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Novel approach to assess the emissivity of the human skin

Francisco J. Sanchez-Marin
Sergio Calixto-Carrera
Carlos Villaseñor-Mora
Centro de investigaciones en optica
Loma del Bosque 115
Lomas del Campestre
Leon, Guanajuato 37150
Mexico
E-mail: sanchez@cio.mx

Abstract. To study the radiation emitted by the human skin, the emissivity of its surface must be known. We present a new approach to measure the emissivity of the human skin *in vivo*. Our method is based on the calculation of the difference of two infrared images: one acquired before projecting a CO_2 laser beam on the surface of the skin and the other after such projection. The difference image contains the radiation reflected by the skin, which is used to calculate the emissivity, making use of Kirchhoff's law and the Helmholtz reciprocity relation. With our method, noncontact measurements are achieved, and the determination of the skin temperature is not needed, which has been an inconvenience for other methods. We show that it is possible to make determinations of the emissivity at specific wavelengths. Last, our results confirm that the human skin obeys Lambert's law of diffuse reflection and that it behaves almost like a blackbody at a wavelength of 10.6 μm. [DOI: 10.1117/1.3086612]

Keywords: emissivity; human skin; infrared; CO_2 laser.

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1 Introduction

Interest in the determination of the temperature of the surface of human skin and of the energy radiated from it has greatly increased. In part, this interest has been due on one hand to the important part played by radiation in the theories of ventilation of the human body and on the other hand to the desire for making a more accurate analysis of the factors involved in human metabolism and widespread diseases such as breast cancer.[1] The optical properties of the skin are also of interest because of their effect on noninvasive optical measurements of deeper tissue and because of the possibility of using the skin as an accessible organ for determining some of the constituents of blood *in vivo*. The difficulties involved in determining the optical properties of tissue *in vivo* are well known. However, tissue excision and storage may produce changes in the optical properties due to blood drainage.[2]

It is clear that to determine the temperature of the skin by the radiation it emits, the emissivity of its surface must be known. This is so because the techniques of skin temperature measurements by means of radiometric instruments depend on its emissive power.[3]

Temperatures of burn wounds have been used in the diagnosis of wound depth and in studies of healing that imply calculations of heat losses. Watmough and Oliver[4] and Boylan et al.[5] have noted that even slight variations due to incorrect values of emissivity can yield to erroneous conclusions. Also, an appropriate knowledge of the skin emissivity is of paramount importance in studies where the effects of thermotherapy are evaluated by infrared technology.[6]

Precise knowledge of the skin emissivity is of interest in diverse areas like veterinary medicine[7] for doing research,[8] to investigate the physiology of animals,[9] and for diagnostic purposes.[10,11] It is also useful in legal medicine,[12] to model the human skin,[13] to monitor the effects of treatments,[14,15] in pediatrics,[16] and for testing biomaterials.[17]

There has long been discussion about the results obtained using different materials and methodologies to determine the emissive power of the skin.[18–20] Hardy, in his pioneering experiments, designed his own measurement devices and found that the skin could be studied as if it was a blackbody.[21,22] Mitchell et al.[2] calculated the emissivity of the skin based on the fact that the rate of transfer of radiant heat between the skin and a radiometer depends not only on the temperature of the skin, but also on the temperature of the radiometer. These authors measured the emissivity of the skin relative to a conical blackbody. Steketee[23] modified a monochromator to measure the emissivity, $\varepsilon(\lambda)$, of living tissue, considering it also as a blackbody, in the infrared region between 1 and 14 μm. He determined $\varepsilon(\lambda)$ for white skin, black skin, burnt skin, and pericardium. His results suggested that $\varepsilon(\lambda)$ is independent of wavelength. Anderson and Parrish[24] studied the skin scattering and absorption coefficients from the UV to the near infrared (NIR), from 250 to 2400 nm, and concluded that the skin is an optical barrier primarily by absorption of radiation, like a blackbody.

Togawa[25] estimated the skin emissivity based on the reflectance measurement upon a transient stepwise change in the ambient temperature. For this, he used two shades at different temperatures that were switched mechanically. The change in radiation from the skin was recorded by a high-resolution radiometer that was sensitive within the 8 to 14 μm range. However, he used curve fitting and ex-

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trapolation to compensate the increment of skin temperature that occurred during his experiments.

Boylan et al.[5] measured the emissivity of wound and normal human skin using an apparatus similar to that used by Togawa,[25] the only difference was that these authors used a cool shade (at about 0°C) instead of a warm one.

Togawa and Saito[26] repeated the experiments previously done by Togawa,[25] but this time using a thermovision camera instead of a radiometer. Thermograms before, immediately after, and 20 seconds after switching the hoods were taken. Then an emissivity image was computed from those thermograms. However, the emissivity images they obtained, as well as the thermal parameter that they defined, contained significant amounts of noise.

In experiments related to heat flow in the human body, frequently, the emissivity of surfaces is estimated by adjusting the emissivity control of an infrared thermometer until its temperature reading equals the value of a contact thermometer reading.[27] This procedure, although simple, depends not only on the calibration, accuracy, and sensitivity of the infrared thermometer, but also on the repeatability of measurements, which is the main inconvenience of this procedure.

It has been found that heat loss by radiation in the human body occurs entirely within the infrared region of the electromagnetic spectrum and that within the range from 5 μm to 20 μm, the skin closely obeys the laws of blackbody emission.[19] As a consequence, one would expect to find practically no reflection within that range[28] and, conversely, complete absorption of radiant energy by the outermost layers of the skin.[29] Despite this, there has been interest in the reflection capacity of the skin in the infrared. Hardy and Muschenheim[22] reported results about the reflective power of the skin beyond 6 μm. The problem that after a few seconds of irradiation, the temperature change in the skin amounted to up to 30% of the "reflected" energy was considered by Hardy.[19] Clark et al.[30] investigated the reflectance of human skin using a tungsten lamp. Their results showed that in the NIR, skin reflectance drops from about 20% to less than 5%, and that beyond 2.5 μm, it is close to zero. Hardy et al.[31] studied the transmittance and reflectance of excised human skin in the NIR. They found that between 1 and 2.4 μm, white and black skin has essentially the same optical characteristics: the skin appeared almost nonabsorbing in that range. Hejazi et al.[32] used a graybody model to derive a set of equations that correlate the effects of emissivity variation and reflection of ambient radiation on the apparent and true temperatures of an object. For this, they constructed a four-wavelength digital thermal imager and validated their model using a phantom that simulated a graybody and human skin. Simpson et al.[33] measured the reflectance and transmittance of Caucasian and Negroid dermis, subdermal fat, and muscle, but only for wavelengths between 620 and 1000 nm, using a single integrating sphere comparison method and a Monte Carlo model.

It is known that the skin emissivity varies as a function of wavelength, especially from the UV to the NIR.[3,22] It is clear that for achieving precise measurements, the variation of emissivity in terms of the implied wavelength has to be taken into account, so a more precise method that explicitly takes into account wavelength is required. Given that the maximum infrared emission of the human skin occurs around 10 μm,[29] in this work, the emissivity of the human skin was investigated for a wavelength of 10.6 μm.

2 Theory

Previous research has shown that although the skin reflects and transmits considerably in the visible and NIR, it is almost a perfect absorber in the region between 3 μm and 14 μm, which Plank's equation gives as the range of the spectrum in which a blackbody at the temperature of a human body radiates practically as the human skin.[22]

A number of attempts have been made to formulate directly the radiation laws of imperfect radiators, but none of them has had complete success.[20] It has been more profitable to consider the degree of imperfection of the radiator, taking as a numerical measure the ratio of the energy radiated by an imperfect and a perfect body under the same conditions. This ratio, having a value between 0 and 1, defines the emissivity of the material. Kirchhoff's law, which states that the sum of the emissivity and reflectivity of an opaque body must be unity, is a connecting link of the theory of important optical constants—that is, for opaque objects, Reflectivity=1 −Emissivity (Ref. 23). Quinn and Compton[34] considered Kirchhoffs law as central to any discussion of emissivity and reflectivity, but they also included the Helmholtz reciprocity relation. So considering that for infrared wavelengths beyond 5 μm, the transmissivity of the skin is practically zero,[22,29,32] and that with ambient temperatures close to that of the object, reflected radiation becomes significant, the Kirchhoff and Helmholtz relations can be written down, respectively, as follows:[34]

$$\varepsilon_a^0 = 1 - \rho_a^{n0}, \tag{1}$$

$$\rho_a^{0n}(\Omega_a^0,\Omega_a^n) = \rho_a^{n0}(\Omega_a^n,\Omega_a^0), \tag{2}$$

where ε is the emissivity, ρ is the reflectivity, and the subscripts refer to elemental surface areas and superscripts refer to directions. So Ω_a^0 is the solid angle subtended by the direction *0* at element a—that is, the left side of Eq. (2) is the fraction of radiation incident on the element of wall a, from a direction 0 in a solid angle Ω_a^0, which is reflected on a solid angle Ω_a^n in the direction of n. The right side of the same equation is the fraction reflected into a hemisphere. For diffuse reflectors, like human skin, reflectivity is independent of the angle of incidence, and the reflected radiation is uniformly distributed. The fraction of the incident radiation reflected from a diffuse reflector per unit solid angle at angle θ to the normal is $(\rho/\pi)\cos\theta$, where ρ is the diffuse reflectivity.

Then, assuming that the radiation field in the monitored skin area (i.e., the object) is isotropic and characterized by the ambient temperature, we can model the energy flux sensed by an infrared detector as:[32]

$$\Phi_1 = \varepsilon\Phi_O + \Phi_A + \rho\Phi_a, \tag{3}$$

where Φ_1 is the total incident radiation energy flux at the detector, Φ_O is the ideal blackbody radiation energy flux at the object temperature (i.e., $\varepsilon\Phi_O$ is the energy flux coming from the object itself), Φ_A is the ambient radiation field that directly falls on the sensor, and Φ_a represents the ambient radiation field reflected by the object. Again, ε and ρ represent the emissivity and the reflectivity of the surface of the object under consideration. However, when a controlled source of radiation is used, Eq. (3) should be modified as

$$\Phi_2 = \varepsilon\Phi_O + \Phi_A + \rho\Phi_a + \rho\Phi_L, \tag{4}$$

where Φ_L represents the energy flux due to the specific controlled source of radiation, which in our case was a laser beam.

Subtracting Eq. (3) from Eq. (4) yields

$$\rho = \frac{\Phi_2 - \Phi_1}{\Phi_L}. \tag{5}$$

With this equation and Eq. (1), it is possible to calculate the emissivity, assuming that the energy fluxes involved can be measured.

On the other hand, to calculate the energies in digital images, in terms of gray levels, the discrete form of the following equation can be used:[35]

$$E = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} i^2(x,y)\mathrm{d}x\ \mathrm{d}y, \tag{6}$$

where i represents the intensity (or gray level) of the image at a given pixel.

3 Materials and Methods

This study was developed with the participation of 40 volunteers who were informed about the type and level of radiation to be used. Prior to the definitive experiments, several tests were done to ensure that the applied levels of infrared radiation were innocuous for the human organism. There was no doubt about this given that the energy levels that were applied to the subjects (about 1 $\mathrm{mW/cm^2}$ during about 5 seconds) were less than the energy level that is radiated by the human body under normal conditions (about 5 $\mathrm{mW/cm^2}$), the difference being that, in our experiments, the applied energy was concentrated in a single wavelength. Participants were advised not to use any kind of cream on the skin of their hands.

Infrared images were acquired with a SATIR infrared camera, model S280 (Guangzhou SAT Infrared Technology Co., Ltd., China), which is sensitive between 7 μm and 13 μm, with a spatial resolution of 1.3 mrad and with a thermal sensitivity of 80 mK at 30 °C. This camera was calibrated as follows: emissivity 1.0, temperature level 34 °C, and spam ±8 °C. Ambient temperature was set to 22 °C, and work temperature ranged from −40 to 160 °C.

To check the range of skin temperatures of the participants, a Fluke 52II thermometer (Fluke Corporation, Everett, Washington) with a type-K thermopar and a resolution of 0.1 °C was used.

A 10.6-μm Synard CO_2 laser (Synard, Inc., Mukilteo, Washington) was used to project a controlled amount of energy on the skin of the back of the hands of the participants. Although the laser was adjusted to yield almost its minimum output power, it was necessary to attenuate the beam using three beamsplitters in order to assure stability in the output power.

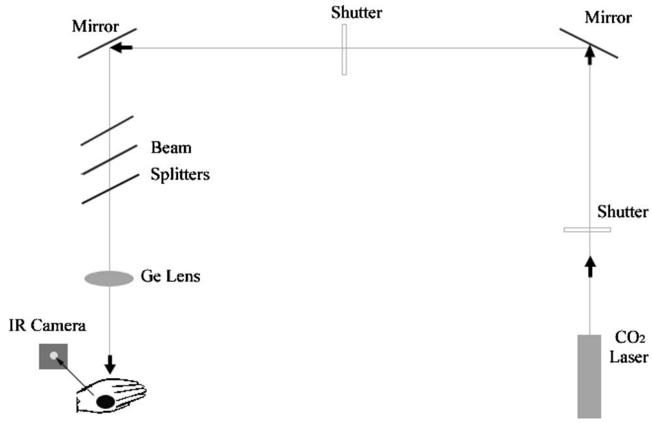

Fig. 1 Experimental setting.

The arrangement used for the experiments is shown in Fig. 1. A germanium lens was used to focus the beam on the desired area, and for security reasons, two shutters were included.

In order to be able to measure the energies of the reflected beams, from the surface of the hands to the IR camera, in terms of gray levels using Eq. (6), a reference image of a beam projected directly on the IR camera was acquired. For that, given the high sensitivity of the IR camera, it was necessary to attenuate the beam by a factor of 85. For this, in addition to the components shown in Fig. 1, it was necessary to include an infrared filter that transmits 27% of the IR at 10.6 μm and two attenuators to reduce the power of the beam that hit the detector of the IR camera. Figure 2 shows the image of the attenuated beam. As can be seen, the Gaussian distribution of the energy of the beam was considerably deformed. However, it was not an obstacle to estimate the power of this beam in terms of gray levels of the image. The power of the beam for the reference image, measured without attenuation, was very close to 7.5 mW. So considering that the area of the circular window of the power meter was 300 $\mathrm{mm^2}$, that the area of the reference image that contained 90% of the power was 30.7 $\mathrm{cm^2}$, and that the wavefront of the beam was Gaussian, the power reaching the hands in the experiments

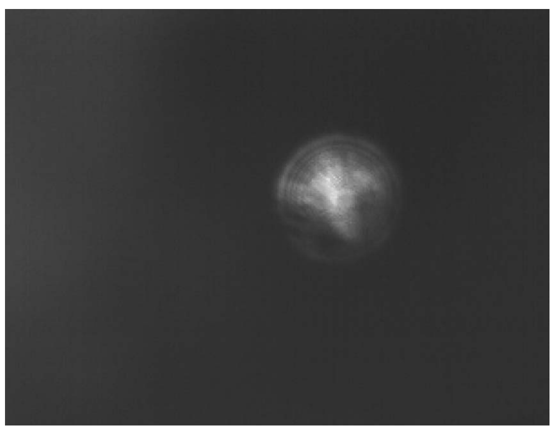

Fig. 2 Image of an attenuated beam that was used as reference image.

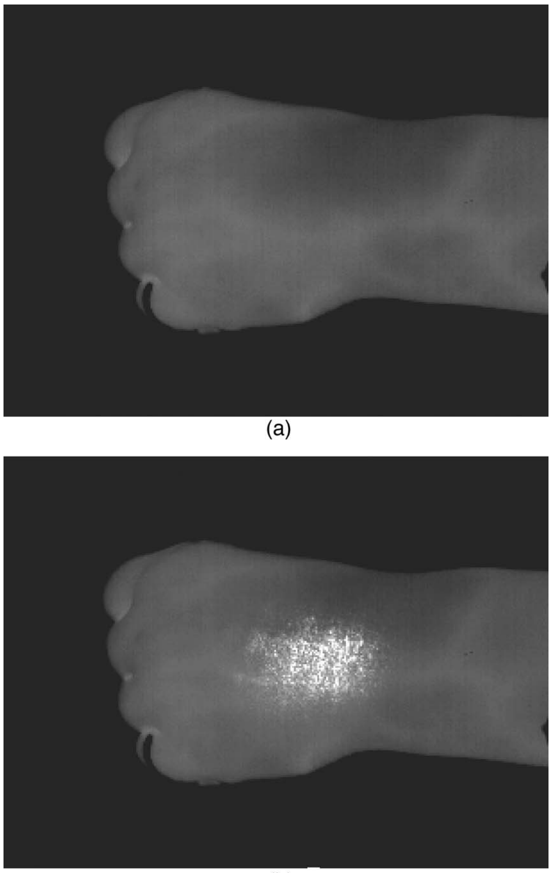

Fig. 3 Images acquired before (a) and after (b) projecting the laser beam on the hand.

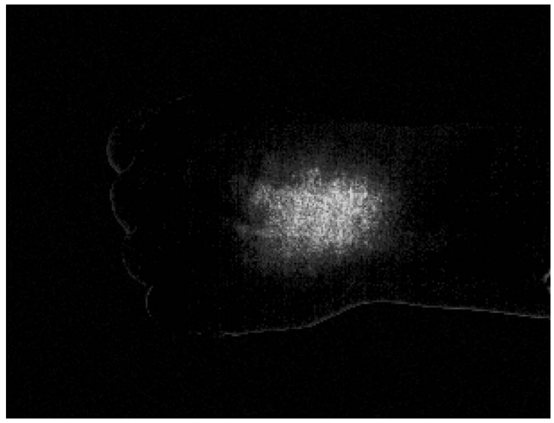

Fig. 4 Image obtained by subtracting the images shown in Fig. 3.

was approximately 56 mW, over an area of about 30 cm^2. In our images, one centimeter corresponded to 16 pixels.

The first step of the experiment consisted on measuring the skin temperature of each participant. Then each participant was asked to grasp an iron bar that was fixed in such a way that the surface of the back of his/her hand was as perpendicular as possible to the trajectory of the reflected beam to the IR camera. The camera was positioned 50 cm from the hands, and a first IR image of the hand was acquired. Next, within a few seconds, with the hand in the same position, the shutters were opened to project the laser beam on the surface of the back of the hand of each participant, and a second IR image was acquired, as shown in Fig. 3. The total time required by the camera to acquire each image was approximately 3 seconds. The power of the beam at the skin surface was adjusted so that a power meter (Field Master, Coherent, Inc., Santa Clara, California) recorded 30 mW, which in the end, as mentioned earlier, amounted to 56 mW on the affected area. The first image was then subtracted from the second, pixel by pixel, to obtain the “difference image,” which consisted of the image of the radiation that was reflected by the skin. Next, the energy of each difference image was calculated using Eq. (6). Such energy corresponds to the numerator of Eq. (5), while its denominator was obtained, again with Eq. (6), from the reference image. The camera produced 23 $\times 240$, 8-bit images.

4 Results

Figure 4 shows the difference image of the images shown in Fig. 3. As can be seen, this image contains, practically, only the infrared radiation that was reflected by the surface of the hand. The image registration was almost perfect, given that the second image was acquired only some seconds after the first one, under the same conditions and geometrical arrangement. As expected, the gray levels of the periphery of the image were zero, and practically all the gray levels beyond a square of 100 pixels per side were equal to zero. This means that the scattering of the reflected radiation was minimal. Images like the one shown in Fig. 4 were obtained for each participant, and their energies were calculated using Eq. (6). Then, applying Eq. (5), as already explained, the reflectivity for the skin of each participant was obtained. Last, the corresponding emissivities were calculated using Eq. (1). The resulting emissivities are listed in Table 1. As can be seen, those values range from 0.990 to 0.999, with a mean value of 0.996. These values are in agreement with the results obtained by Hardy and Muschenheim,[22] who found that at 10.6 μm and 30.8 °C, the human skin emits, practically, like a blackbody. In their experiments, where the emissivity was measured by reflection, they found $\varepsilon = 98.9 \pm 1\%$. Our results also agree with previous work in that the visible color of the skin is not important regarding the radiating power of the skin.[3] By measuring the rate of transfer of radiant heat between the skin and the radiometer, Mitchell et al.[2] found that the emissivity of a sample of excised skin was 0.996 ± 0.005. Steketee[23] found that the emissivity of the skin was independent of the wavelength between 3 and 14 μm and equal to 0.98 ± 0.01. Boylan et al.,[5] using Togawa’s method,[25] found emissivities of wound tissues that ranged from 0.976 to 0.992. As can be seen, previous results are very similar to the values obtained in this work. However, our method is more precise, since a single wavelength is involved. To assess the precision of our measurements, 10 measurements on the same subject were done. Given that the corresponding standard error was 0.00035, the use of three significant figures is justified.

5 Discussion

It is known that in the NIR, the human skin transmits considerably through both the corneum and Malpighian layers, but

Table 1 Values of the skin emissivity for the 40 participants.

Subject	Emissivity	Subject	Emissivity	Subject	Emissivity	Subject	Emissivity
1	0.996	11	0.998	21	0.994	31	0.998
2	0.994	12	0.996	22	0.998	32	0.999
3	0.998	13	0.991	23	0.997	33	0.997
4	0.999	14	0.998	24	0.997	34	0.999
5	0.998	15	0.992	25	0.995	35	0.995
6	0.998	16	0.992	26	0.999	36	0.992
7	0.996	17	0.997	27	0.990	37	0.998
8	0.996	18	0.995	28	0.993	38	0.998
9	0.992	19	0.998	29	0.999	39	0.994
10	0.998	20	0.997	30	0.997	40	0.995

that beyond 3 μm, transmission falls off markedly.[14,17,26] In fact, 95% of the infrared beyond 5 μm is absorbed by a layer of skin 0.2 mm thick.[18] That is, according to most related studies, for the far-infrared, the human skin behaves practically like a blackbody, so an image like the one shown in Fig. 4 could be considered as unexpected given that, according to the work published by Hardy and Muschenheim,[22] beyond 7 μm, one would expect practically no reflection on the skin. The discrepancy seems to be due to the relative low sensitivity of the radiometer used by Hardy, as compared with the sensitivity of the IR camera that was used in this work. Apart from the sensitivity of the sensors, in previous works, the sources of radiation included a relatively wide ranges of wavelengths: Hardy and Muschenheim,[22] for instance, used a hot stove as source of radiation that emitted from 1.3 to 50 μm, and Boylan et al.[5] used a radiometer that was sensitive over the range 8 to 14 μm, so those authors measured the radiation over a considerable range of wavelengths. With our method, a single wavelength is used so that the obtained information is more precise.

With the method proposed in this work, noncontact measurements are achieved, and the determination of the skin temperature is not needed, which has been an inconvenience in other methods. In addition, as the skin surface obeys Lambert's law (as confirmed by our difference images) of diffuse reflection, it is necessary to make the comparison at only a single angle of reflection.[22]

6 Conclusions

Although according to Togawa's results,[25] the skin emissivity from 8 to 14 μm is practically constant, more research using monochromatic sources is needed to precisely determine whether there is variation of the skin emissivity as a function of wavelength.[36] Given the sensitivity of modern cameras, like the one used in this work, nowadays it is possible to detect energy variations in the range of microwatts and, with lasers as a complement, it is possible to make determinations of emissivity at specific wavelengths. Our results confirm that human skin behaves almost like a blackbody at a wavelength of 10.6 μm.

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