	0.0	10.0
SS Melanosome Content (%)	0.0	10.0
SB Melanosome Content (%)	3.0	10.0
SG Colloidal Melanin Content (%)	1.35	15.0
SS Colloidal Melanin Content (%)	1.35	15.0
SB Colloidal Melanin Content (%)	1.35	15.0
SB Melanosome Dim. ($\mu m \times \mu m$)	0.41×0.17	0.69×0.28
Eu. Con. (mg/mL)	32.0	50.0
Melanosome Pheo. Conc. (mg/mL)	2.0	4.0
PD Blood Content (%)	0.3	2.5
RD Blood Content (%)	0.3	2.5

III. RESULTS AND DISCUSSION

The results of our *in silico* experiments depicted in Figure 1 indicate that the IDBF impact is more significant in the visible region, while the TEWL impact is more significant beyond 1400 nm. These observations are consistent with the strong absorption behaviours of blood-borne pigments, notably the functional hemoglobins (oxygenated and deoxygenated) and water, respectively, in these spectral regions [7]. It can also be observed that while the spectral variations associated with IDBF are more noticeable for lightly pigmented specimens in the visible region, which is also consistent with visual observations of this phenomenon [8], the spectral variations associated with TEWL for both the lightly and the darkly pigmented specimen are similar across the entire spectral range of interest (250-2500 nm). This can also be explained by the strong absorption behaviour of the main skin pigments, namely the melanins and the hemoglobins, in the visible region [7]. However, although the latter and water are all characterized by a relatively weak absorption behaviour [7], in the 700-900 nm region, the effects of IDBF are noticeable, while the effects of TEWL are unremarkable.

TABLE II

DATASE OF GENERAL PARAMETERS EMPLOYED IN THE CHARACTERIZATION OF BOTH SKIN SPECIMENS, LIGHTLY AND DARKLY PIGMENTED, CONSIDERED IN THIS INVESTIGATION. THE REFRACTIVE INDICES FOR THE SKIN LAYERS WERE MEASURED AT 1300 nm AS REPORTED IN THE LISTED SOURCES. THE ACRONYMS SC, PD AND RD REFER TO THE STRATUM CORNEUM, PAPILLARY DERMIS AND RETICULAR DERMIS, RESPECTIVELY.

Parameter	Value
Oxygenated Blood Fraction (%)	75.0
SC Refractive Index	1.55
Epidermis Refractive Index	1.4
PD Refractive Index	1.39
RD Refractive Index	1.41
Melanin Refractive Index	1.7
Methemoglobin Conc. in Whole Blood (mg/mL)	1.5
Carboxyhemoglobin Conc. in Whole Blood (mg/mL)	1.5
Sulfhemoglobin Conc. in Whole Blood (mg/mL)	0.0
Whole Blood Bilirubin Conc. (mg/mL)	0.003
SC Beta-carotene Conc. (mg/mL)	2.1E-4
Epidermis Beta-carotene Conc. (mg/mL)	2.1E-4
Blood Beta-carotene Conc. (mg/mL)	7.0E-5
SC Water Content (%)	35.0
Epidermis Water Content (%)	60.0
PDWater Content (%)	75.0
RD Water Content (%)	75.0
SC Lipid Content (%)	20.0
Epidermis Lipid Content (%)	15.1
PD Lipid Content (%)	17.33
RD Lipid Content (%)	17.33
SC Keratin Content (%)	65.0
SC Urocanic Acid Density (mol/L)	0.01
Skin DNA Density (mg/mL)	0.185

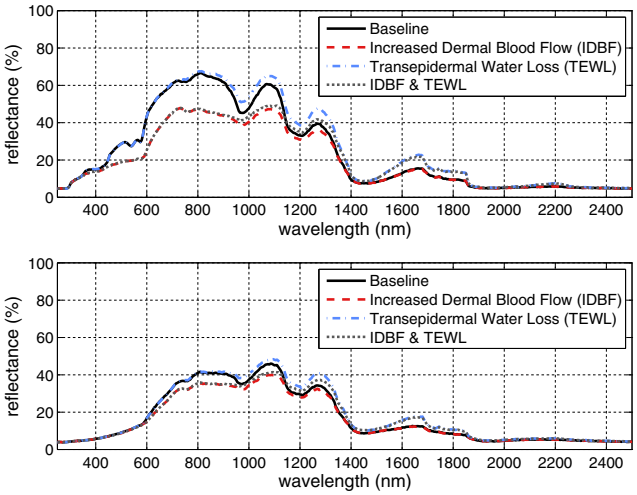

Fig. 1. Modeled reflectance spectra obtained for a lightly pigmented specimen (top) and a darkly pigmented specimen (bottom) to examine spectral variations triggered by adverse environmental conditions such as overexposure to sunlight, excessive heat, low humidity and rapidly flowing winds. More specifically, the effects of the following physiological processes triggered by these environmental stimuli are examined: increased dermal blood flow, transepidermal water loss, and their combined action.

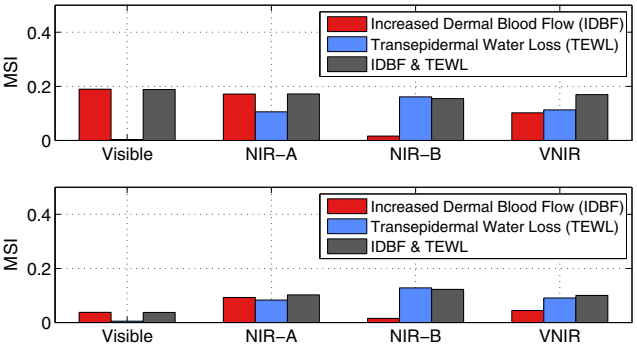

Fig. 2. Mean sensitivity index (MSI) values computed for a lightly pigmented specimen (top) and a darkly pigmented specimen (bottom) considering the effects of increased dermal blood flow, transepidermal water loss and their combined action. The MSI values were computed for each modified reflectance curve (across selected visible (400-700 nm), NIR-A (700-1400 nm), NIR-B (1400-2500 nm) and VNIR (400-2500 nm) ranges) with respect to the baseline curve associated with the respective specimen (Figure 1).

The outcomes of our sensitivity analysis presented in Figure 2 further illustrate the dominant impacts of IDBF and TEWL processes on the responses of human skin in the visible and NIR-B regions, respectively. It also worth noting that similar qualitative trends with respect to the impact of each physiological process under investigation (Figure 2) can be observed for both specimens despite their different levels of pigmentation. This qualitative similarity also applies to the compound ranges of the spectral variations caused by these processes (Figure 3). These observations suggest that the qualitative influence of these processes on the spectral signatures of human skin can be reliably assessed when considering specimens subjected to acute physiological variations.

The differentiation of signatures of target materials from the signatures of complex background materials usually involves the computation of detection indices based on reflectance values captured at selected wavelengths [18]. For example, in the case of plants, the normalized difference vegetation index is computed using values captured at visible and NIR-A (or NIR-B) regions [18]. In the case of human skin, the observations reported in this work demonstrate that variations in reflectance values due to physiological processes triggered by adverse environmental stimuli can be substantial. Hence, they should be taken into account by skin detection procedures in order to mitigate the occurrence of false positives, or false alarms. Since the undue investigation of such situations may lead to the misuse of valuable resources, they can seriously compromise applications that depend on the effectiveness of these procedures such as search and rescue operations.

The observations reported in this work also demonstrate that the derivation of skin quantities from spectral responses (*e.g.*, to determine dehydration levels under adverse environmental conditions [19]) cannot rely solely on light absorption and scattering formulae with respect to a target material constituent. It needs to fully account for the interplay between these light interaction processes. Furthermore, more reliable results are likely to be obtained at sample points not only where the target material constituent has a clear dominant

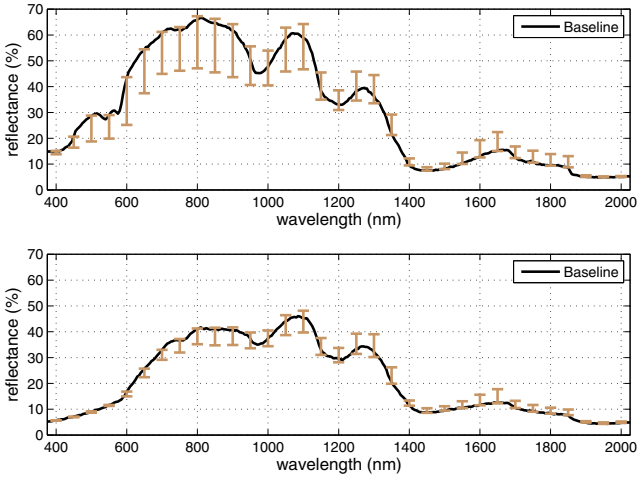

Fig. 3. Close view of the compound range of the significant spectral variations (indicated by the bars) caused by the examined physiological processes (increased dermal blood flow, reduced cutaneous water content, and their combined action) with respect to the baseline modeled reflectance curves obtained for a lightly pigmented specimen (top) and a darkly pigmented specimen (bottom).

role, but also where its extinction coefficient is relatively small so that variations in its content can lead to measurable reflectance variations. For example, in the case of water, the 1650 nm sample point would satisfy these guidelines since it is located in a "window" between two water absorption bands [7] (Figure 1). In the case of blood, a sample point around 800 nm would not only satisfy these guidelines (Figure 1), but it would be also neutral with respect to blood oxygenation variations since it corresponds to an isosbestic point of the functional hemoglobins [20].

IV. Conclusion

Although the correct assessment of skin spectral variations due to exogenous stimuli is of value for all related applications cited in this work, it is particularly crucial for the success of time-critical operations such as those aimed at quickly finding and saving the lives of individuals who are lost and exposed to adverse conditions in vast natural environments [21]. The investigation presented in this paper was motivated by these efforts, with a primary focus on contributing to the strengthening of the scientific basis required for the development of skin differentiation systems capable of providing results with a high reliability to cost ratio under adverse environmental conditions.

Despite its importance, the remote identification and interpretation of human skin signatures can still be considered emerging areas of research. Future advances in these areas will continue to involve the pursuit of efficient solutions for technical challenges posed by the intrinsic complexity of this biological material. We believe that the availability of reliable and diverse data, notably with respect to skin specimens subjected to distinct physiological conditions, will be crucial for the success of these initiatives. This, in turn, will likely require close collaborations among research groups devoted to the measurement, simulation and analysis of skin responses in the hyperspectral domain.

References

[1] R. Flewelling, "Noninvasive optical monitoring," in *The Biomedical Engineering Handbook*, 2nd ed., J. D. Bronzino, Ed. CRC Press LLC, 2000, pp. 86:1–12.

[2] P. Cavalcanti, J. Scharcanski, and G. Baranoski, "A two-stage approach for discriminating melanocytic skin lesions using standard cameras," *Expert Systems with Applications*, vol. 40, no. 10, pp. 4054–4064, 2013.

[3] J. Herweg, J. Kerekes, and M. Eismann, "Hyperspectral imaging phenomenology for the detection and tracking of pedestrians," in *IEEE International Geoscience and Remote Sensing Symposium - IGARSS 2012*, July 2012, pp. 5482–5485.

[4] T. Tamura, Y. Maeda, M. Sekine, and M. Yoshida, "Wearable photoplethysmographic sensors- past and present," *Electronics*, vol. 3, pp. 282–302, 2014.

[5] M. Eismann, A. Stocker, and N. Nasrabadi, "Automated hyperspectral cueing for civilian search and rescue," *Proc. of IEEE*, vol. 97, no. 6, pp. 1031–1055, 2009.

[6] N. Charkoudian, "Skin blood flow in adult thermoregulation: How it works, where it does not, and why," *Mayo Clin. Proc.*, vol. 78, pp. 603–612, 2003.

[7] R. Anderson and J. Parrish, "Optical properties of human skin," in *The Science of Photomedicine*, J. Regan and J. Parrish, Eds. N.Y., USA: Plenun Press, 1982, pp. 147–194.

[8] P. Agache, "Assessment of erythema and pallor," in *Measuring the Skin*, P. Agache and P. Humbert, Eds. Springer, 2004, pp. 591–601.

[9] G. Kelfkens and J. van der Leun, "Skin temperature changes after irradiation with UVB or UVC: implications for the mechanism underlying ultraviolet erythema," *Physics in Medicine and Biology*, vol. 34, no. 5, pp. 599–608, 1989.

[10] I. Blank, "Factors which influence the water content of the stratum corneum," *J. Investig. Dermatol.*, vol. 18, no. 6, pp. 433–440, 06 1952.

[11] B. Ventura, C. Lemerle, K. Michalodimitrakis, and L. Serrano, "From *in vivo* to *in silico* biology and back," *Nature*, vol. 443, pp. 527–553, 2006.

[12] T. Chen, G. Baranoski, B. Kimmel, and E. Miranda, "Hyperspectral modeling of skin appearance," *ACM Transactions on Graphics*, vol. 34, no. 3, pp. 31:1–14, April 2015.

[13] Natural Phenomena Simulation Group (NPSG), *Run HyLIoS Online*, School of Computer Science, University of Waterloo, Ontario, Canada, 2014, http://www.npsg.uwaterloo.ca/models/hylios.php.

[14] G. Baranoski, T. Dimson, T. Chen, B. Kimmel, D. Yim, and E. Miranda, "Rapid dissemination of light transport models on the web," *IEEE Comp. Graphics & Applications*, vol. 32, no. 3, pp. 10–15, 2012.

[15] A. Krake, J. McCullough, and B. King, "Health hazards to park rangers from excessive heat at Grand Canyon Natonal Park," *Applied Occupational and Environmental Hygiene*, vol. 18, pp. 295–317, 2003.

[16] D. Hamby, "A review of techniques for parameter sensitivity analysis of environmental models," *Environmental Monitoring and Assessment*, vol. 32, pp. 135–154, 1994.

[17] F. Hoffman and R. Gardner, "Evaluation of uncertainties in radiological assessment models," in *Radiological Assessment A Textbook on Environmental Dose Analysis*, J. Till and H. Meyer, Eds. Washington, DC, USA: Division of Systems Integration, Office of Nuclear Reactor Regulation, U.S. Nuclear Regulatory Commision, NRC FIN B0766, 1983, pp. 1–55, chapter 11.

[18] G. Baranoski and T. Chen, "On the remote detection of human skin signatures," School of Computer Science, University of Waterloo, Ontario, Canada, Tech. Rep. CS-2014-25, 2014.

[19] I. Cheng, A. Kiss, and L. Lilge, "An observational study of personnal ultraviolet dosimetry and acute diffuse reflectance skin changes at extrem altitude," *Wilderness & Environmental Medicine*, vol. 24, pp. 390–396, 2013.

[20] S. Fantini and M. A. Franceschini, "Frequency-domain techniques for tissue spectroscopy and imaging," in *Handbook of Optical Biomedical Diagnostics*, V. Tuchin, Ed. SPIE Press, 2002, pp. 405–453.

[21] C. Leonard, M. J. DeWeert, J. Gradie, J. Iokepa, and C. Stalder, "Performance of an EO/IR sensor system in marine search and rescue," in *Airborne Intelligence, Surveillance, Reconnaissance (ISR) Systems and Applications II*, S. Wyatt, Ed., vol. 5787. SPIE, 2005, pp. 122–133.