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Infrared imaging used to observe the thermal response of the human skin to local cooling

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Abstract

Thermal imaging can provide novel data in laboratory exercises in physics and especially in quantitative physiology, for both quantitative analysis and modelling. In this paper we describe an exercise where the skin of the forearm is briefly cooled locally, the skin's temperature recovery is observed with a thermal camera and the observations are analysed with the aid of simple thermal models. Although the thermal models applied are simple, they introduce several concepts from heat transfer and inspire quantitative modelling of the experimental data. The former model is very simple and is based on Newton's law of cooling and it invites a second slightly more involved model including some analysis of heat transfer. The observed rate of temperature recovery is shown to be related to thermal properties of the skin and perfusion, and the experiment is a non-invasive measure of one aspect of the human thermoregulation. Thermal cameras are handy, they are becoming ever more accessible and can reveal novel insights when observing various physiological thermal process. This experiment may be of particular interest to students in health and biosciences that are taking undergraduate general physics courses and training data analysis.

Keywords: thermal modelling, infrared imaging, introductory laboratory, skin thermal response

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1. Introduction

In introductory physics courses, thermal imaging is becoming a common practice to demonstrate some basic principles of physics (e.g. Mollmann and Vollmer 2007, Haglund *et al* 2015, Oss 2022a) and often even a simple smartphone thermal camera may be sufficient (e.g. Kubsch *et al* 2017, Oss 2021). Thermal imaging along with proper theoretical thermal models can be used to measure thermal properties of material and heat transfer coefficients, as outlined by Hanisch and Ziese (2021). It is of educational value to observe with a thermal camera the evolution of some particular temperature distribution, collect some relevant data and then delve into finding potential thermal models that may fit the observations. Hence, thermal imaging can provide quantitative information to ascertain and develop simple physical models of inherently complex transient thermal processes, including physiological processes of the human body. In particular, Oss (2021) used thermal models and simple thermal camera to demonstrate effectively when one may apply lumped thermal models, by comparing thermal diffusion in copper and plexiglas cylinders. Thermal imaging is being used in thermal and exercise physiology (Tattersall 2016, Hillen *et al* 2020) and has for some time been applied in human medicine (Ring and Ammer 2012), in veterinary medicine (Turner 2001) as well as in studies of wild animals (Cilulko *et al* 2013, McCafferty 2007). Moreover, to assess human perspiration Subhash *et al* (2024) used high resolution infrared thermal imaging to observe the activation of sweat pores before and after physical activity.

The skin is the boundary between the warm human body and, most often, the colder environment, and is fundamental in controlling the body's thermal balance as part of its homeostasis. This thermal balance is to a large degree kept by regulating the blood's flow to the skin. Therefore skin's temperature reflects the peripheral perfusion, which can effectively be observed by thermal imaging. During physical activity the body must balance two competing mechanisms, vasoconstriction in the skin influenced by the demand of increased blood flow to active muscles and vasodilation in the skin to increase warm blood flow to the skin due to thermoregulation. How well the body adapts to these competing effects is of interest for example in physical training and sport, and thermal imaging of the whole body or part of it can be used to observe the transition between these opposing processes (Merla *et al* 2010, Tanda 2015).

Although thermal infrared radiation is not so far from the visible electromagnetic spectrum it has some interesting properties distinct from visible light. For example, thermal radiation cannot easily pass through regular glass, like in windows, although it can be used to 'see' through common visually opaque black plastic bags. When observing the skin's temperature by thermal imaging it is important to realize that thermal images of the human skin show only the temperature of the outermost skin because thermal infrared radiation attenuates very fast in water, hence also in live tissue. Tattersall (2016) provides introduction to infrared thermography in the context of thermal physiology and the fundamentals of thermal imaging is covered in Haglund *et al* (2022) along with several examples and case studies of the use of thermal imaging in science education.

Thermal cameras measure the heat radiating from the surface being measured, and therefore they measure the temperature indirectly. To get a more accurate measure of the temperature from a thermal camera two parameters are most often involved, the emissivity of the material of the radiating surface measured and the temperature of the surrounding environment (e.g. Tattersall 2016). These two values are selected and then set in the thermal camera, but depending on the software used in analyzing the thermal images these values can also be adjusted afterwards. The emissivity of the surface measured gives the thermal emission relative to blackbody radiation (Mollmann and Vollmer 2007, Tattersall 2016). The

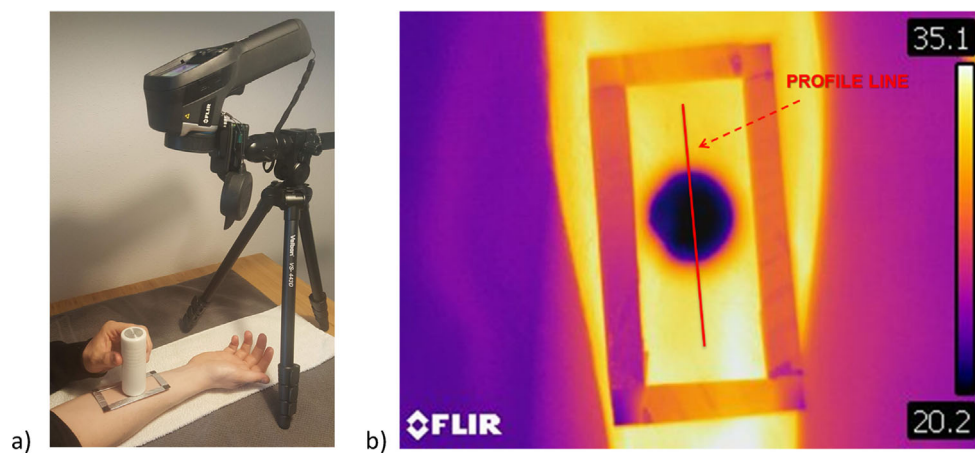


Figure 1. (a). Experimental setup, showing the ventral (inward) side of the arm being measured, the cooling stick (white cylinder) and the thermal camera (FLIR E60bx) attached to a tripod. Figure 1(b). Thermal image of the forearm showing clearly the localized cooling. The rectangular frame is for reference only. Numbers on the scalebar show the temperature scale in °C. In this case the temperature is 20 °C at the center of the spot and 35 °C for an unaffected skin far from the cooled spot. The temperature measurements along the profile line are the ones shown in figure 2.

emissivity is a value between 0 and 1, and for the human skin in the infrared it may range between 0.95 and 0.99 (Herman 2007). The effect of the reflected radiation from the environment is relatively low when measuring surfaces with high emissivity like the human skin, and for measurements indoors air temperature is often taken as the temperature of the surrounding environment (Tattersall 2016).

The aim of the present study was to develop a laboratory exercise where thermal imaging is used to provide quantitative information that may be used to develop simple thermal models of intrinsically complex system, the human skin in this case. Although the thermal models introduced here are simple, they introduce several concepts from heat transfer and quantitative modeling. The experiment is a non-invasive measure of the human thermo-regulation and vascular reactivity and may be of particular interest to students in health and biosciences that are taking general physics courses. The experiment is simple to perform and requires only minimal setup, basically a thermal camera and a laptop to analyze the images and make graphs, and the data analysis can be either simple or involved as needed.

2. Methods

In this experiment the skin is thermally stimulated by localized cooling of the forearm done by placing softly on the skin a cylinder of aluminum 30 mm in diameter and held in place for about half minute. Initially the cylinder is cooled to about 10 °C–15 °C in cold water and wiped dry. Figure 1(a) shows the setup. The thermal camera is used to take images of the cooled areas every 15–30 s for about 5 min. Figure 1(b) shows a typical thermal image obtained of the cooled arm. To analyze the skin's response and how the heating evolves with time we make several profiles across the cooled spot in the thermal images and the resulting profiles are shown in figure 2. The temperature profiles can be extracted from the thermal images, but for modeling purposes as presented here, it may be enough to observe the temperature at the center of the spot and record its evolution with time. Like for so many

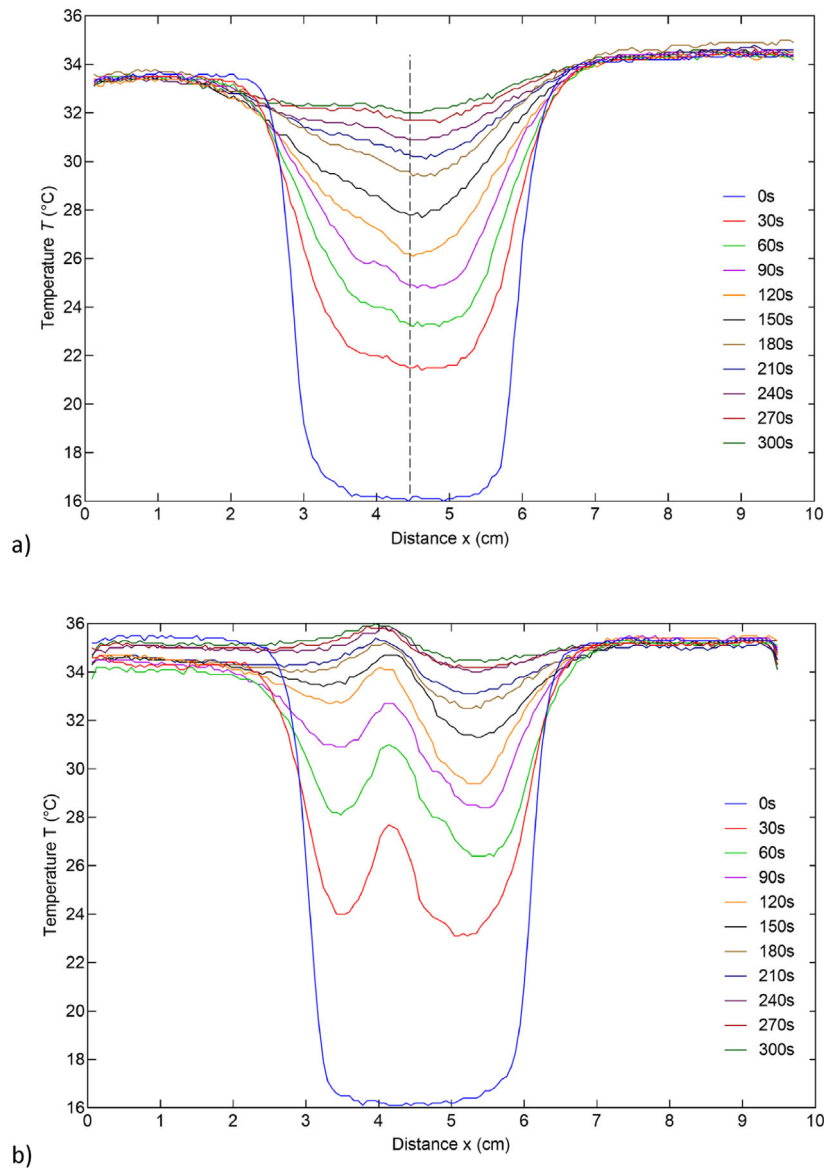


Figure 2. The graphs show the evolution of temperature profiles across the cooled spot of the forearm (shown in figure 1). Thermal images are taken right after the initial cooling (30 mm wide cooling stick) and then every 30 s. The labels for the curves show the respective times from the initial cooling. Temperature from the center of the cooled spot, indicated by the vertical dotted line, are shown in figure 3. Figure 2(a) shows profiles from the dorsal (outward) side of the forearm. Figure 2(b) shows profiles from the ventral (inward) side, showing clearly the proximity of the deeper veins of the forearm.

physiological experiments there are many variables that can affect the measurements. To minimize these, one should aim for a room with normal temperature and still air, and that the person being tested is comfortable, neither cold nor hot, relaxed such that the heart rate is normal, and the skin should be dry. For the thermal imaging in this study all the

measurements were done in a calm environment, the temperature in the room was between 20 °C and 22 °C with negligible airflow and the skin was dry.

The thermal camera we used (FLIR E60bx) has a resolution of 320×240 pixels, the stated accuracy is ± 2 °C or $\pm 2\%$ of reading and the thermal sensitivity is < 0.045 °C according to manufacturer specifications. For extracting the numerical values of the temperature from the thermal images, we used the software FLIR Tools provided by the manufacturer of the camera (Teledyne FLIR, USA) and for the regression we used Excel (Microsoft Corporation, USA). For the emissivity of the skin, we used 0.98 (Herman 2007) and for the temperature of the surrounding environment we used 20 °C.

Although this experiment is non-invasive and involves only mild cooling of the skin and contactless monitoring of the skin for only a few minutes, an informed consent should always be considered in classroom setting especially if additional data is collected for further analysis. In the experiment presented here all 40 individuals measured gave informed written consent.

3. Results

3.1. Measured temperature profiles

Temperature profiles from the thermal images are shown in figure 2(a) from the dorsal (outward) side of the arm, but for profiles made on the ventral (inward) side of the arm, contributions from deeper lying veins are superimposed on the previous pattern, as can be seen clearly in figure 2(b). Veins are closer to the skin on the ventral side of the forearm (e.g. Pennes 1948), and they can explain the significantly faster recovery compared to the dorsal side.

Figure 2(a) shows that the rate of temperature increase at the center of the cold spot decreases with decreasing temperature difference between the spot and the surrounding unaffected areas, suggesting that an exponential curve may fit the measurements. Figure 3(a) shows one example of the observed temperature recovery with time and a fitted curve. To better analyze the rate of temperature recovery, figure 3(b) shows the natural logarithm of the reduction in the temperature difference, from 17.1 °C to eventually zero, further supporting the idea that a simple exponential curve fits the data and the regularity of the recovery.

3.2. Data analysis and simple model for the rate of recovery

The measurements above reveal a regular course of the skin's recovery and beg for a quantitative model that may provide further information on the processes involved. One simple thermal model of the temperature recovery is to assume that the rate of temperature increase at the center of the cooled spot is proportional to the temperature difference between the cold spot $T(t)$ and the unaffected surrounding skin, T_0 :

$$\frac{dT}{dt} = \lambda(T_0 - T), \quad (1)$$

where λ is a proportionality constant. This simple model, that the rate of temperature change is proportional to the temperature difference of some small volume and its surrounding, is often referred to as Newton's law of cooling. Despite its name, the law applies as well to heating like in this case. Here we refer to Newton's law as an empirical description of the complex process of heat transfer through a perfused volume of tissue and heat exchange with

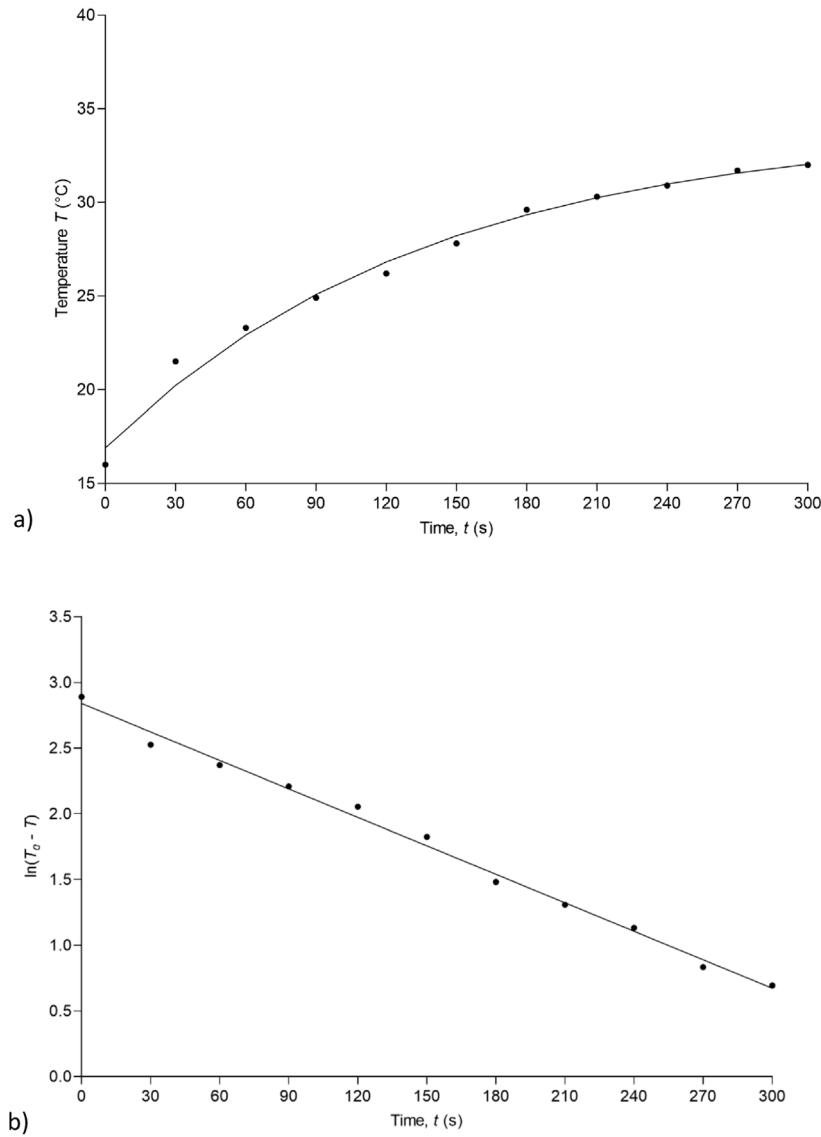


Figure 3. (a) Measured temperature in the middle of the cooled spot using the data from figure 2(a). The curve is a best fitting exponential ($T = 34.0\text{ }^{\circ}\text{C} - 17.1\text{ }^{\circ}\text{C} \cdot \exp(-t/138\text{ s})$). (b) The natural logarithm of the temperature reduction shown in (a), i.e. from the maximum difference of $17.1\text{ }^{\circ}\text{C}$. Best linear fit as shown is $\ln(T_0 - T) = 2.84 - 0.0072\text{ s}^{-1} \cdot t$. The calculated standard error of the slope is 0.00019 s^{-1} and the 95% confidence interval of the slope is from -0.0068 to -0.0077 s^{-1} .

the environment. Strictly, Newton's law applies to simpler situations and a recent discussion on the application of Newton's law may be found in Oss (2021).

Solution of (1) is:

$$T(t) = T_0 - (T_0 - T_C) \cdot e^{-t/\tau} \quad (2)$$

Here T_C is the initial temperature at the center of the cooled spot and τ is the characteristic time of recovery ($\tau = 1/\lambda$) and provides a quantitative measure of how fast the skin recovers.

The stable temperature T_0 can be measured before the cooling or as the final equilibrium temperature. This equation shows that the initial temperature deviation ($T_0 - T_C$) decays exponentially with time. As shown in figure 3(a) equation (2) fits the measurements very well suggesting that this simple model fits the measurements well and is a quantitative description of the temperature recovery. We measured the characteristic time for 16 males and 24 females, and except for one individual the measured average for the 39 individuals was 130 s and the distribution had a standard deviation of 23 s. The one exception had a characteristic time of 263 s, which was distinctly high. Applying the same analysis as described above on the measurements made on the ventral side of the arm (figure 2(b)) shows again good fit to the data and faster recovery, as expected due to greater proximity to veins and arteries (e.g. Pennes 1948). The physical meaning of the characteristic time will emerge in the revised thermal model, which is discussed in the next section.

3.3. Lumped thermal model of the skin

Although the simple thermal model above fits the data well, it is empirical and therefore it may be revealing to develop the model further in an effort to give physical meaning to the characteristic time τ . Detailed thermal model of the skin is complex, as it must incorporate the skin's anatomy and dynamic processes, like temperature sensing and homeostasis regulation of the body's temperature and how it regulates the blood's perfusion to the skin. To involve all these factors would not serve the purpose of this study. Therefore, in the following we will consider a slightly more involved model than the one before in an effort to provide insight into the dominating thermal processes that control the rate of heat recovery of the skin after local cooling. This is a lumped thermal model of the outermost part of the skin intended to describe the skin's main thermal characteristics as observed with the thermal camera. Lumped model means that details of complex processes are simulated and specified with only a few parameters and the temperature within the 'lump' under consideration (here the thin skin) is approximately uniform (a discussion of lumped systems can for example be found in Oss 2021).

The components of the thermal model are shown in figure 4, composed of a small volume with area A and thickness D . Conservation of the local thermal energy requires that the change in thermal energy within the volume is equal to the flow of heat into the volume plus the internal heat produced within it minus the heat flow escaping from it.

We assume the temperature $T(t)$ to be uniform through the thin volume, but its value will change with time due to different rate of heat transferred out of the volume through the top (outside of the skin) and into the volume from below (inside of the skin). Heat transferred to the skin is assumed to be by the warm blood microvascular perfusion through the lower surface of the volume. It is this perfusion that dominates the transferred heat to the skin during the recovery, hence its temperature. Therefore, although thermal conduction is also contributing to the heat transfer from deeper tissue, it is small compared to the efficiency of the perfusion of blood to and within the skin. This heat transfer to the volume is proportional to the temperature difference between the circulating blood and the volume (e.g. Pennes 1948). Hence, the rate of heat transfer q_b (W) by perfusing blood is:

$$q_b = Ah_b(T_b - T), \quad (3)$$

Here T_b is the blood's temperature, T is the temperature of the volume and h_b is the effective blood to tissue heat transfer coefficient ($\text{W m}^{-2} \text{ } ^\circ\text{C}^{-1}$) (see figure 4). Heat transfer from the skin to the ambient surrounding air at temperature T_a is predominantly due to thermal radiation and convection, and for small temperature difference the rate of heat transfer is

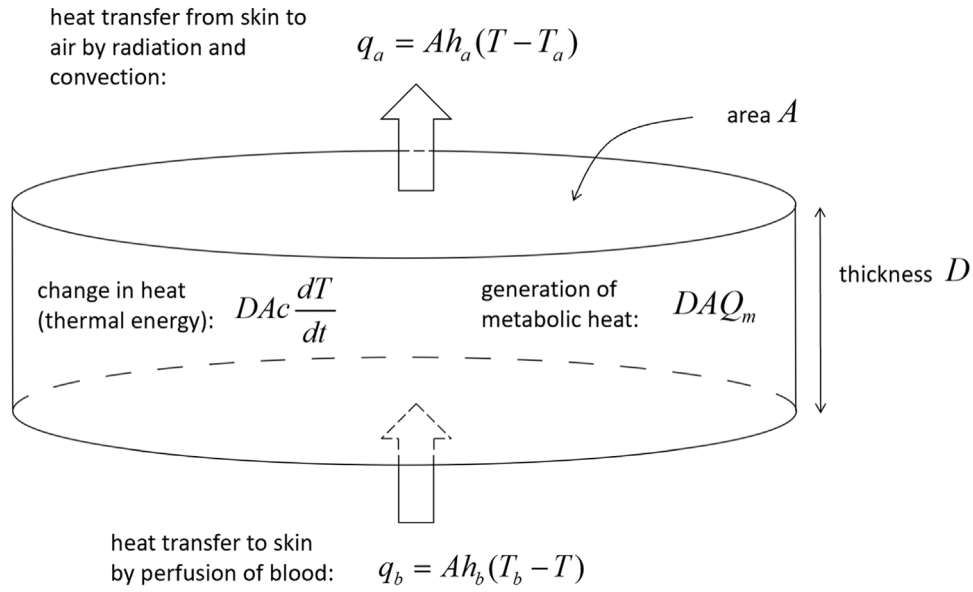


Figure 4. Schematic of the lumped thermal model of the skin consisting of a thin volume, sandwiched between the warm body below and the colder environment above. At the upper surface of the volume heat is lost to the environment and the lower surface delineates where heat enters the volume. Within the volume the temperature is considered uniform, but its value may change with time due to imbalance of heat transfers and generation of metabolic heat.

proportional to the temperature difference for both processes (e.g. Herman 2007):

$$q_a = Ah_a(T - T_a), \quad (4)$$

Here the proportionality coefficient h_a incorporates the two heat transfer processes, such that $h_a = h_r + h_c$, where h_r and h_c stand for the heat transfer coefficients for radiation and convection, respectively. Within the volume there may be some generation of metabolic heat, Q_m (W m^{-3}). The net rate of change in thermal energy within the volume is:

$$q_{\text{int}} = DAC \frac{dT}{dt}, \quad (5)$$

where c is the specific heat capacity ($\text{J m}^{-3} \text{ } ^\circ\text{C}^{-1}$). Adding these three contributions, the conservation of the local thermal energy now becomes:

$$DAC \frac{dT}{dt} = DAQ_m + Ah_b(T_b - T) - Ah_a(T - T_a). \quad (6)$$

Equation (6) has the solution:

$$T(t) = T_0 - (T_0 - T_C) \cdot e^{-t/\tau}, \quad (7)$$

where the characteristic time:

$$\tau = \frac{cD}{h_b + h_a}. \quad (8)$$

The lumped thermal model solution (7) is identical to the solution (2) for the previous simple model and therefore fits the measurements as well as before using the simple model. The previous model was an empirical fit to the measurements, but the lumped

model provides a physical basis for the temperature evolution by the analysis of the thermal processes involved. What is of interest here is that this model provides a physical interpretation of the characteristic time τ of temperature recovery, i.e. it increases with the heat capacity and thickness of the skin (thermal mass cD) and it shortens with increasing rate of heat transfer $h_b + h_a$. Therefore, one can use the measured value of τ to do further quantitative analysis of the skin's recovery and hence of the dynamics of the body's thermal control.

Most of the parameters defining the characteristic time depend on the particular skin and individual being studied. Even so one can use equation (8) to make a rough estimate of the blood to skin heat transfer coefficient h_b . Our measurements give the average value of $\tau = 130$ s, and using that the effective thickness D of the skin for this model is approximately 1–2 mm (epidermis and upper part of the subdermal layer) and that the heat capacity of tissue is $c \approx 4 \times 10^6 \text{ J m}^{-3} \text{ }^\circ\text{C}^{-1}$, then the value of $h_a + h_b$ is $30\text{--}60 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1}$. Herman (2007) gives typical value for $h_a \approx 8 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1}$, and therefore our best estimate of h_b is between 20 and $50 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1}$ during recovery from the cooling. If the skin is at a temperature above some threshold, evaporation of sweat significantly adds to the heat transfer, but in our case the temperature is lower such that the effect of evaporation can be omitted.

According to the thermal model expressed by (6) the stable final (equilibrium) temperature of the skin is:

$$T_0 = \frac{DQ_m}{h_a + h_b} + \frac{h_a T_a + h_b T_b}{h_a + h_b}. \quad (9)$$

Inserting realistic numbers as are used in the text above, it shows that the contribution for Q_m is negligible and that T_0 is approximately 32°C – 33°C , which is in agreement with the measurements and with published values (e.g. Herman 2007 which gives 34°C , and Pennes 1948), but the skin's temperature may vary depending on the individual, location on the body and the environment (Pennes 1948). The heat produced by metabolism within the skin is much lower than the heat transferred to and from the skin. An upper estimate of Q_m is to use the average power density of an individual, i.e. maximum $Q_m \approx 1000 \text{ W m}^{-3}$, and using realistic values in equation (6) shows that Q_m can easily be omitted in the equations above (i.e. $DQ_m \ll h_b T_b + h_a T_a$ in equation (6)).

More complex models of the heat transfer through the skin have been proposed and used in the literature, but often they require more involved mathematics (e.g. Xu *et al* 2009 and Oss 2022b). In particular, Steketee and Van der Hoek (1979) made a theoretical thermal model of the skin to explain its recovery after cooling, incorporating heat transfer within the skin by both conduction and blood perfusion. Their model predicted temperature recovery curves with two time constants, but after one minute or so the longer one dominated and then their model showed the same characteristics as the one discussed here. Ley *et al* (2011) monitored temperature variations in fingertips after occlusion of the brachial artery to induce ischaemia and subsequent hyperaemia to study microvascular reactivity, and in analyzing their data they used a thermal model similar to the one presented here. The analysis of Oss (2022b) on the perceived temperature when touching different materials produces a much shorter response times, which is appropriate for the initial touch, and his thermal model is based on the effusivity of the outermost skin. The model of Oss (2022b) does not involve the percolation of blood as is done here and which produces much longer characteristic times.

4. Discussion

The aim of the present work was to develop a laboratory experiment where thermal imaging is used to provide quantitative information on temperature recovery and to ascertain potential thermal models of the human skin. The experiment shows how a thermal camera can be used to measure the skin's temperature recovery after local cooling. The recovery can be modeled very well by a very simple thermal model deduced directly from empirically applying Newton's law of cooling and one can easily extract the characteristic time of recovery from the measurements. That in itself is valuable and provides some training in quantitative modelling. Furthermore, one can construct a slightly more involved thermal model of the outermost part of the skin. This lumped dynamic thermal model predicts the same behavior as the initial simple model, but its contribution is a physical interpretation of the rate of temperature recovery by relating the measured characteristic time to just a few parameters of the skin's thermal model. The experiment is an inquiry with some quantitative analysis and may well fit students that are studying physics and are oriented towards biology or the health sciences.

All the measurements were made by a student at the master level and no difficulties were encountered. Performing the measurements was straightforward and although the extraction of the characteristic constant from the measurements was simple, it became clear that the data collected could easily be used for further analysis.

5. Conclusion

In this study we have outlined a simple experiment using thermal imaging of the human skin to observe its thermal response to local cooling. The analysis starts with an empirical approach in describing the data which then leads to the development of a very simple thermal model of the skin that provides physical interpretation of the observed skin's rate of recovery. The experiment therefore involves quantitative analysis and development in analyzing data, both of which may be of particular interest for students. The analysis presented is simple but can with ease be expanded on. This may include a more detailed numerical analysis and explore the uncertainties involved in quantitative thermal imaging, use of additional variables, comparing different thermal models of the skin and their limitations and analyze the results with respect to the physiology of thermal regulation of the body and the anatomy of the skin.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Appendix

On the Biot number. The criteria for assuming that a component of a thermal system can be treated as lumped, as is done here for the thin homogeneous layer presented in figure 4, is that the ratio of the convection at the surface of the body is much less than the conduction within the body. This ratio is often quantified by the Biot-number and it should be much less than one if the system can be regarded as lumped ($Bi < 0.1$ is often used) (i.e. Oss 2021). Typical values for the skin tabulated by Herman (2007) are $k \approx 0.96 \text{ W m}^{-1} \text{ }^\circ\text{C}$ (normal hand) and $h \approx 8 \text{ W m}^{-2} \text{ }^\circ\text{C}^{-1}$ (air-skin interface), and for our model $D \approx 1 \text{ mm}$, hence $Bi = hD/k \approx 0.01$. Increasing h to include also the heat transfer at the blood-skin interface will increase the Biot-number, but it will still be within the limit of 0.1.

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