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***Abstract*—The increasing adoption of lasers in medical procedures has highlighted some limitations of the technique, such as the influence of melanin on thermal effects. This study focuses on analyzing the local temperature during and after the irradiation for different skin tones using optical phantoms, with a low intensity 660 nm laser. It was shown that as the sample was more pigmented, the temperature increased faster, and it was observed that the temperature rise is equivalent to a logarithmic pattern, while the decreasing temperature after irradiation was well described by Newton's law of cooling.**

***Index Terms*—Photobiomodulation, skin tone, thermal effects.**

I. Introduction

The use of lasers in medicine, physiotherapy and aesthetic methods has increased in the last decades, providing less invasive and more precise procedures [1], [2] and acting as a complement in the treatment of pain and inflammations [3]. Although there are promising applications of lasers, it has been reported that their use in highly pigmented skin types can cause adverse reactions, such as heating, hypo or hyper pigmentation and even muscle lesions in the irradiation area [4]. Sanchez [5] also mentioned that Latinos with African ancestry, which is more than half of the Brazilian population [11], can also suffer damage from laser procedures, which highlights the need for studies of collateral effects of laser applications in diverse populations.

Photobiomodulation therapy (PBM) is a treatment technique that uses low-intensity light sources to induce biological processes. While several studies indicate that there is no significant temperature increase at PBM treatment site [7], others suggest that the temperature shift depends on wavelength [8], energy density, exposure time, thickness and type of target tissue and skin tone [12], the aim of this study.

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In this study, we aim to discuss the conversion of laser-emitted light into thermal energy as a function of skin tone, using phantoms that mimic different cutaneous phototypes.

II. Methodology

A. Samples

In this study, five pigmented phantoms were used to mimic the optical properties of human skin [6] . The samples thickness is 1.3 ± 0.2, and were manufactured using epoxy resin (Avipol, Brazil) as matrix, compact facial powder (Ruby Rose, Brazil) of different shades in the proportion of 2% (w/w) of the resin as absorber agent and titanium dioxide (TiO_2) (Synth, Brazil) as scattering agent. The components were weighed using a precision analytical balance (Mark 210A, BEL Engineering, Italy) and mixed until homogenized. After being poured in a plastic mold, they were inserted into a vacuum pump (Prismatec, Brazil) to eliminate bubbles, placed in an oven to accelerate the curing process, and then sliced.

B. Optical Characterization

The reduced scattering coefficient of all phantoms was 1.6 ± 0.1 mm^{-1} in 660 nm, computed with the inverse addition-doubling (IAD) method [13], using experimental diffuse reflectance and transmittance measured with a double integrating spheres set up [9]. A 400 mW Xenon lamp (Newport, USA) light source and a RPS900R (International Light Technologies, USA) spectrometer were used. The phantoms used in this study have the same absorption coefficient profile from 500 to 900 nm similar to human skin [6], while the coefficient values range from 0.012 ± 0.001 mm^{-1} to 0.398 ± 0.014 mm^{-1} in 660 nm.

C. Colorimetry

To analyze the influence of skin tone phototypes, the samples were classified using the Individual Typology Angle

(ITA), which can be calculated with CIELab values through Eq. 1:

$$ITA(degree) = \frac{180}{\pi} arctan(\frac{L^* - 50}{b^*}) \quad (1)$$

were L* describes brightness or luminance, b* is related to blue and yellow colors, and a* corresponds to green and red colors but has minimal impact on ITA. The ITA categorization follows the following sequence: very light 55^o > light 41^o > intermediate 28^o > tan 10^o > brown -30^o > dark. The CIELab values were acquired using a 450G colorimeter (Delta Vista, Brazil) and the ITA of the phantoms are: $60.9^o \pm 0.6°$ (very light), $23.7° \pm 0.7°$ (tan), $-2.1° \pm 0.2°$ (brown), $-19.2° \pm 0.6°$ (brown) and $-55.9° \pm 1.1°$ (dark).

D. Irradiation Parameters

A 660 nm Twin Flex Evolution laser (MMOPTICS, Brazil), with a maximum power of 40 mW and irradiation time set to 180 s, was used. A LabMax Top potentiometer (Coherent, USA) was used to measure the nominal fluence, which was 180 J/cm^2. However, after correcting for the actual spot size in the phantom, the effective fluence at the irradiation site was 91.4 J/cm^2. No photobiomodulation protocol was considered in this study, as the irradiation time was set at the maximum to provide a heating profile for analysis.

E. Thermal Evaluation

A T450sc thermal camera (FLIR Systems, Sweden), with a precision of 0.1 °C and emissivity set to 0.98, was used. The distance between the camera and the sample was fixed using a holder to ensure a consistent source-sample spacing across all measurements. The phantoms were irradiated under thermal equilibrium conditions, with an initial temperature of 22.2 ± 0.1 °C.

III. Result and Discussions

Fig. 1 shows the temperature increasing over time as a function of the skin tone of the skin phantoms.

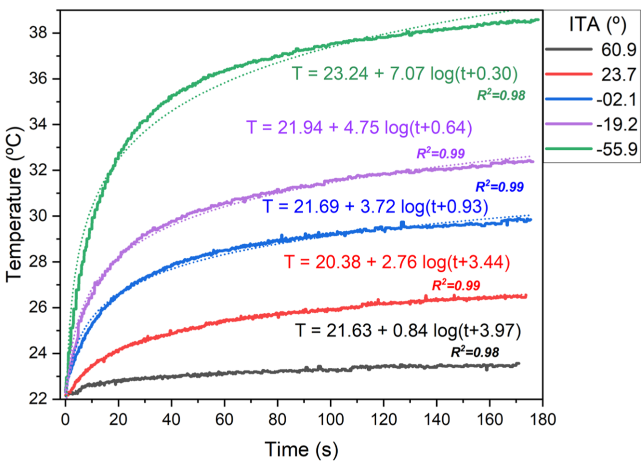

Fig. 1. Surface heating temperature during laser irradiation for all five phantoms.

For the analysis of the irradiated region, the increase in temperature was described as a logarithmic expression:

$$T = a + b \cdot log(t + c) \quad (2)$$

where T is the surface temperature, t is the irradiation time and a, b, and c are the model parameters. It can be observed that the temperature rise of all samples followed a similar profile. Some models were tested and a logarithmic pattern was proposed, which was well adjusted considering that R^2 was higher than 0.98 for all samples, indicating that the fit was adequate.

Analyzing the expression, it is possible to correlate that the parameter "a" is the initial temperature, although any of the fittings converged to the experimental data of 22.2 ± 0.1 °C. However, the parameters "b" and "c" seem to be related to skin tone, once they all increase or decrease proportionally to ITA. Despite these indicators, the low number of skin tones and measurements interferes with more detailed analyses to validate a complete model.

Once a model was found to describe the heating profile, it is worth considering that lower values of ITA showed not only a faster increase in temperature but also higher values. One parameter that can be analyzed in thermal effects is the activation of heat-sensitive ion channels at 43 °C [10] that, considering the body core temperature around 37 °C, is a temperature increase of 6 °C. In figure 1, it can be seen that this threshold is achieved for the -2.1 °C sample after one minute of irradiation, after 20 seconds for the -19.2 °C sample and with less than 10 seconds for the darker sample of ITA -55.9 °C. In those cases, a complete model that describes the increase in temperature over time and dependence on skin characteristics would prevent thermal injuries. For personalized protocols, specific studies would be necessary to analyze the influence of wavelength and irradiance, and pigmented phantom samples have been proven to be a good approximation for skin tissue, considering their similar optical properties. In addition, the epoxy resin matrix was chosen due to close values of thermal diffusivity with the skin [14], suggesting that this experiment is a good approximation for *in vivo* procedures.

Since heating was analyzed, the cooling process was also considered to better understand the thermal process of the skin. The cooling data were acquired until 180 seconds after the interruption of irradiation and are shown in figure 2.

In this analysis, it was considered Newton's law of cooling, as shown in Equation (3).

$$T = T_s + (T_o - T_s)e^{-kt} \quad (3)$$

where T_o is the initial temperature, T_s is the surrounding temperature and k is a constant. This model also fitted well considering the R^2=0.99 for all samples. In this case, the only undefined parameter is "k", which is different for each object, and was hypothesized to be similar for all phantoms due to the epoxy resin matrix, but was not observed for lighter samples. Considering that the surrounding temperature has not

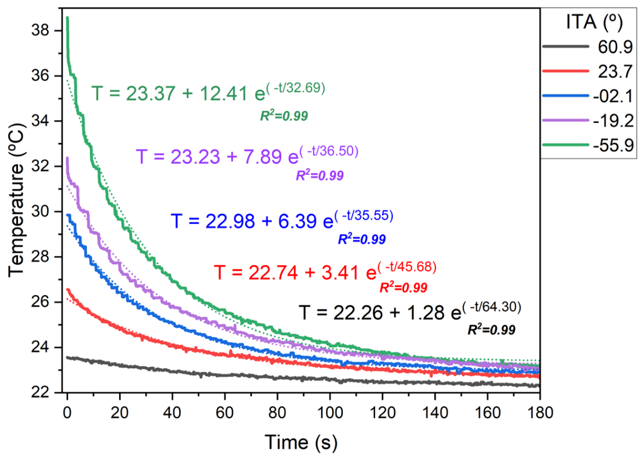

Fig. 2. Time function of surface cooling after the irradiation for all five phantoms.

converged with the experimental data and the "k" constant was not defined for the phantom characteristics, specific studies are necessary to complement the model analyzes.

The importance of studying the skin cooling process is that many procedures need to cool the irradiated area, such as contact cooling or coolant spray [15], to prevent burns and hyperpigmentation, or sequential fractionated doses protocols are used to avoid overheating of the tissue, although any of these applications used in photobiomodulation. In this case, the temperature after 180 seconds was analyzed, which in figure 3 is shown as the initial temperature found in Newton's cooling law fit.

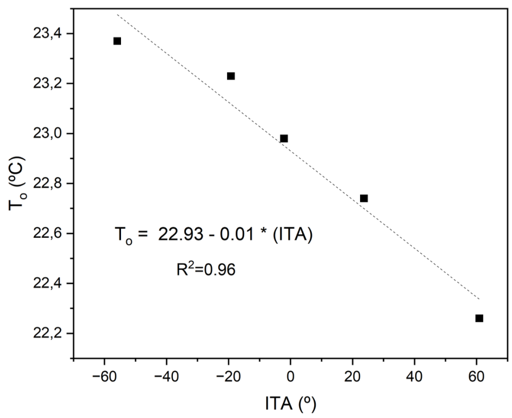

Fig. 3. Final temperature as function of ITA values after 180 seconds cooling.

Samples with lower ITA, after 3 minutes of cooling, kept higher temperatures than lighter samples, with a difference of up to 1.5 °C, indicating that darker skins need more time to return to body temperature. Figure 2 also shows that after 80 seconds, the cooling slows, demonstrating that darker samples need more time to stabilize at the initial temperature. This analysis shows that for darker skins, consecutive applications on the same area are not recommended, since it can elevate the temperature on the spot even more if the recovery time is not respected.

The results presented in Figures 1, 2 and 3 indicate that brown and dark skins may require personalized protocols considering the heating and cooling profiles due to the optical characteristics of the tissue that contribute to transforming absorbed light into heat. Considering that this study only evaluated the 660 nm laser, with a low power of 40 mW, and half of the nominal irradiance, because of the distance between the laser point and the samples, further studies are necessary to expand clinical applications and more skin shades are needed to improve the suggested models.

IV. Conclusion

This study analyzed different skin tones response to laser irradiation, showing that darker skins present an increased local temperature and a longer time to recover body temperature. It also proposed models to estimate the temperature over time for specific skin tones during the irradiation and in the cooling process, for a 660 nm laser with 91.4 J/cm^2 fluence, and exposed the need for temperature recovery until the next application in darker skins. These findings highlight the gap in laser therapy for darker skins and suggest further studies to adapt protocols for different skin tones to avoid undesired thermal effects.

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