Received: 13 January 2024 | Accepted: 23 February 2024

DOI: 10.1111/srt.13622

ORIGINAL ARTICLE

WILEY

Variations of skin thermal diffusivity on different skin regions

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Funding information
Leo Foundation, Grant/Award Number: LF-OC-19-000031; Swiss Innovation Agency—Innosuisse, Grant/Award Number: 27193_2

Abstract

Background and Objective: Skin thermal diffusivity plays a crucial role in various applications, including laser therapy and cryogenic skin cooling.This study investigates the correlation between skin thermal diffusivity and two important skin parameters, melanin content and erythema, in a cohort of 102 participants.

Methods: An in-house developed device based on transient temperature measurement was used to assess thermal diffusivity at different body locations. Melanin content and erythema were measured using a colorimeter. Statistical analysis was performed to examine potential correlations.

Results: The results showed that the measured thermal diffusivity values were consistent with previous reports, with variations observed among subjects. No significant correlation was found between thermal diffusivity and melanin content or erythema. This suggests that other factors, such as skin hydration or epidermis thickness, may have a more dominant influence on skin thermal properties.

Conlcusion: This research provides valuable insights into the complex interplay between skin thermal properties and physiological parameters, with potential implications for cosmetic and clinical dermatology applications.

KEYWORDS
erythema, melanin, pigmentation, skin, thermal diffusivity

1 | INTRODUCTION

Many measurement methods have been applied to investigate the human skin,[1,2] some of them being established as gold standard-like (bio)impedance spectroscopy.[3] Among the different techniques, the measurement of the thermal properties of the skin is promising as such parameters could lead to new insights in the field of clinical dermatology, for example, for personalized treatment or the effectiveness of skin care products. Thermal parameters generally refer to thermal conductivity k (in W/(m · K)), heat capacity c (in J/(kg ·K)) and, density ρ (in kg/m^3), often bundled into one single parameter the thermal diffusivity $\alpha = \frac{k}{\rho c}$ (in m^2/s). Skin perfusion ω (s^{-1}) is sometimes considered in the literature as an additional thermal parameter as it contributes to the Bioheat equation as a source or sink term.[4] As the

skin's thermal properties dictate how the heat diffuses through the different skin layers, those parameters are particularly relevant when employing lasers for both cosmetic and non-cosmetic applications[5] or cryogenic skin cooling.[6] They also play an important role in thermal imaging methods.[7–9]

Numerous devices have been proposed in the literature to measure the thermal properties of the skin in vivo.[10–26] More recently, wearables have emerged as a solution for continuous monitoring.[27–37] However, to date, only a few studies have been devoted to investigating the potential correlation between thermal parameters and relevant physiological value. Webb and co-workers for example, noticed a strong correlation between epidermal thickness and stratum corneum hydration with thermal conductivity but the number of subjects was limited to 25.[29] Wearables based on transient temperature measurements have been used to monitor perfusion.[28] While pigmentation and erythema are traditionally considered optical properties, the link to thermal properties may not be straightforward. However, given the complex relationship between the composition of the skin and its thermal behavior, it is plausible that variations in melanin content and erythema could influence the thermal diffusivity of the skin. Melanin, as a pigment, absorbs light and converts it into heat, which can influence the general thermal properties of the skin. Similarly, erythema, which indicates increased blood flow, may introduce variations in thermal parameters due to changes in blood flow.

In this study, using an in-house developed device, we analyze the relationship between skin thermal diffusivity and skin pigmentation (melanin content) and redness (erythema).

2 | MATERIALS AND METHODS

2.1 | Measuring thermal diffusivity

The apparatus used in this study has been previously reported.[26] The fitting method of the device is validated using a fully numerical 3D model of the thermal properties of the skin. Figure 1A shows a picture of the device that consists of a handheld apparatus (Figure 1B), in contact with the skin and a base station. The base station is connected via a Universal Serial Bus (USB) cable to a personal computer which runs a specific software that controls the handheld device, records the transient skin surface temperature, and analyses the resulting data (Figure 1C). We briefly describe how the hand-held device works: a massive hollow cylinder, actively cooled by a Peltier metal cylinder, is brought into contact with the skin, while a thermopile measures contactless the transient skin surface temperature in the center of the cylinder (Figure 1D). A spring system ensures a reproducible pressure on the skin surface.

The device is calibrated using a polydimethylsiloxane (PDMS) block with known diffusivity ($\alpha = 1.28 \times 10^{-7}$ m^2/s).[38] The specific material used is the Sylgard 184 from Dow Corning. The PDMS block has been prepared by mixing a ratio of 10:1 of monomer and curing agent. After casting, it dried at room temperature for 2 days.

The reproducibility of the device is assessed in vivo. An area on the lower back of a subject is marked and 10 measurements are performed sequentially waiting 10 min between each measurement to allow the skin to return to equilibrium temperature. The 10 transient temperature curves are fitted (Figure 2) using an exponential function (Equation 1). The mean value obtained for the thermal diffusivity is 1.13×10^{-7} m^2/s with a standard deviation of 0.06×10^{-7} m^2/s (Supplementary Information SI-1 and SI-2).

2.2 | Mathematical model

Different mathematical models can be used to extract the skin's thermal diffusivity from the transient's temperature.[29,39,40] For the present measurement geometry and the induced cooling impulse by the cylinder, we used a specific algorithm that accounts for the lateral heat flux near the skin surface. The 1D bioheat equation was extended with an additional heat sink/source therm to improve the accouracy of the extracted parameters and improve the systematic errors introduced by oversimplifying the model. The lateral heat flux was The mathematical model used in this study is presented in detail in a separate publication.[41] However, the fitting equation employed for this research will be explained in the following.

The cooling of the skin surface using an annular element can only be modeled properly if taken into account the lateral heat transfer. Within a 1D model, this can be achieved by adding a heat sink similar to the perfusion term of the Pennes' equation. It is composed of the heat equation and a heat source term describing the heat loss due to the lateral heat transport.

$$\rho c_p \partial_t T(x,t) + \rho_b c_p^b \omega_b \left(T(x,t) - T_{sink}(x)\right) = \kappa \partial_x^2 T(x,t)$$

The tissue depth below the skin surface x (m) is assumed to take negative values and to be infinite in the x-direction. The parameters describing the skin are the mass density ρ ($in\ \frac{kg}{m^3}$), the thermal conductivity κ ($in\ \frac{W}{mK}$), and the specific heat capacity c_p ($in\ \frac{J}{kgK}$). The blood thermal properties are described by the mass density ρ_b ($in\ \frac{kg}{m^3}$)„ the heat capacity c_p^b ($in\ \frac{J}{kgK}$)., its temperature $T_b(K)$, and the blood perfusion rate ω ($in\ \frac{1}{s}$). $T_{sink}(x)$ is the heat sink temperature

$$T_{sink}(x) = T_b + e^{\lambda_0 x}\left(T_s - T_b\right),$$

with λ_0 the decay constant of the heat sink temperature and T_s the heat sink temperature at the skin surface.

The boundary conditions in the skin surface ($x = 0$) are of convective heat transfer to the air. Thereby, radiation is linearised and included in the convective heat transfer. The convective heat transfer coefficient is thus modified to take radiation into account.

$$h_a\left(T(0) - T_a\right) = -\kappa \partial_x T(0)$$

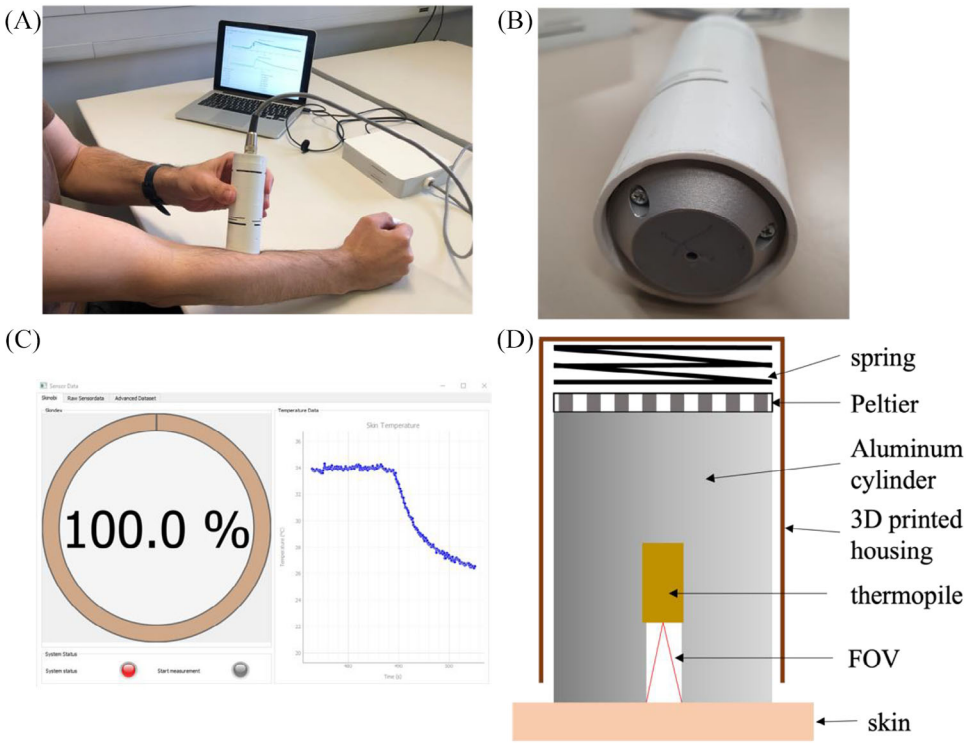

FIGURE 1 (A) Picture of the in-house developed apparatus used in this study to measure the thermal diffusivity. The device consists of a handheld apparatus and a base station. (B) Zoomed picture of the hand-held apparatus illustrating the measurement aperture of the device. (C) User interface of the software. (D) Schematic of the transient temperature measurement thermopile incorporated in the hollow Peltier metallic cylinder of the handheld device.

And the temperature approaches the asymptotic value T_b at large depths. The temperature of the skin surface at contact time $T(x, 0)$ is obtained from the time-independent Pennes' equation

$$\rho_b c_p^b \omega_b \left(T^{eq}(x) - T_b\right) = \kappa \partial_x^2 T^{eq}(x)$$

using the same boundary conditions as for the transient temperature.

An analytical solution exists for the temperature evolution of the skin surface $T(0, t) \equiv T(\tau)$ (41)

$$T(\tau) = T^{eq} + e^{-\tau}\,\delta_T \left(\frac{(\gamma+1) - \text{erfcx}\left(-\sqrt{\tau}\right)}{(\lambda-1)(\gamma-\lambda)} - , \frac{(\lambda+1)\,\text{erfcx}\left(\gamma\sqrt{\tau}\right)}{(\gamma-1)(\gamma-\lambda)} - \frac{(\gamma+1)\,\text{erfcx}\left(\sqrt{\tau}\right)}{(\gamma-1)(\lambda-1)} \right) \quad (1)$$

with $\tau = \alpha\beta^2 t$ an undimensionalized time, $\alpha\beta^2 = \rho_b\, c_p^b\, \omega\, (\rho\, c_p)^{-1}$ a normalized perfusion rate, $\gamma = \text{h}_\text{a}\ /(\text{»}\ .)$ the undimensionalized heat loss parameter, $- = \frac{\lambda_0}{\beta}$ the undimensionalized sink decay rate and $\delta_T = T^i - T^{eq}$ the range of the temperature change between the initial T^i and the equilibrium T^{eq} values. Finally, $\text{erfcx}(x) = e^{-x^2}\,(1 - \text{erf}(x))$ is the scaled complementary error function.

2.3 | Measurement of erythema and melanin content

To objectively measure skin pigmentation, we used a colorimeter (DSM III Colorimeter, Cortex Technology, Denmark). The device functions by illuminating the respective skin area with two white LEDs and measuring the reflected light by a photodiode behind a green light interference filter on the one hand and a red light interference filter on the other. Based on the absorption characteristics of human skin, a value for the melanin content and skin redness is determined. The calculated melanin index (MI) is based on the diffuse reflectance measurement (R_r) in the red spectrum at 680 nm where melanin has the highest absorption $MI = 100 \times log_{10}(\frac{1}{R_r})$. The erythema index (EI) is calculated as an index of hemoglobin relative to melanin. The diffuse reflectance for melanin of red light (R_r) is measured at 680 nm. For hemoglobin, the diffuse reflectance is measured at green light centered at 555 nm. The EI is expressed as $EI = 100\,\text{x}\log_{10}\frac{R_r}{R_g}$.

2.4 | Study

A total of 102 participants were enrolled in the study between 09/16/2021 and 12/27/2021. Of these, 34 were male and 64 were female with ages ranging from 18 to 67 years (mean 28 years). Individ-

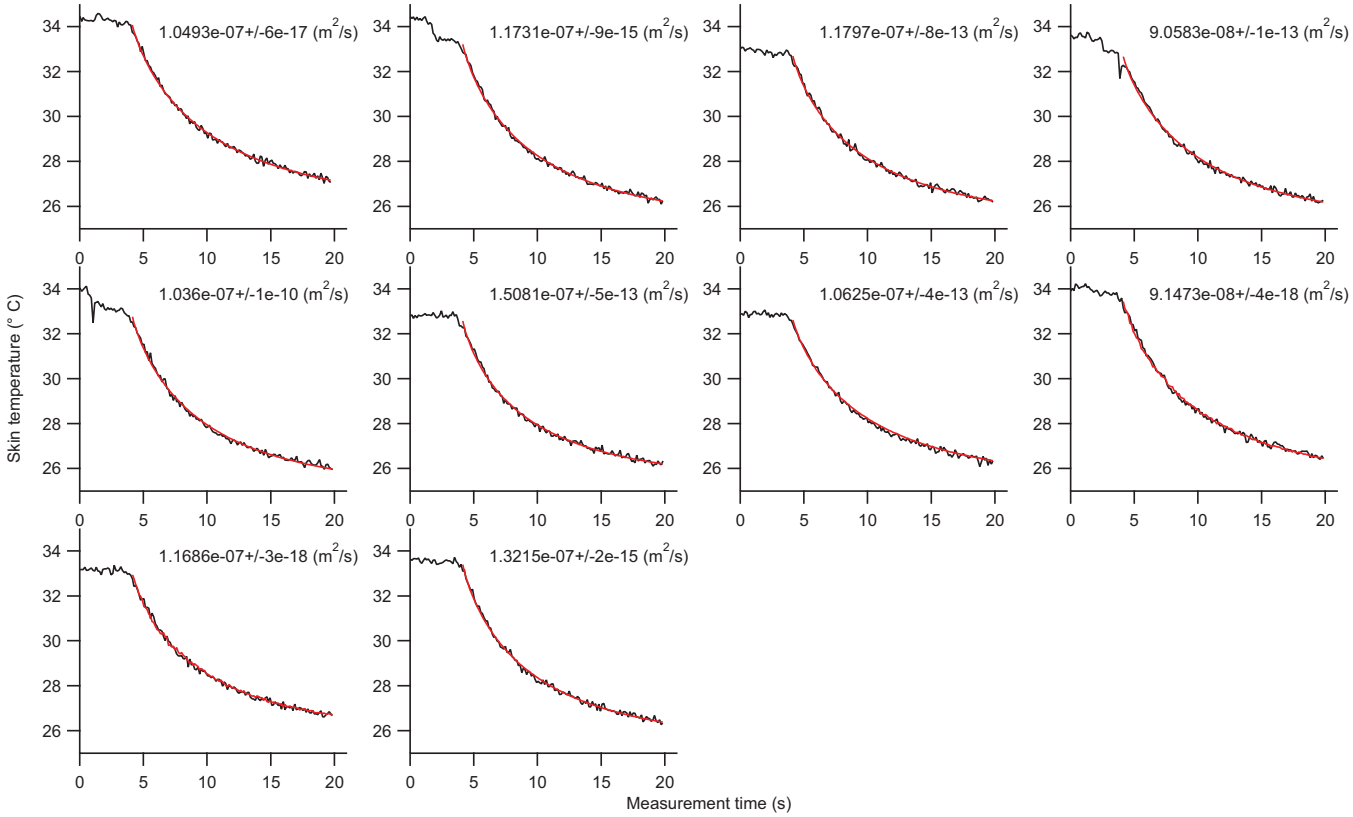

FIGURE 2 Transient temperature signals measured 10 times consecutively on the same skin area, 15 min between each measurement so that the skin has time to come back to equilibrium temperature. Red lines represent the fit obtained with the equation derived in the mathematical model section with the resulting skin thermal diffusivity.

uals with pre-existing skin disorders, tattoos, or large scars as well as pregnant women and underage subjects were excluded from the study. Although we were not selective about the skin color of the subjects, 87 of the participants were of full or partial European ancestry. The participants had no special thermoregulation during the measurement and were wearing everyday clothes. All patients have been in a thermoneutral condition without shivering or sweating. The measurements were taken in a patient room at room temperature (22C°). The measurement were taken after the mandatory consultation and were therefore carried out 15 min after entering the room in a sitting position. We obtained the Ethical approval for this study from Swissethics. Written and oral informed consent was obtained for anonymized patient information to be published in this article.

2.5 | Statistical analysis

For the statistical analysis, the correlations between thermal diffusivity and melanin content as well as erythema were analyzed at three different measurement points (lower back, cheek, lower leg right). Erythema and melanin content for the left lower leg were not measured and therefore not included in the analysis. Spearman correlation coefficients and corresponding *p*-values were used to assess the strength of these relationships. Heat maps were created to provide a combined view of these correlations. To ensure the robustness of the analysis, outliers in the diffusivity data could be identified using the Interquartile Range (IQR) method. Data points with values that exceed 1.5 times the IQR could be considered outliers and subsequently excluded from the dataset. All thermal diffusivity values obtained on different body locations (including outliers) are plotted in Supplementary Information SI-2.

3 | RESULTS AND DISCUSSION

Figure 3 represents the thermal diffusivity in m^2/s computed for four body locations (cheek, lower back, lower leg left, and lower leg right). The obtained diffusivity values are in the same range compared to previously reported values.[25,29,42] Mean thermal diffusivity values for the left and right leg are similar (2.60×10^{-7} m^2/s and 2.40×10^{-7} m^2/s). The cheeks demonstrate the diffusivity (2.73×10^{-7} m^2/s) while the lower back exhibits (1.62×10^{-7} m^2/s). Webb and co-workers reported a correlation between epidermis thickness (EP) and thermal diffusivity with higher thicknesses being associated with lower diffusivity values.[29] Our results do not follow this trend according to EP from the literature.[43] Nonetheless, Webb et al. measured the EP thickness for each subject and their results did not follow previously reported literature data with low values for example, for the palm.[29,43]

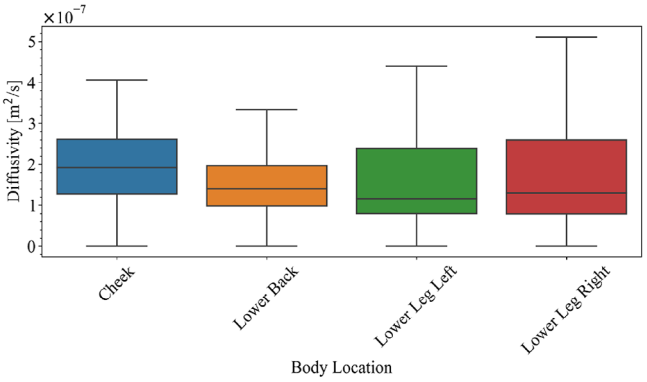

FIGURE 3 Computed thermal diffusivity for different body locations. The values obtained are in the range of previously reported studies. Lower leg left and right demonstrate comparable mean values. Cheek exhibits higher thermal diffusivity.

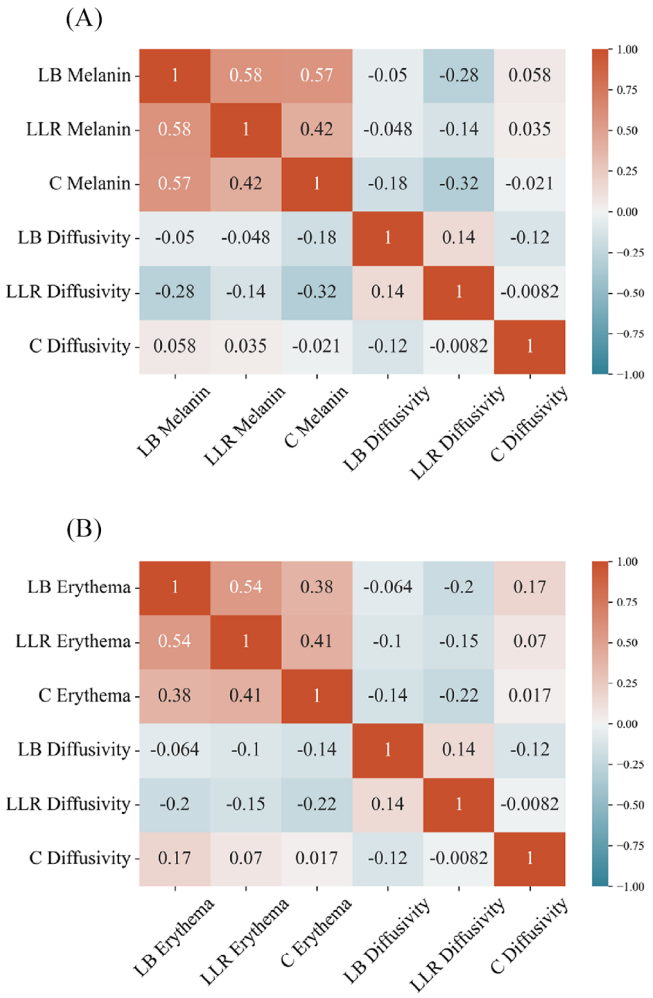

FIGURE 4 (A) Statistical correlation analysis between melanin content and thermal diffusivity of the different body locations (LB, LLR, and C). No statistically relevant correlation between melanin and diffusivity is evident. (B) Statistical correlation analysis between erythema and thermal diffusivity for the body locations. Also here no statistically relevant correlation is discernible. LB, lower back; LLR, lower leg right; C, cheek.

An important goal of this study was to investigate if and how melanin content and erythema affect thermal diffusivity. Melanin is a complex pigment produced by melanocytes in the epidermis of the skin. It occurs mainly as eumelanin (black-brown) and pheomelanin (yellow-reddish). Depending on the combination of the two melanin types and especially the amount of melanin determines the color of the skin and leads to different skin phenotypes.[44] Beyond its aesthetic significance, melanin plays a crucial role as a photoprotector against ultraviolet (UV) radiation. The high light absorption and scattering capacity of melanin ensures that harmful UV radiation is either scattered or absorbed in the uppermost layer of the skin and therefore protects the underlaying layers from DNA photodamage.[45] Such a behavior leads to inaccuracies in optical measurements for dark skin people[46,47] due to the high absorption characteristics of melanin as well as the fact that cosmetic procedures such as hair follicle removal or port wine stain treatment are not as effective for all phenotypes.[48,49] As hypothesized in the study by Charlton et al., radiative properties of human skin may not be affected by melanin.[50] However, it could modify the skin's thermal diffusivity leading to different heat diffusion for dark skin in comparison to light skin.

Figure 4A represents the correlation map between melanin and the thermal diffusivity measured with our device on three body sides. No correlation was found between melanin content and thermal diffusivity. In solid form, melanin exhibits a thermal diffusivity of 0.13 mm^2/s[51] in the same order as previous values obtained on skin.[29] Nevertheless, it could be that that confounding physiological variations, such as the thickness of the epidermis, dominate the measurements and the statistical analysis. In addition, the variation in melanin content was limited in the study, as only very few subjects with dark skin were included, making it difficult to find a correlation.

Erythema means redness of the skin caused by increased blood flow in the superficial capillaries. It can have various causes, such as inflammation, allergic reactions, sunburn, or autoimmune diseases. Some studies already linked superficial blood flow with thermal properties[27,28] but measurements were performed continuously over a longer period. As blood has a thermal diffusivity of 370 mm^2/s,[52] it is expected that higher perfusion leads to higher thermal diffusivity. Figure 4B presents the correlation heat map between thermal diffusivity and erythema. No correlation can be seen. As previously mentioned, it could be that other physiological variations (e.g., EP) dominate. Another potential explanation is that the duration of the measurement (30 s) is too short to assess change in perfusion.

In our device, the pressure applied between the cooling block and the skin plays a major role. Indeed the thermal contact resistance is a parameter that is, fitted and obtained from in vitro measurement on PDMS. Therefore it should be identical for each measurement. To minimize pressure variations, we implemented a spring system in our apparatus (Figure 1D). Potential improvements could be using a longer spring or implementing pressure sensors to monitor the pressure during the measurement. Another limitation lies in the timing or when the block is in contact with the skin and the spring is fully compressed. It is currently challenging to identify this moment on the transient tem-

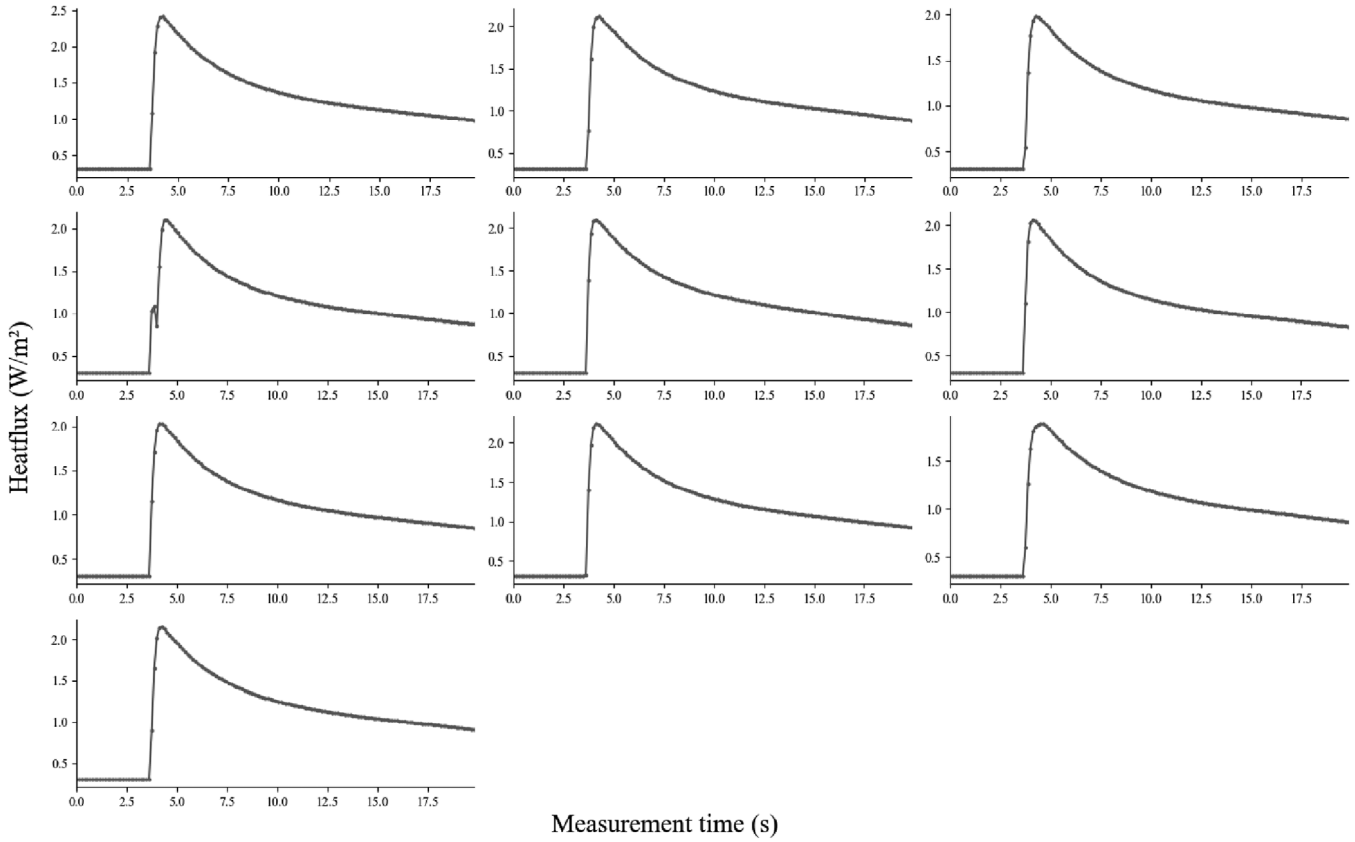

FIGURE 5 Transient heat flux measured 10 times on the same skin location with the heat flux sensor embedded into the measurement head (Supplementary Information SI-3). In comparison to transient temperature measurements (Figure 2), the signals are less noisy. Such an additional heat flux sensor should allow to better determine the start measurement timing (when the sensor is positioned onto the skin) as well as increase the accuracy when calculating the skin thermal diffusivity.

perature curves (see Figure 2). A last issue is the lack of features in the transient temperature curves that limit the sensitivity of the device and avoid the extraction of additional parameters such as blood perfusion.

To address the above-mentioned limitations, we integrated an additional heat flux sensor (gSkin-XU, GreenTEG AG, Switzerland) into the sensor head. The sensor is positioned next to the thermopile measurement area, but far enough to not disturb the noncontact temperature measurement. The addition of such a sensor demonstrates several advantages (Supplementary SI-3). First, it allows an easier identification of the start of the measurement as the heat flux exhibits a sharp rise (Figure 5). Second, in combination of the transient temperature measurement, it allows the extraction and monitoring of the thermal contact resistance between the metallic block and the skin. Finally, it allows a more precise determination of the thermal diffusivity providing an additional fitting curve. Altough preliminary measurements are promising (Figure 5), more measurements are needed to improve the sensitivity of our apparatus.

4 | CONCLUSION

In this article, we reported the measurements of the skin thermal diffusivity of 102 healthy subjects on four body locations using an in-house developed device based on transient temperature measurement. The values obtained are in the range of previously reported data. Large variations of diffusivity values can be noticed among the subjects. In addition, skin color and erythema were acquired with a commercial apparatus. We see no correlation between erythema and thermal diffusivity, nor between pigmentation and thermal diffusivity. Further analysis is needed to determine if potential variations are too small to be detected with our apparatus or if other skin parameters such as hydration dominate the signal.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support of the Leo Foundation (Grant Number LF-OC-19-000031) as well as from the Swiss Innovation Agency—Innosuisse (Grant Number 27193_2).

ETHICS STATEMENT

We obtained the Ethical approval for this study from Swissethics. Written and oral informed consent was obtained for anonymized patient information to be published in this article.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Bajrami D, Zubiaga A, Renggli T, et al. Variations of skin thermal diffusivity on different skin regions. *Skin Res Technol*. 2024;30:e13622. https://doi.org/10.1111/srt.13622