Chapter 2
Physics Principles of the Infrared Thermography and Human Thermoregulation

Jose Ignacio Priego Quesada, Rosario Salvador Palmer and Rosa María Cibrián Ortiz de Anda

Abstract Although it is easy to capture a thermal image with infrared thermography, it is necessary to have the basic knowledge about how it works and the physical laws relating to it, as well as the radiative characteristics of the different bodies, and how heat is transferred between space and bodies. This knowledge is essential to establishing a logical hypothesis, using the camera rigorously, and interpreting the thermal data correctly. The aim of this chapter is to present the basic physical principles of infrared thermography, heat transfer and human thermoregulation.

2.1 Introduction

In recent years, infrared thermography has become more popular in sport science due to several applications, such as injury prevention and screening [1], performance assessment [2, 3] and clothing assessment [4, 5].

Many researchers have recently begun studies using infrared thermography in sport science for different reasons. Firstly, it has many advantages: infrared thermography is non-invasive method that can be used at a distance and does not interfere in the human thermoregulation, unlike other skin measurement methods [1, 6, 7]. Secondly, it has great applicability as will be shown in the different chapters of this

J.I. Priego Quesada (✉) · R. Salvador Palmer · R.M. Cibrián Ortiz de Anda
Biophysics and Medical Physics Group, Department of Physiology,
University of Valencia, Valencia, Spain
e-mail: j.priego.gibd@gmail.com

R. Salvador Palmer
e-mail: rosario.salvador@uv.es

R.M. Cibrián Ortiz de Anda
e-mail: rosa.m.cibrian@uv.es

J.I. Priego Quesada
Research Group in Sport Biomechanics (GIBD), Department of Physical Education and Sports, University of Valencia, Valencia, Spain

© Springer International Publishing AG 2017

J.I. Priego Quesada (ed.), *Application of Infrared Thermography in Sports Science*, Biological and Medical Physics, Biomedical Engineering,
DOI 10.1007/978-3-319-47410-6_2

book. And finally, another important reason is the decrease in price of infrared cameras in recent years.

In the journal peer review process of different recent studies in sport science using infrared thermography performed by the authors of these chapters, we observed a high number of studies with important issues that make publication difficult. Most of these issues are related to methodological aspects or with the establishing logical reasoning to support the study hypotheses and to interpret the results. In this context, it is necessary that new users of infrared thermography in sport science have the necessary physics background to understand the technique, in order to avoid methodological issues. In addition, it is important to always remember that infrared thermography is commonly used to calculate surface temperatures, and, in this sense, knowledge about heat transference and thermophysiology is necessary to establish logical hypothesis and to correctly interpret the thermal results.

The present chapter will present the basic physical knowledge of infrared thermography, heat transference and thermoregulation. Because this book is not oriented towards physical scientists, all aspects will be discussed in a simple way in order to provide scientists in sports science the minimum knowledge necessary for its study. In order to study the physical aspects in more detail, it is therefore recommended to use other sources. Likewise, in this chapter, thermoregulatory aspects will be displayed briefly; in the following chapters, it will be explained in more detail and applied to the different topics.

2.2 Heat Transfer

First of all, it is important to define the concept of heat and temperature. **Heat** is energy in transit that passes from a warm body to a cold body and its unit is the joule (J). J/s or Watt are the common units used to measure heat flow per unit time. Hot body decreases its internal energy and cold body increases due to heat transfer.

On the other hand, the **temperature** is a measure of the internal energy of bodies. Temperature can be defined as the "measure" of the average kinetic energy of one body [8]. There are different scales for measuring temperature and the most well known are the degree Celsius, Kelvin and degree Fahrenheit. The degree Celsius is used by most countries in the world. The degree Fahrenheit is used in the Anglo-Saxon world and it can be changed to the Celsius scale using the following expression:

$$^{\circ}C = (^{\circ}F - 32) * \frac{5}{9} \tag{2.1}$$

Equation 2.1. Fahrenheit to Celsius formula

However, in the international system of units, the temperature is expressed using the Kelvin scale (K). This scale is called absolute, because it is not possible, by imperative of the laws of thermodynamics, to have bodies with lower values than the 0 K (−273.16 °C). The Kelvin scale is used in all aspects related to the physics of thermography.

The term heat, therefore, should be understood as heat transfer and only occurs when there is a temperature difference between two bodies. Therefore, the heat is always transferred following a gradient, from the hotter body to the cooler. This transference of energy is called **heat flow or heat flux** (Fig. 2.1). When two bodies are at the same temperature, they are in **thermal equilibrium** [9]. In addition, when one body has a constant temperature, it is considered that it is in a thermal equilibrium, and it could be a result of the environment being at the same temperature as the body, or because it has a constant supply of heat that keeps it at a constant temperature even though the environment is different (as in the case of the internal temperature of the human body, see Sect. 2.6).

Heat flow is an important concept in the human body. As will be shown in the next chapters, thermal gradient between the core and the skin, and between the skin and the environment are important in the rate of the heat transference. For example, the greater the difference between core temperature and skin temperature, the easier the transference from the core to the skin. Contrary, if both temperatures are similar, the heat dissipation from the core will be more costly [10]. Another example might be the temperature of the skin and the environment. In hot environments where the air temperature is similar or warmer than the skin, the body increases temperature due to the heat transfer by radiation.

Furthermore, the transference of heat is commonly explained by three mechanisms: conduction, convection and radiation. The three mechanisms are explained below, putting in context how they occur in the human body.

Conduction: heat transfer by the contact of two solid bodies at different temperatures. The amount of heat transferred by conduction is given by Fourier's law. This law states that the rate of heat conduction through a body per unit of cross-sectional area and is proportional to the temperature gradient existing in the body, being the proportionality constant material conductivity.

In the human body, the conduction transference is between the different structures of the body, and also between the human body and clothing. Regarding heat transference through the human body tissues, it is a slow process; in the limbs, it is mainly dependent on the temperature gradient between muscle and skin and the thermal conductivity of muscle [11]. For this reason, transference of heat by conduction is facilitated when the temperature gradient between the muscle and the skin is increased, occurring mainly by sweat evaporation during exercise or during

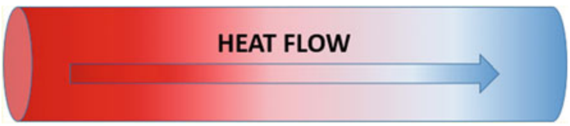

Fig. 2.1 Heat flow: the heat is transferred from the hotter side to the cooler

exercise in cold environments [10, 11]. Breathability and insulation properties of clothing will have an effect on this type of heat transfer. However, conduction heat loss is usually considered negligible unless the skin is in contact with highly conductive surfaces for a prolonged duration [12].

Convection: heat transfer by the contact of a solid body with a liquid or gaseous element. The convective heat exchange between the body and the fluid is given by the Newton's cooling law and depends on the temperature gradient and surface contact area of both, and the convective heat transfer coefficient (determined by the density, heat capacity, thermal conductivity and velocity of the fluid) [12].

In the human body, this convection could be explained by the heat dissipation via the blood flow; when blood flow through the core is heated, and that blood in turn heats the skin as it passes through. Convection also explains the effect of the wind on the skin. Wind convection also facilities sweat evaporation [12]. This heat transfer system is very important when the body is immersed in water. In this setting, it is considered that the 100% of heat loss occurs via convection due to the contact between the skin and the water. In the sports world, it is of interest to consider clothing insulation because it can promote or reduce convective heat loss.

Radiation: heat transferred by the body by emission of electromagnetic radiation. All of the objects with temperature above absolute zero (0 K or −273.16 °C) emit electromagnetic radiation according to the Stefan-Boltzmann law (see Sect. 2.4), which indicates that the energy radiated is proportional to the fourth power of its temperature. Furthermore, objects absorb electromagnetic energy emitted by the environment. Since the emission of energy implies a decrease in internal energy and thus the temperature of the object, if the object maintains a constant temperature (thermal equilibrium), it is because the energy emitted is compensated by the energy absorbed, but if a body is at a higher or lower temperature than the environment, the net radiative heat transfer is the difference between the absorbed and the emitted radiation.

Commonly, the human body emits more heat radiation than it absorbs, due to the environment being cooler. However, in close proximity to warm objects or hot environments (e.g.,a fire), this radiation is absorbed by the body, resulting in the body heating [9]. During outdoor exercise, the most common source of radiation is the sun [12].

Radiation is heat transfer that detects thermography, while conduction and convection are important for proper thermography protocols. Furthermore, conduction and convection could affect skin temperature, and therefore human radiation.

As will be shown in the following section, the emitted radiation of the human body temperature is in the range of infrared radiation in the electromagnetic spectrum and is called thermal radiation.

2.3 Electromagnetic Spectrum and Infrared Radiation

Electromagnetic radiation is a way of energy propagation through a vacuum or a material medium without mass transport. An electromagnetic wave can be defined as the propagation of the vibration of an electric field (E) and magnetic field (B), which together form an angle of 90° (Fig. 2.2). The propagation direction is perpendicular to both the plane of vibration of the electric field and the vibration of the magnetic field. It is therefore a transverse wave whose propagation velocity in the medium is $2.99792458 * 10^8$ m/s (this value is usually rounded to 3.10^8 m/s).

The quantities that characterize the electromagnetic waves are the amplitude of the electric field and the magnetic field and the frequency of the wave. The wavelength is the spatial period of the wave, which is the distance between two points with identical vibration state (from pulse to pulse), measured in meters, micrometers, nanometers, etc. (Fig. 2.2). Frequency is a quantity that measures the number of repetitions of the wave per unit time, and its unit is s^{-1} (Hz). Both quantities are related through the fundamental equation of wave motion:

$$\lambda = \frac{c}{f} \tag{2.2}$$

Equation 2.2. Relationship between the wavelength and the frequency. Where λ is the wavelength, C is the electromagnetic wave velocity (speed of light = 3.10^8 m/s) and f is the frequency

It can be observed in (2.2) that when the frequency increases, the wavelength decreases.

The **electromagnetic spectrum** comes from the concept that electromagnetic radiation has different characteristics depending on its wavelength and frequency. The electromagnetic spectrum is a representation of the frequency distribution of all the electromagnetic waves (Fig. 2.3). Regarding a body, the electromagnetic spectrum is all the electromagnetic radiation that is emitted (emission spectrum) or absorbed (absorption spectrum). The electromagnetic spectrum extends from the radiation of lower energy (or longer wavelength) such as the radio waves,

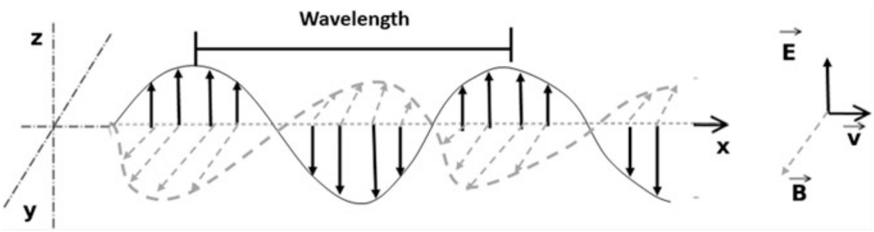

Fig. 2.2 Representation of an electromagnetic wave with the vibration of the electric field (E) and magnetic field (B) and the direction of the propagation of the wave

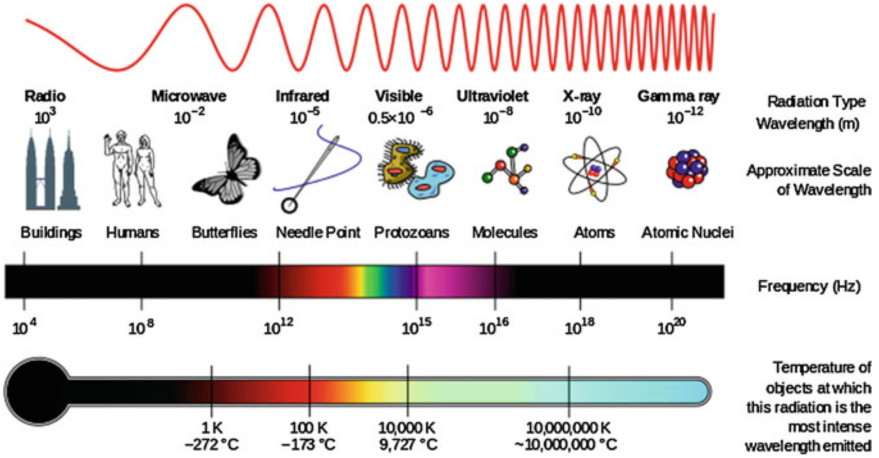

Fig. 2.3 Representation of the electromagnetic spectrum (Figure modified from the free media repository of Wikimedia Commons)

the microwaves, the infrared rays or the visible light, to electromagnetic radiation with higher energy (and shorter wavelength) such as ultraviolet light (UV), X rays and gamma rays. Most waves are commonly known to everyone. For example, X-rays are known for their medical applicability. UV is known due to the ozone hole, and it is widely known that a high incidence of this radiation increases the likelihood of skin cancer. The remaining types of radiation, such as the microwave or the radio waves, and its applications are also known to everyone.

For the different types of radiation, different imaging techniques were developed in the medical field, such as the X-ray or the arthroscopy [1] (Fig. 2.4).

The radiation that will be the focus of this chapter is infrared radiation. This radiation is also known as thermal radiation, and its wavelength range is from 760 nm to 1 mm. Infrared radiation is known as thermal radiation because there is a relationship between temperature and infrared radiation. In the Sect. 2.2, temperature was defined as the average kinetic energy of one body [8]. In other words, temperature is associated with the movement of the molecules in a body. More heat means more movement and more kinetic energy of the molecules. Changes in the speed and agitation of the molecules results in the emission of infrared radiation. Following on from this concept, it is easier to understand that all bodies that present a temperature above absolute zero (0 K or −273.15 °C) emit infrared radiation [9, 13]. This relationship between temperature or kinetic energy of one body and its emission of infrared radiation is the first concept to explain why it is possible to calculate temperatures from emitted infrared radiation. However, it is important to understand that bodies with very high temperature are capable to emit other radiations (visible and even UV), and bodies are heated during the absorption of their radiation. However, in bodies in which the temperature is close to the

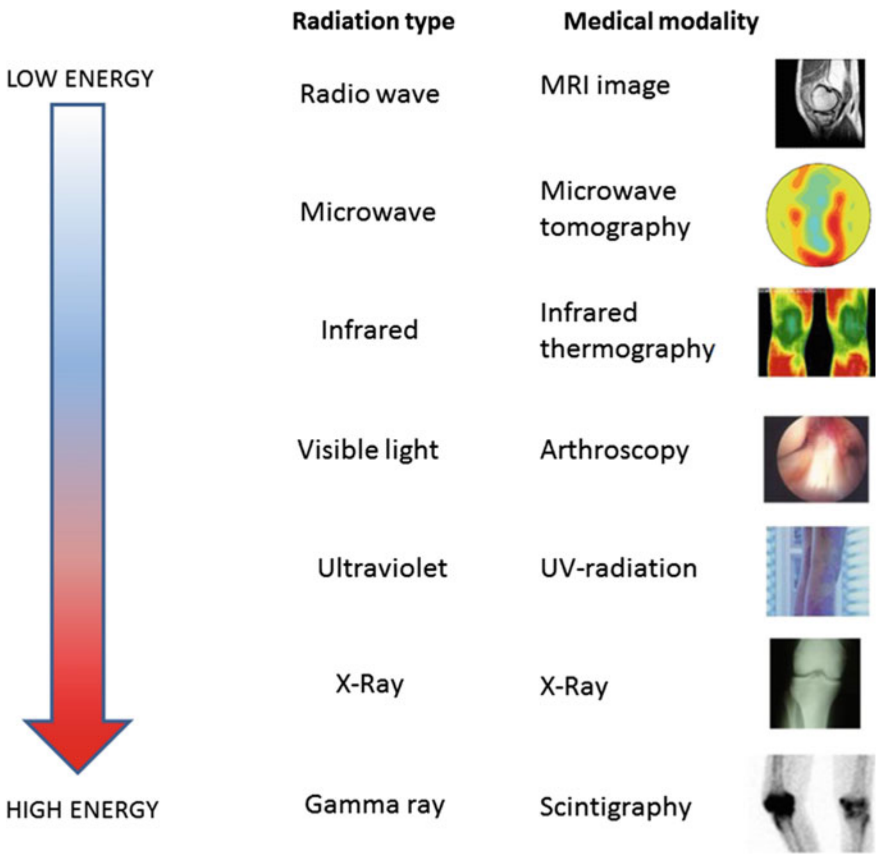

Fig. 2.4 Medical imaging techniques and its relation to the electromagnetic spectrum. Figure modified from Hildebrandt et al. [1]

environmental temperature, the energy radiated is from the infrared wavelength of the electromagnetic spectrum [14].

On the other hand, **infrared spectrum** is usually classified in three ranges: near infrared, middle infrared and far infrared (Fig. 2.5). The main reason for this division is because objects emit more radiation in one region than in others. For example, the human body emits most of its radiation in the far infrared [1, 15]. However, different gases and other elements can be transparent in the far infrared, but are visible in the near or middle infrared. Because of this, there are specific cameras to view specific wavelengths [16]. Cameras with detectors for the far infrared are the most commonly used because they register most bodies, including humans. However, there are also infrared cameras for the near or middle infrared, which are much more expensive but they are capable of visualizing specific gases (Fig. 2.6). There is also one specific window of the middle infrared (between 5 and

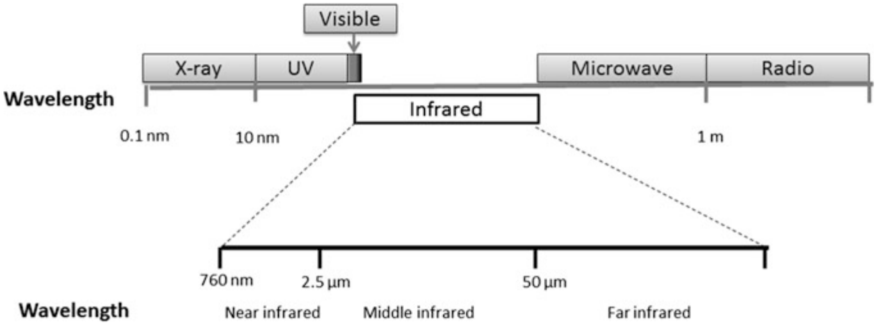

Fig. 2.5 Electromagnetic spectrum focusing on the infrared radiation spectrum

Fig. 2.6 Infrared camera with detector for visualizing the middle infrared, and then the CO_2 exhaled in the respiration. Figure extracted from Walther and Weimann [17]

7.5 µm) that is rarely used because it is the region where the atmosphere absorbs infrared radiation, and the air is opaque for infrared cameras [14].

Regarding infrared radiation, infrared thermography was developed. The next section is focused on the laws governing the emission of infrared radiation by bodies.

2.4 Physical Laws of Infrared Radiation

The physical laws of infrared radiation and its relationship to temperature are based on the theory of the **black body**. The concept of the black body was introduced by Gustav Kirchhoff in 1860. A black body is a theoretical object that absorb all incident electromagnetic radiation, and its absorption is equal to its emission. None of the incident radiation is reflected or passes through the black body. The black body also has a uniform surface and a uniform temperature. The black body is therefore an ideal perfect emitter of infrared radiation. Three properties are determined for the idea of the black body [16]:

1. A black body absorbs all the incident radiation, independently of the wavelength and the direction of the radiation.
2. For a specific temperature and wavelength, there is no surface that can emit more energy than a black body.
3. The emitted radiation of a black body depends on the wavelength; however, their radiance does not depend on the direction, it behaves like a Lambertian radiator (an object in which the surface has the same radiance from any angle).

Originally, black bodies were accomplished by a hollow sphere, covered internally with an insulate surface (in matte black) with a small aperture (Fig. 2.7a). This small aperture acts as a black body because any radiation that penetrates through it undergoes multiple reflections inside the cavity, each of which is partially absorbed, such that this radiation is completely extinguished before finding the exit. Currently, there are electronic instruments known as black body sources that are instruments with a stable and accurate temperature surface, with a high emissivity, that are configured with a specific temperature emission (Fig. 2.7b).

The quantity characterizing the emission of electromagnetic radiation by a body is called the **total emissive power**, E; that is, the energy emitted by unit of time and surface. Because this total emissive power is not equal in all the wavelengths (λ), there is also the **spectral emissive power**, E_{λ}, which is the energy emitted by unit of surface, time, and range of wavelength.

The graphical representation of the experimental curves corresponding to the spectral emissive power of the black body for each wavelength at different temperatures is shown in Fig. 2.8. This figure shows how the body emits radiation at different frequencies according to its temperature. For example, the sun, because it is at a temperature between 5000 and 6000 K, emits its radiation in the ultraviolet, visible and infrared spectrum; however, its emission peak is in the range of visible radiation (526 nm, corresponding to the green–yellow colors of the visible light). Humans visualize the sunlight as white because this emission peak is at the center

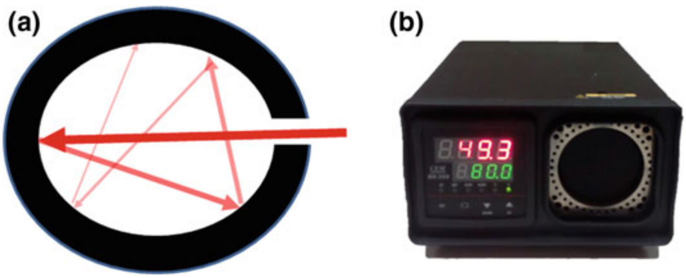

Fig. 2.7 **a** Origin of the concept of realization of a black body. **b** Current electronic black body source

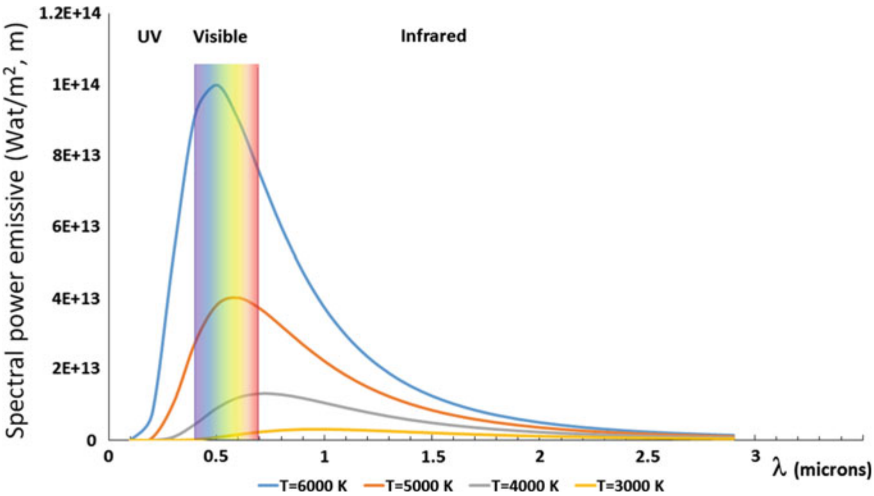

Fig. 2.8 Spectral emissive power of the black body for each wavelength at different temperatures

of the visible radiation [16]. As the temperature is lower in the bodies, its emission is higher in the infrared region. A black body with a temperature close to the room temperature does not emit in the visible range and emits all its radiations as infrared radiation [9] (Fig. 2.9). Thus, it is understood that for the 37 °C of human body (370 K), the maximum emitted energy is 9.3 μm, and therefore all its radiation is infrared radiation; more specifically, the 90% of the emitted infrared radiation is in the far infrared [1, 15] (Fig. 2.9).

Theoretical interpretation of these curves was not performed until 1900, representing a drastic change in the conception of physics, from classical physics to modern physics. It was also considered to be a pioneering result of modern physics and quantum theory [16]. However, the laws that govern the thermography were experimentally established much earlier.

Wien's displacement law was established by Wilhelm Wien in 1893. This physical law established that the wavelength of the peak of the blackbody radiation curve decreases as the body temperature is increased. The equation of Wien's displacement law is:

$$\lambda_{\text{max}} = \frac{a}{T} \tag{2.3}$$

Equation 2.3. Wien's displacement law. Where λ_{max} is the wavelength of emission peak in meters, a is the Wien's displacement constant ($2.897 * 10^{-3}$ m K), and T is the absolute temperature in kelvin

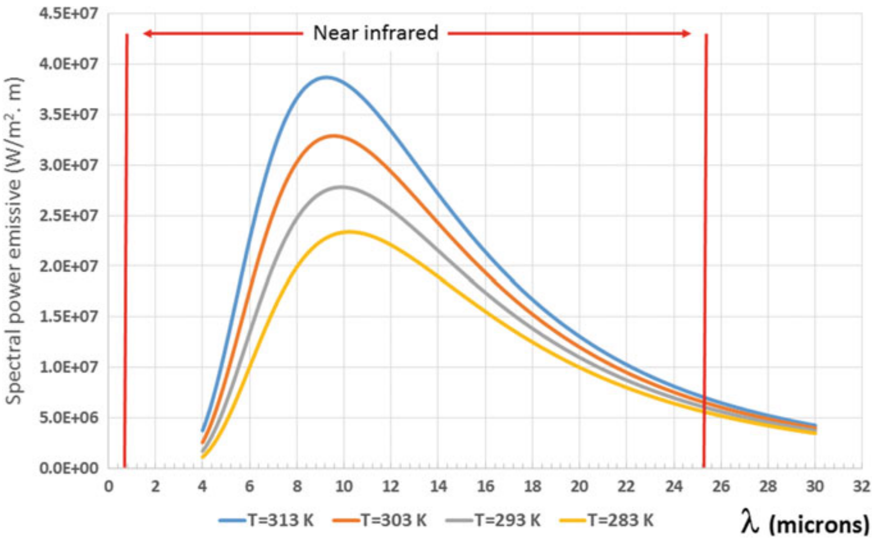

Fig. 2.9 Spectral emissive power of the black body at the following temperatures: 313 K (40 °C), 303 K (30°), 293 K (20°) and 283 K (10°). At these temperatures, all spectral emissive power is inside of the infrared spectrum

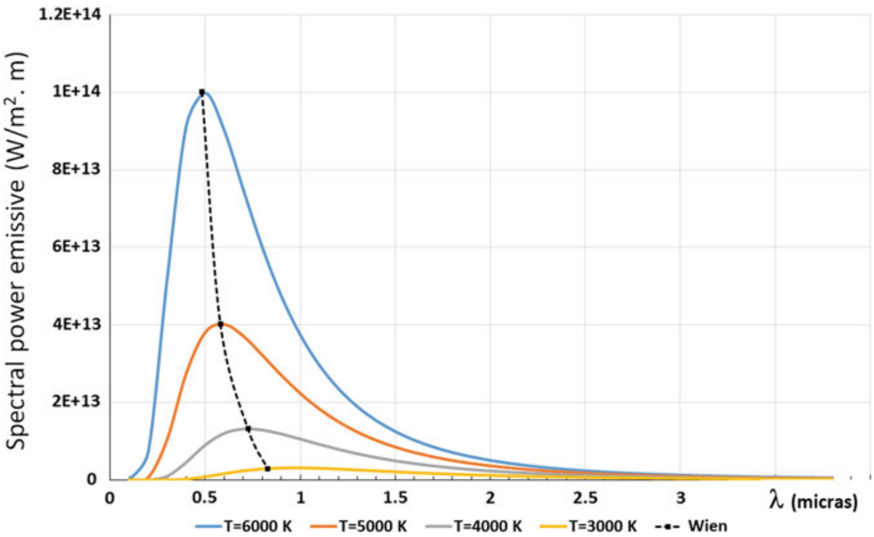

Fig. 2.10 Representation of Wien's displacement law at different temperatures of the black body

Representation of Wien's displacement law in the experimental curves corresponding to the spectral emissive power of the black body for each wavelength at different temperatures is shown in Fig. 2.10.

Stefan-Boltzmann's law was deduced by Josef Stefan in 1879 on the basis of experimental measurements made by John Tyndall and was derived from theoretical considerations by Ludwig Boltzmann in 1884. Stefan-Boltzmann's law expresses that the total emissive power or radiated energy from a black body is proportional to the fourth power of its absolute temperature:

$$E = \sigma * T^4 \tag{2.4}$$

Equation 2.4. Stefan-Boltzmann's law. Where E is the total emissive power (W/m^2), σ is the Stefan-Boltzmann's constant ($5.67 * 10^{-8}$ W/m^{-2} K^{-4}), and T is the temperature in kelvin

Small changes in temperature resulted in big changes in the emissive power. This is really easy to see in the Stefan-Boltzmann's equation because the temperature is expressed as the fourth power. This relationship is very important because it explains how the calculation of the temperature from the emissive power is very sensitive and allows differentiation of areas at different temperatures, as they will have different emissive powers. It can be considered that the Stefan-Boltzmann's law is the fundamental law that governs infrared thermography.

For real surfaces, the Stefan-Boltzmann's equation is modified with the incorporation of emissivity (2.5). The concept of emissivity and also the consequence of this parameter in the equation will be explained in the next section. Most of the infrared cameras and radiation thermometers made the calculations using the modified Stefan-Boltzmann's equation [9].

$$E_0 = \varepsilon * \sigma * T^4 \tag{2.5}$$

Equation 2.5. Modified Stefan-Boltzmann's equation (2.4) where the value of the emissivity (ε) is incorporated

Wien's displacement law and Stefan-Boltzmann law were obtained experimentally before 1900. However, these laws were corroborated by the law established by Max Planck in 1900:

$$E_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \tag{2.6}$$

Equation 2.6. Planck's law. Where $E_\lambda(\lambda, T)$ is the spectral radiance as a function of temperature and wavelength, λ is the wavelength of emission in meters, T is the temperature in kelvin, h is the Planck constant ($6.6256 * 10^{-34}$ Js), c is the speed of light in the medium ($3 * 10^8$ ms^{-1}), and k is the Boltzmann's constant ($1.38054 * 10^{-23}$ W s K^{-1})

Integrating Planck's law for all frequencies leads to the Stefan-Boltzmann's law [13]. Applying the function maximum condition to the Plank equation (first derivative equal to zero) the Wien's displacement law is obtained.

After knowing the physical laws that explain the calculation of the temperature using infrared radiation, it is important to understand the radiative characteristics of one body in terms of its absorptivity, emissivity, reflectivity and transmissivity.

2.5 Radiative Characteristics of the Bodies

Infrared radiation has a behavior very similar to visible radiation. For this reason, its propagation can be described in the same way as the geometric optics [16]. In homogeneous materials, infrared radiation propagates in a straight line as if it were rays. Furthermore, the geometrical properties of reflection and refraction are also applied to infrared radiation, so that geometrical characteristics of the surfaces, such as uniform or roughened surfaces, have an effect on the emission and absorption of infrared radiation [16]. In the visualization of the human body, these considerations are important in understanding why the delimitation of the body in the image presents a lower estimation of the temperature. In this sense, the loss of infrared radiation in the outline of a body was identified as an important source of error (Fig. 2.11) [18–20].

Infrared radiation that arrives on a body can be absorbed, reflected or can pass through the body, depending on its physical characteristics (Fig. 2.12). These characteristics define the behavior of one body in relation to the infrared spectrum:

- Absorptivity (α): capacity of one body to absorb infrared radiation.
- Emissivity (ε): capacity of one body to emit its own infrared radiation. This parameter corresponds to the absorptivity ($\alpha = \varepsilon$).
- Reflectivity (ρ): capacity of one body to reflect the infrared radiation that comes from the environment.
- Transmissivity (τ): capacity of one body to let pass through it the radiation. If radiation is not transmitted through the body, this body it is therefore called opaque.

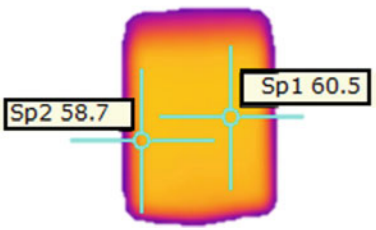

Fig. 2.11 Effect of curvature in the infrared emission and the temperature calculation of an object with a homogenous temperature surface

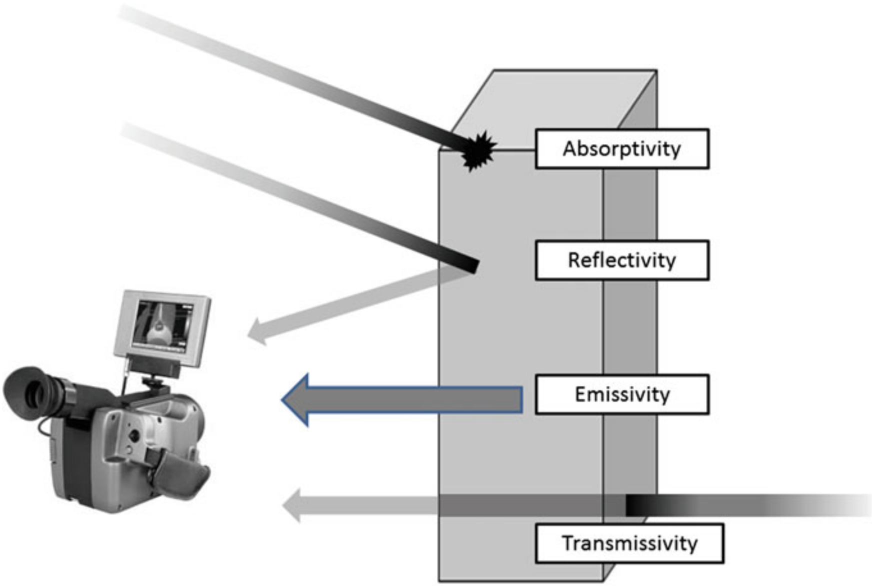

Fig. 2.12 Radiative characteristics of one body

The proportion of these components in a body are expressed by the following equations:

$$\alpha + \rho + \tau = 1 \tag{2.7}$$

Equation 2.7. Destinations of the incident radiation in a body: absorbed (α), reflected (ρ) or transmitted radiation (τ)

$$\varepsilon + \rho + \tau = 1 \tag{2.8}$$

Equation 2.8. Sources of the outgoing radiation of a body: emitted (ε), reflected (ρ) or transmitted radiation (τ)

As we discussed in the previous section, a black body is an ideal with values of emissivity and absorptivity equal to 1, and without reflectivity and transmissivity, and is therefore considered to be the perfect infrared emitter surface.

In the calculation of the temperature of a body, it is essential, in order to have an accurate calculation, that the body presents a zero transmissivity and an emissivity as close as possible to 1. Bodies with high values of reflectivity will result in temperature calculations with many errors because most of the outgoing radiation comes from the environment.

Behaviour of different bodies can be different in the visible region compared with the infrared. And for this reason it is essential to know the radiative characteristics of the bodies. One important example is water. In the visible region, water is more transparent and reflective. However, in the infrared, the characteristics of water are different. In the infrared, the water is opaque, with a higher emissivity than 0.9 [21]. If we do not know the radiative characteristics at the beginning of a thermography swimming study, we will probably want to measure while the swimmer is submerged in water, but this is impossible because of the opacity of the water (Fig. 2.13a). Another example is glass. Glass is transparent in visible light, but is opaque in infrared. Therefore we cannot see anything that is behind glass (Fig. 2.13b). An example of this is that the infrared cameras used at airports as fever screening method require glasses to be removed, in order to measure the temperature of the inner canthi of the eyes.

In this sense, knowing the emissivity of a body is of vital importance. Emissivity is a number ranging from 0 to 1, and it can be interpreted as the ratio of the actual

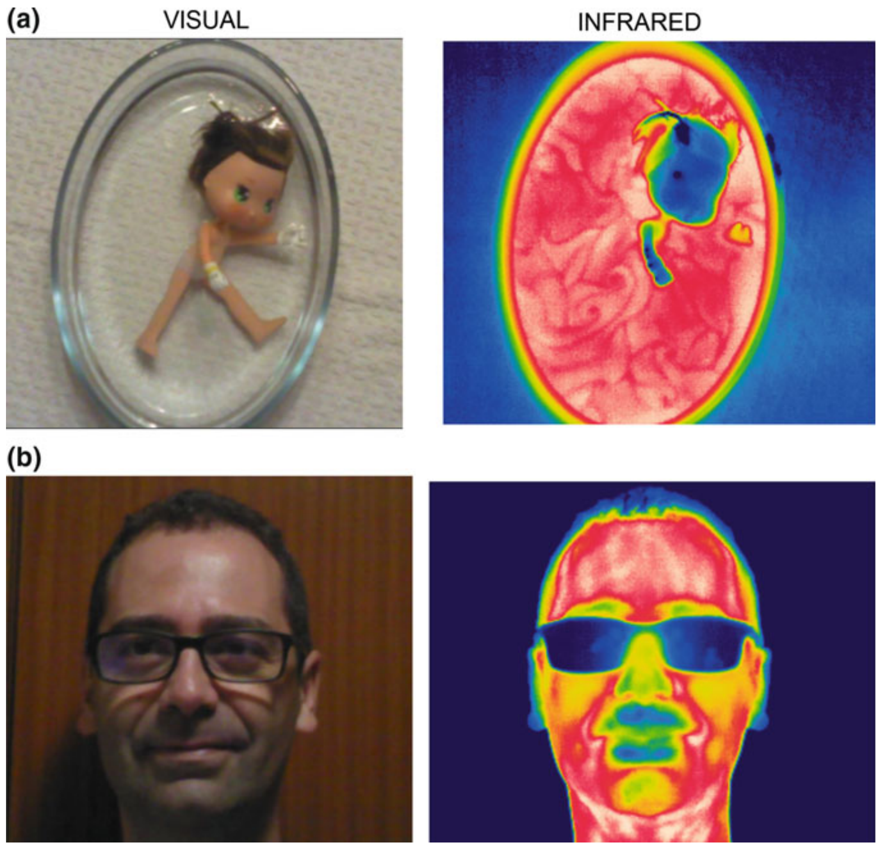

Fig. 2.13 Examples of the different behaviour of some objects in the infrared and visible spectrum. Infrared opacity of water (**a**) and glasses (**b**)

Table 2.1 Emissivity values of different materials

Material	Emissivity value
Skin	0.98 [23]
Enamel of human teeth	0.65 [24]
Cotton fabric	0.95 [25]
Water	~0.9 [21]
Aluminum (polished)	0.02 [26]
Black paper	0.9 [26]
Building materials: plaster	0.57–0.84 [27]
Building materials: porous stone	0.61–0.9 [27]
Building materials: marble	0.68–0.94 [27]

amount of infrared energy emitted compared with the theoretically perfect amount that could be emitted (black body) [22]. This means that one object with an emissivity value of 0.7 emits only the 70% of the maximum theoretical amount of infrared energy, and the other 30% of outgoing radiation comes from another sources. If we recall the modified Stefan-Boltzmann's equation, the emissivity was incorporated in the formula. The aim of this modification is to considerer only the percentage of radiation from the body, and to remove from the calculation the percentage of the reflected temperature. Table 2.1 presents the emissivity values of different materials.

In sports science, the most important "material" is usually the skin. **Skin emissivity** was determined with values between 0.97 and 0.99 with an standard deviation of 0.01 by different studies [23, 28, 29]. In scientific studies, an emissivity of 0.98 is commonly established. This means that the skin is a good emitter of infrared radiation and it is possible to accurately calculate its temperature.

However, for the thermography assessment of sports equipment and garments, it is necessary to know the emissivity of its materials in order to measure its temperatures correctly. In this sense, two strategies could be considered. First, it is of interest to review the scientific literature to determine whether previous studies have measured the emissivity of materials. The second strategy is to calculate the emissivity of a material or to check whether this emissivity measurement obtained is similar to that observed in the literature. The second strategy is always recommended because although is possible to find the emissivity value of one material, this value can be different in a given equipment/garment due to a different composition or different condition of the surface (e.g., polished, oxidized or scaled). Although there are more accurate methods, a method that is easy to perform and therefore can be carried out in any laboratory will be explained. This method consists of the following steps:

1. Attach a material with a known emissivity to the object of interest. Tapes with a known emissivity (with emissivity values between 0.95 and 0.99) are commonly used.

2. Heat the object of interest with the aim of having a higher contrast between the object and the environment. Ideally, this heat should be homogenous. For this reason, hot plates from laboratories are recommended.
3. Use the infrared camera to determine the temperature of the material with known emissivity.
4. Set the emissivity of the object of interest until obtaining the same temperature as the material with known emissivity. This is the estimation of the emissivity of the object of interest.
5. Repeat the experiment different times, at different temperatures and with different samples of your object of interest, in order to obtain a robust average of the emissivity.

After all these physical concepts, it is possible to better understand how thermal imaging cameras can measure temperatures from the detection of infrared radiation. In addition, the importance to know the radiative characteristics of an object with the aim to appreciate if it is possible to measure its temperature and the error during the measurement. The following section will discuss the processes of heat transfer and thermoregulation. These concepts are essential for the prediction and/or the interpretation of the thermographic results of an experiment.

2.6 Thermoregulation

Human thermoregulation can be defined as the integrative physiological responses of the body with the aim of maintaining core temperature within a few tenths of a degree of 37 °C, despite a wide range of activities and environments [9, 30]. These responses are coordinated mainly by the hypothalamus [30–32]. The hypothalamus integrates inputs from the temperature of the hypothalamus itself, the core and the thermoreceptors in the skin [30, 32, 33]. Furthermore, non-thermal factors also are responsible for the thermoregulatory response (e.g., sweating) [32] (Fig. 2.14).

To the three heat transfer processes detailed in the Sect. 2.2 (convection, conduction and radiation), it is necessary to add human body thermoregulation in terms of the **sweat evaporation** and **respiration**. Sweat evaporation is considered to be the main mechanism of heat dissipation during exercise. Evaporation results in a temperature decrease of the skin surface [1]. It is important to understand that it is the evaporation of sweat that is responsible for the temperature decrease and not the sweat production itself. Sweat rate is related to the ambient temperature, exercise intensity and absolute heat production [12]. In addition, the amount of evaporation is inversely proportional to the relative humidity of the air [9]. In an environment with 100% relative humidity, humidity could be condensed in the body resulting in a heat gain, at the same time as heat is lost by evaporation [9]. During respiration (specifically in the expiration), heat is lost to the environment via convection and

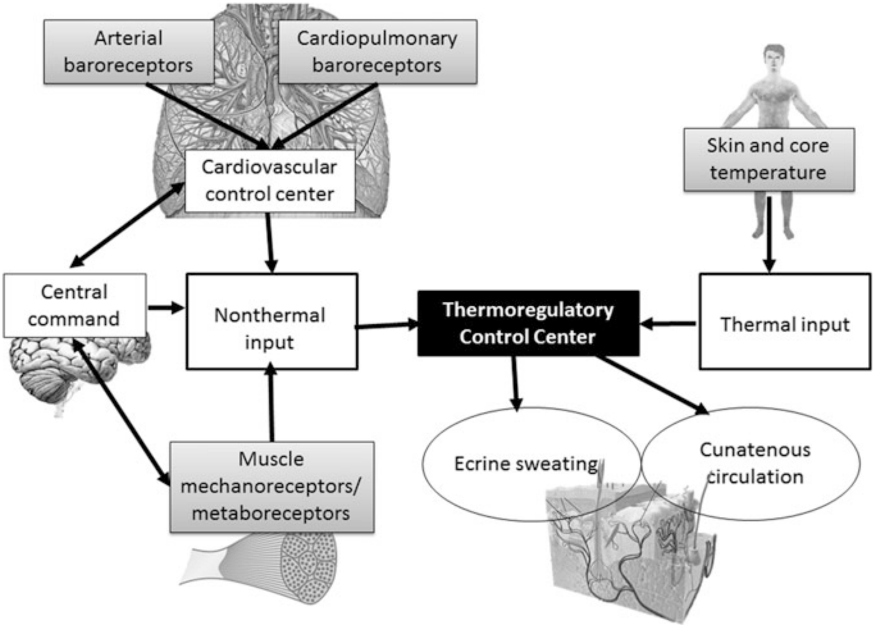

Fig. 2.14 Schematic representation of the human thermoregulatory system. Figure modified from Kenny and Journeay [32]

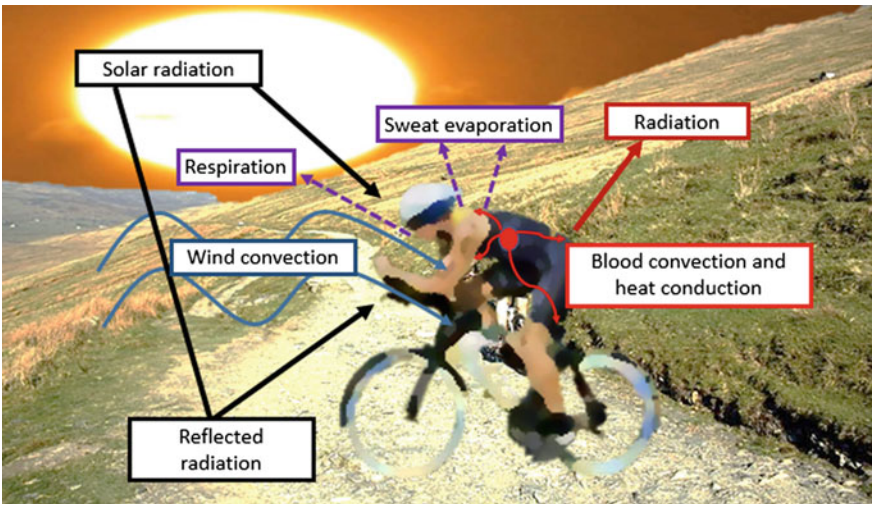

Fig. 2.15 Heat exchange between the body and the environment during exercise

evaporation [12]. Heat loss by respiration is higher in cold and dry environments; however, there is a low contribution of respiration in whole-body heat loss [12].

All these discussed processes are shown graphically in Fig. 2.15.

Following the first law of thermodynamics, the **heat balance equation** is commonly used in thermoregulation studies, where heat production is on one side of the equation and heat loss is on the other side. More specifically, this equation is defined as follows:

$$\text{M-W} = (\text{K} + \text{C} + \text{R} + \text{ESK}) + \text{S} \tag{2.9}$$

Equation 2.9. Heat balance equation where M is the rate of metabolic heat production, W is the rate of mechanical work, K is the rate of conductive heat loss, C is the rate of convective heat loss from the skin, R is the rate of radiative heat loss from the skin, ESK is the rate of evaporative heat loss from the skin, and S is the rate of body heat storage

All the concepts from Fig. 2.15 that have been discussed are expressed in the heat balance equation. However, there is one concept that we have not yet discussed and that is heat production. Heat production is the difference between metabolic heat production and the rate of mechanical work (M-W). Metabolic heat production was defined by Cramer and Jay [12] as "the rate of free energy released from the catabolism of carbohydrate, fat, and amino acids to resupply adenosine triphosphate (ATP) for cellular activities such as biosynthesis, transport, and muscular contractions". Some of this energy is converted in external work (W) and the rest is converted into heat [12]. For this reason, heat production is the difference between all the energy produced (M) and the energy used for external work (W). The body is very inefficient in transforming the energy in mechanical work, and between 30–70% of the energy produced, depending on activities, results in thermal energy [11]. Heat production is usually calculated by the combination of ergometers, which measure the work and indirect calorimetric measurements (gas exchange) that measure metabolic heat production [12]. Exercise results in an increment in heat production that the body needs to dissipate. We can exemplify how heat production increases with the intensity of the activity using different values of heat production. The heat production of sleeping, walking, cycling at 250 W and running at 16 km/h are 1.0, 4.0, 13.3 and 20.0 W/kg, respectively.

It is important to know the processes of human thermoregulation during exercise with the aim of obtaining the maximum possible performance and protecting athletes from injury, especially in extreme environments [31]. Thermoregulatory responses are different depending on the thermal environment (neutral or moderate, cold and warm/hot) [30]. Exemplification of the two most extreme scenarios help us to better understand human thermoregulation.

In warm/hot environments, the main objective of human thermoregulation is heat dissipation. This heat dissipation is mainly produced by two mechanisms, cutaneous vasodilation and sweat evaporation [9, 30]. Cutaneous vasodilation consists of the increase of skin blood flow in order to transfer the heat from the core to the body by the blood [30]. It is important to considerer that during exercise in hot environments, there is a "competition" between the active muscles and the skin for the available cardiac output, resulting in an increase in cardiovascular stress [34]. In sweat evaporation, the evaporation reduces the skin temperature. It increases the heat transfer from the core to the skin [30]. In addition, heat acclimation (heat exposure during a time) produces adaptations in these mechanisms [35]. Core temperature is reduced due to an increase in skin blood flow and sweating [35]. Furthermore, the volume of plasma is increased in order to minimize dehydration during exercise [35]. Figure 2.16 shows the adaptations to heat exposure in relation to the exposition time.

In cold environments, the main objective of human thermoregulation is heat conservation. Two of the main mechanisms of heat conservation are cutaneous vasoconstriction and thermogenesis [9, 30]. Cutaneous vasoconstriction consists of the opposite process to thermoregulation: skin blood flow is reduced in order to avoid heat dissipation via convection. Thermogenesis is produced mainly by shivering. Shivering consists of involuntary contractions of skeletal muscle with the aim of producing more heat [30]. Cooling acclimatization is a complex process with different patterns depending on the type and severity of chronic cold exposure [33]. The first adaptation is habituation, consisting of a less pronounced physiological responses (e.g., vasoconstriction and shivering) [33]. The second adaptation is an increase in heat production due to an exaggerated shivering or development of nonshivering thermogenesis [33]. Finally, there are insulation-related adjustments resulting in an enhanced vasoconstrictor response to cold exposure [33]. Figure 2.17 shows the schematic diagram of these adaptations.

During exercise, clothing affects heat exchange. Clothing increases insulation and reduces the convective and evaporative heat loss [37]. Furthermore, if the clothing is excessive, it can increase sweat production in response to decreasing core temperature,

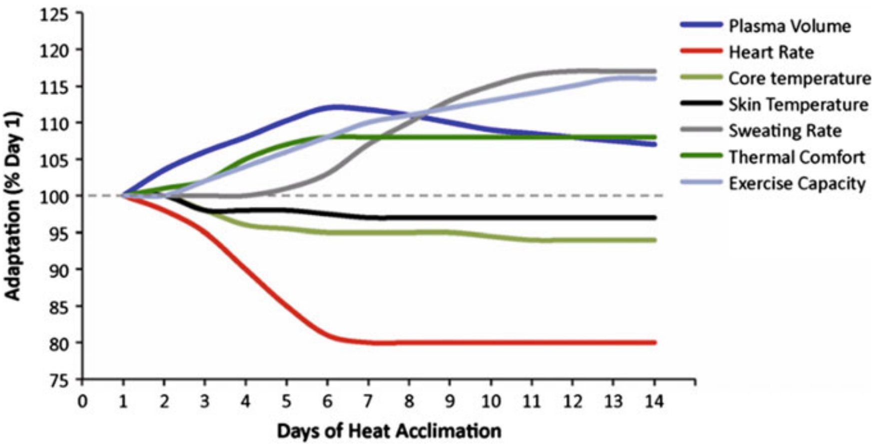

Fig. 2.16 Heat acclimatization adaptations. Figure obtained from Périard et al. [36]

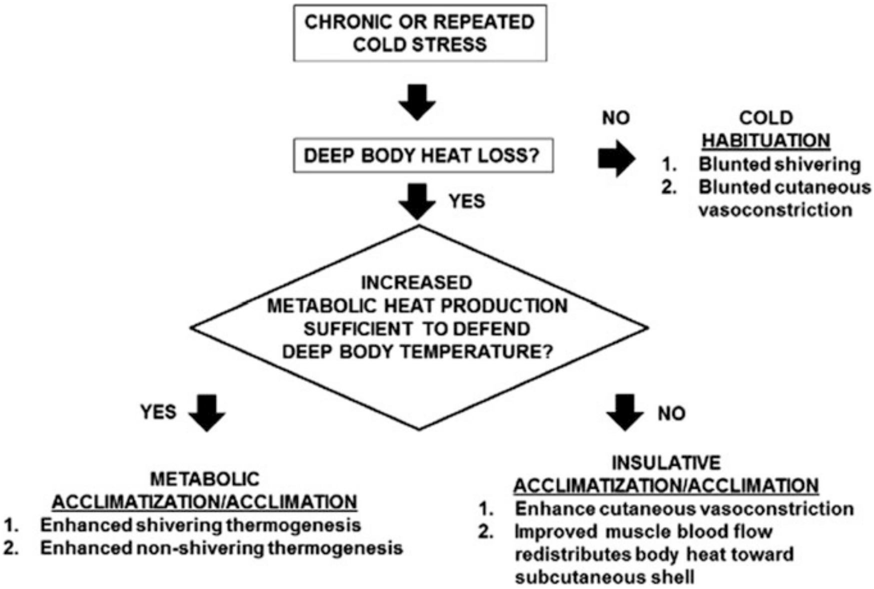

Fig. 2.17 Different patterns of human cold acclimatization. Figure obtained from Castellani and Young [33]

but this is not accompanied by efficient sweat evaporation [37]. Sweat or vapor may travel through clothing and it may be sorbed and desorbed by the textile fibers, or may condensate in the outer layer if these are colder than the skin [38]. This could result in an increase of the skin wetness and then a lower thermal comfort. For these reasons, usually the demands for sport clothing are based on allowing sweat evaporation [37]. However, these demands will be different for each kind of environment. Thermoregulatory aspects related to sports clothing will be discussed in the Chap. 7 of this book.

2.7 Conclusions

Infrared thermography researchers in sport science need to have knowledge about the physical principles of infrared thermography, heat transference and thermoregulation. This knowledge is necessary in order to understand the operation of infrared camera, to avoid and to know methodological issues, to establish logical hypotheses, and to correctly interpret the thermal results. Different conclusions can be extracted from this chapter:

- All the bodies that present a temperature above absolute zero emit infrared radiation and infrared cameras are capable of capturing this radiation. However, depending on the body, its emission is in a specific range of the infrared spectrum.

For some specific applications, such as the visualization of gases, special cameras are needed.

- Radiated energy from a black body is proportional to the fourth power of its absolute temperature. This relationship explains the high sensitivity of thermal cameras.
- It is necessary to know the radiative characteristics of a body in order to know if it is possible to calculate its temperature and to design a study without errors. In this sense, estimation of the temperature will be more accurate in bodies with high emissivity values. Skin is a good emitter of infrared radiation (emissivity of 0.98), which is important in sport science studies, because it is commonly the "material of interest". However, for other materials, it is necessary to know its emissivity values in order to correctly calculate the temperature.
- It is necessary to understand heat transference mechanisms in thermography studies. More specifically, in human studies, it is necessary to understand the mechanisms involved in the thermoregulation.

References

1. Hildebrandt C, Raschner C, Ammer K (2010) An overview of recent application of medical infrared thermography in sports medicine in Austria. Sensors 10:4700–4715
2. Chudecka M, Lubkowska A (2010) Temperature changes of selected body's surfaces of handball players in the course of training estimated by thermovision, and the study of the impact of physiological and morphological factors on the skin temperature. J Therm Biol 35:379–385
3. Duc S, Arfaoui A, Polidori G, Bertucci W (2015) Efficiency and thermography in cycling during a graded exercise test. J Exerc Sports Orthop 2:1–8
4. Fournet D, Ross L, Voelcker T et al (2013) Body mapping of thermoregulatory and perceptual responses of males and females running in the cold. J Therm Biol 38:339–344. doi:10.1016/j.jtherbio.2013.04.005
5. Priego Quesada JI, Lucas-Cuevas AG, Gil-Calvo M et al (2015) Effects of graduated compression stockings on skin temperature after running. J Therm Biol 52:130–136. doi:10.1016/j.jtherbio.2015.06.005
6. de Andrade Fernandes A, dos Santos Amorim PR, Brito CJ et al (2014) Measuring skin temperature before, during and after exercise: a comparison of thermocouples and infrared thermography. Physiol Meas 35:189
7. Priego Quesada JI, Martínez Guillamón N, Ortiz Cibrián, de Anda RM et al (2015) Effect of perspiration on skin temperature measurements by infrared thermography and contact thermometry during aerobic cycling. Infrared Phys Technol 72:68–76. doi:10.1016/j.infrared.2015.07.008
8. Parsons K (2002) Human thermal environments: the effects of hot, moderate, and cold environments on human health, comfort and performance, 2nd edn. CRC Press, USA
9. Vardasca R, Simoes R (2013) Current issues in medical thermography. In: Topics in medical image processing and computational vision. Springer, Berlin, pp 223–237
10. Cuddy JS, Hailes WS, Ruby BC (2014) A reduced core to skin temperature gradient, not a critical core temperature, affects aerobic capacity in the heat. J Therm Biol 43:7–12. doi:10.1016/j.jtherbio.2014.04.002

11. González-Alonso J (2012) Human thermoregulation and the cardiovascular system. Exp Physiol 97:340–346. doi:10.1113/expphysiol.2011.058701
12. Cramer MN, Jay O (2016) Biophysical aspects of human thermoregulation during heat stress. Auton Neurosci Basic Clin 196:3–13. doi:10.1016/j.autneu.2016.03.001
13. Jones BF (1998) A reappraisal of the use of infrared thermal image analysis in medicine. IEEE Trans Med Imaging 17:1019–1027. doi:10.1109/42.746635
14. Astarita T, Carlomagno GM (2012) Infrared thermography for thermo-fluid-dynamics. Springer, Berlin
15. Ng E-K (2009) A review of thermography as promising non-invasive detection modality for breast tumor. Int J Therm Sci 48:849–859
16. Vollmer M, Möllmann K-P (2011) Infrared thermal imaging: fundamentals, research and applications. Wiley, Weinheim
17. Walther M, Weimann G (2006) Infrared imaging with InAs/GaSb type-II superlattices. Phys Status Solidi A 203:3545–3549. doi:10.1002/pssa.200622385
18. Watmough DJ, Fowler PW, Oliver R (1970) The thermal scanning of a curved isothermal surface: implications for clinical thermography. Phys Med Biol 15:1. doi:10.1088/0031-9155/15/1/301
19. Salter DC (1976) The effect of obliquity in clinical thermograms. Phys Med Biol 21:980
20. Ammer K (2008) The Glamorgan Protocol for recording and evaluation of thermal images of the human body. Thermol Int 18:125–144
21. Mitchell HJ, Salvaggio C (2003) MWIR and LWIR spectral signatures of water and associated materials. In: Proceedings of SPIE image exploit. Target recognition, algorithms multispectral hyperspectral ultraspectral image, vol IX, pp 195–205
22. Bernard V, Staffa E, Mornstein V, Bourek A (2013) Infrared camera assessment of skin surface temperature—effect of emissivity. Phys Med 29:583–591. doi:10.1016/j.ejmp.2012.09.003
23. Steketee J (1973) Spectral emissivity of skin and pericardium. Phys Med Biol 18:686
24. Kells BE, Kennedy JG, Biagioni PA, Lamey PJ (2000) Computerized infrared thermographic imaging and pulpal blood flow: Part 1. A protocol for thermal imaging of human teeth. Int Endod J 33:442–447
25. Carr WW, Sarma DS, Johnson MR et al (1997) Infrared absorption studies of fabrics. Text Res J 67:725–738
26. Marinetti S, Cesaratto PG (2012) Emissivity estimation for accurate quantitative thermography. NDT E Int 51:127–134. doi:10.1016/j.ndteint.2012.06.001
27. Avdelidis NP, Moropoulou A (2003) Emissivity considerations in building thermography. Energy Build 35:663–667. doi:10.1016/S0378-7788(02)00210-4
28. Togawa T (1989) Non-contact skin emissivity: measurement from reflectance using step change in ambient radiation temperature. Clin Phys Physiol Meas 10:39
29. Sanchez-Marin FJ, Calixto-Carrera S, Villaseñor-Mora C (2009) Novel approach to assess the emissivity of the human skin. J Biomed Opt 14:24006–24006–6. doi:10.1117/1.3086612
30. Charkoudian N (2016) Human thermoregulation from the autonomic perspective. Auton Neurosci Basic Clin 196:1–2. doi:10.1016/j.autneu.2016.02.007
31. Lim CL, Byrne C, Lee JK (2008) Human thermoregulation and measurement of body temperature in exercise and clinical settings. Ann Acad Med Singapore 37:347–353
32. Kenny GP, Journeay WS (2010) Human thermoregulation: separating thermal and nonthermal effects on heat loss. Front Biosci Landmark Ed 15:259–290
33. Castellani JW, Young AJ (2016) Human physiological responses to cold exposure: Acute responses and acclimatization to prolonged exposure. Auton Neurosci 196:63–74. doi:10.1016/j.autneu.2016.02.009
34. González-Alonso J, Crandall CG, Johnson JM (2008) The cardiovascular challenge of exercising in the heat. J Physiol 586:45–53. doi:10.1113/jphysiol.2007.142158
35. Périard JD, Travers GJS, Racinais S, Sawka MN (2016) Cardiovascular adaptations supporting human exercise-heat acclimation. Auton Neurosci 196:52–62. doi:10.1016/j.autneu.2016.02.002

36. Périard JD, Racinais S, Sawka MN (2015) Adaptations and mechanisms of human heat acclimation: Applications for competitive athletes and sports. Scand J Med Sci Sports 25:20–38. doi:10.1111/sms.12408
37. Gavin TP (2003) Clothing and thermoregulation during exercise. Sports Med Auckl NZ 33:941–947
38. Havenith G, Bröde P, den Hartog E et al (2013) Evaporative cooling: effective latent heat of evaporation in relation to evaporation distance from the skin. J Appl Physiol Bethesda Md 114:778–785. doi:10.1152/japplphysiol.01271.2012