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Review Article

Thermal Radiation of the Human Body: Medical Applications

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Abstract

The physical and biophysical properties of thermal radiation are used in medicine, in particular for diagnostic purposes. Inflammatory processes change the local body temperature. Therefore, remote recording of electromagnetic radiation signals from different parts of the human body allows non-contact and non-invasive determination of their temperature. This diagnostic method is called thermography or thermal imaging. Experimental studies of medical applications of the thermography method have shown that the process of temperature relaxation is characterized by a gradual approach of temperature to its equilibrium value in the form of free damped temperature oscillations, as a result of non-linear feedback effects in the human body.

Keywords: *Thermal Radiation; Human Body; Thermography*

Introduction

Thermal (temperature) radiation of the human body is electromagnetic radiation arising from the presence of internal energy due to the thermal movement of atoms and molecules of this body.

The thermal radiation of the human body has a continuous spectrum, the maximum of which depends on temperature. With an increase in temperature, the total energy of thermal radiation increases sharply, while the wavelength corresponding to the maximum thermal radiation of the human body shifts towards shorter wavelengths.

The theoretical basis of thermography (thermal imaging) is formed by the laws of thermal radiation, which will be considered below, mainly at a qualitative level. A quantitative description of the laws of thermal radiation can be found, for example, in a textbook "Medical and Biological Physics" for students of the highest medical educational institutions [1]. Additional information about the use of modern physical methods in medicine (in particular, thermography or thermal imaging methods) is contained in [2-16].

The main characteristics of thermal radiation

We shall first introduce such basic characteristics of thermal radiation as the radiation flux F, the radiation emmitance of the body R, and the spectral density of the radiation emmitance r_λ.

The radiation flux F is (a) the average radiation power over a period of time significantly exceeding the period of electromagnetic oscillations; (b) the energy of electromagnetic radiation per unit of time, measured in the watt (W).

The radiation emmitance of the body R is the flux of electromagnetic radiation coming out of a unit area S of the body surface and measured in the watt per m^2 (W/m^2).

The spectral density of the radiating emmitance r_λ of a body is the radiating ability related to a unit of length of the spectral interval of wavelengths λ and measured in the watt per $m^3 (W / m^3)$ The dependence of the magnitude of the spectral density of the radiation emmitance on the wavelength λ is called the radiation spectrum of the body $r_\lambda = f(\lambda)$.

Since all the quantities introduced above characterized the radiative emmitance of the body, we will also introduce the characteristics of the absorbing properties of the body.

The absorption coefficient α is the value of the ratio of the radiation flux F_{abs} absorbed by the body to the radiation flux F_{inc} incident on the body. If the value of α refers to a single spectral interval of wavelengths λ, then this value determines the monochromatic absorption coefficient α_λ.

Let us introduce the concept of «absolute black body» as a body for which the monochromatic absorption coefficient is equal to unity in the entire spectral range and for any temperature, i.e. $\alpha_\lambda^{b.b.} = 1$. A cavity with a very small hole can serve as a model of an absolute black body. It is for such a model that the monochromatic absorption coefficient should be close to unity. A fairly good real example of an absolute black body is a platinum crucible at a temperature close to the melting point of platinum $T_{melt} = 2046.6$ K.

In the theory of thermal radiation, the concept of «gray body» is also introduced, as such a body for which the absorption coefficient is less than unity. Thus, the human body can be considered gray in the infrared part of the spectrum, since in this spectral range the absorption coefficient is $\alpha_\lambda^{g.b.} \approx 0.9$.

Basic laws of thermal radiation

Let us now turn to the consideration of the basic laws of thermal (temperature) radiation [1,7,8,13,16]:

1. The Kirchhoff's law. This law was discovered by the German physicist Gustav Kirchhoff in 1859 and establishes a relationship between the radiating and absorbing abilities of a body. G. Kirchhoff's law is formulated as follows: the ratio of the spectral density of the radiation emmitance r_λ of a body to the monochromatic absorption coefficient a_λ is the same for all bodies at a given temperature and is equal to the spectral density of the radiation emmitance ε_λ of an absolute black body at the same temperature.

2. The law of absolute black body radiation was discovered by the German physicist Max Planck in 1900 using the hypothesis formulated by him about the change in the electromagnetic energy of radiation and absorption by minimal portions (quanta). This hypothesis marked the beginning of quantum mechanics, one of the most outstanding achievements of the natural sciences of the 20th century, for which Max Planck was awarded the 1918 Nobel Prize in Physics. M. Planck's radiation law specifies the dependence of the spectral density of the radiation emmitance ε_λ of an absolute black body on the wavelength λ (or frequency ν) of electromagnetic radiation. It should be noted that the radiation law of M. Planck is in full agreement with the experimental curves of the dependence of the emission spectra $r_\lambda = f(\lambda)$.

3. The Stefan-Boltzmann law is formulated as follows: the radiation emmitance R of an absolute black body is directly proportional to the fourth power of its absolute temperature T. This law was established by two Austrian physicists Josef Stefan and Ludwig Boltzmann, first experimentally by I. Stefan in 1879, and then theoretically derived by L. Boltzmann in 1884.

The corresponding formula of the Stefan-Boltzmann law has the following form: $R = \sigma T^4$, where the value $\sigma = 5.67 \cdot 10^{-8}$ $W / m^2 \cdot K^4$ is called the Stefan-Boltzmann constant.

4. The Wien's displacement law. This law, established by the German physicist Wilhelm Wien in 1893, gives a relationship between the absolute temperature *T* and the wavelength $\lambda_{\max}$ corresponding to the maximum spectral density of the radiation emmitance in the spectrum of thermal radiation of an absolute black body. For the discovery of this law, Wilhelm Wien was awarded the 1911 Nobel Prize in Physics. The Wien's displacement law is formulated as follows: the wavelength $\lambda_{\max}$, which accounts for the maximum spectral density of the radiation emmitance ε_λ of an absolute black body, is inversely proportional to its absolute temperature T. This formulation of Wien's displacement law corresponds to the following formula:

   $\lambda_{\max} = b / \mathrm{T}$, where the coefficient $b = 2{,}9 \cdot 10^{-3}$ м·К is called Wien's constant.

Thus, the wavelength $\lambda_{\max}$, characterizing the maximum spectral density of the radiation emmitance of an absolute black body, shifts towards shorter wavelengths with increasing temperature *T*. It is this fact, confirmed by the experimental curves of energy distribution in the spectra of thermal radiation, that gives reason to call Wien's law the "displacement law".

Special properties of thermal radiation of the human body

Based on the Wien's displacement law, we may estimate the value of the wavelength $\lambda_{\max}$, which accounts for the maximum value of the radiation emmitance of the human body. The surface layer of human skin has an approximate average temperature of $t \approx 32$°C on the Celsius scale or $T \approx$ (273 + 32) K $\approx$ 305 K on the Kelvin scale. Then, according to Wien's displacement law, we have such a numerical value of $\lambda_{\text{мах}} \approx 10\ \mu m$ It follows that the waveleng $\lambda_{\max} \approx 10\,\mu m$ of the human body falls on the infrared range of electromagnetic waves, which is not perceived by the human eye. The reason for this fact is that a person can see the world around him or her in a rather narrow range of wavelengths of the visible light from λ = 0,40 μm (blue light) to λ = 0,76 (red light). It should be noted that the Earth's atmosphere has a so-called "transparency window" for the wavelength interval $\lambda \approx 8\mu m - 14\mu m$, which also includes the wavelength of thermal infrared radiation of the human body $\lambda_{\max} = 10\ \mu m$. In other words , we can say that electromagnetic radiation of this wavelength is almost not absorbed by atoms and molecules of the Earth's atmosphere. If there was no such window of transparency in atmospheric air, then people could, under certain conditions, "roast" in their own electromagnetic radiation.

In addition to the calculation of the wavelength $\lambda_{\max}$, which characterizes the maximum value of the radiation emmitance of the human body, the use of other laws of thermal radiation (more precisely, the Stefan-Boltzmann law) allows us to estimate the surface power of thermal radiation of the human body. Strictly speaking, the application of the Stefan-Boltzmann law to real bodies is, of course, a fairly significant approximation. The emissivity of real bodies (especially under the condition of their organic nature) should depend on many factors (the geometric shape of the body, the state of its surface, temperature changes, the course of various physiological processes, etc.), which are usually not taken into account in the Stefan-Boltzmann law.

At the same time, taking into account a certain limitation of this approach and considering the surface of the human body as a "gray" body, the following approximate formula can be used to estimate the radiation emmitance of the human body in the environment:

$R = \delta\ (T_{body}^4 - T_{env}^4)$. Here, T_{body} = 305 K is the surface.

temperature of the human body; T_{env} = 293 K is the ambient temperature, which we will consider equal to $t = 20^0 C$

The coefficient δ = ασ (it is also sometimes called the emissivity coefficient) is equal to the product of the Stefan-Boltzmann's constant σ and the monochromatic absorption coefficient α. For the human body, as noted above, the last coefficient has a value of $\alpha_\lambda^{g.b.} \approx$ 0.9 in the infrared part of the electromagnetic spectrum.

As a result of substitution of the given numerical values of the emissivity coefficient = ασ and temperatures T_{body} and T_{inv}, we obtain the following estimate of the surface radiation emmitance (surface power) R of the infrared thermal radiation of the human body: R= 64. 5 W/m^2.

Taking the average value of the entire surface of the human body $S \approx 1.5m^2$, we have the numerical estimate for the power P_{body} of the thermal radiation of the human body in the infrared range of electromagnetic waves: $P_{body} = R \cdot S \approx 100$ Watt. It should be noted that thermal radiation in the infrared spectrum of electromagnetic waves is the more significant source (channel) of the physical fields of the human body.

Experiment studies of thermal radiation of the human body

Experimental studies of the thermal radiation of the human body in the infrared range of electromagnetic waves, revealed interesting and unexpected results, allowing to formulate the following main conclusions (see reference in [1]):

- The temperature of the human body changes periodically, but not in the form of harmonic, but rather relaxation temperature oscillations, the frequency of which coincides with the heart rate. As for the amplitude of these oscillations, it reaches about 0.5^{0}C relative to the average local body temperature (say, about 32^{0}C on the surface or 36.6^{0}C inside the human body).
- After heating a local area of the body (for example, up to 50^{0}C), the temperature in the process of cooling «slips» its initial surface value of 32^{0}C due to the fact that thermal receptors work with a «reserve». In this case, the temperature decreases to about 27°C, and then, with damped oscillations, approaches its average initial value.
- At conjugate points of the body, the same effect of temperature change is also observed with its initial value "slippage" (for example, when a certain point on the left hand is heated, a synchronous temperature change is observed at the conjugated point of the right hand).

In this review article, we reproduced some of the earlier experimental studies of the features of thermal radiation of the human body. In particular, experimental measurements of the process of temperature relaxation (i.e. the process of gradually approaching the temperature to its equilibrium value) of the thermal radiation of the human body at a biologically active point between the thumb and forefinger on the hand were carried out. The time dependence of human skin temperature was obtained using an infrared thermometer (pyrometer) NIMBUS of the "Kharkov-device" company, which had the following technical characteristics: temperature measurement range from -32^{0}C to 420^{0}C, temperature measurement resolution 0.2^{0}C. The initial average temperature of the human skin at the biologically active point on the hand was 31^{0}C. The temperature, to which the local heating of this area of the skin occurred, was 41^{0}C, that is, the temperature amplitude of heating was 10^{0}C.

Figure 1 shows a graph of the time dependence of the temperature relaxation of the thermal radiation of the human body to its thermodynamic equilibrium value of 31^{0}C in the coordinates "temperature T, ^{0}C - time t, minutes". In confirmation of the conclusions made earlier, the temperature has slipped through the initial thermodynamic equilibrium value T=31^{0}C by about 2^{0}C below. The difference in the temperature amplitudes of the damped oscillations is explained by the significantly lower (approximately 2 times) initial heating amplitude.

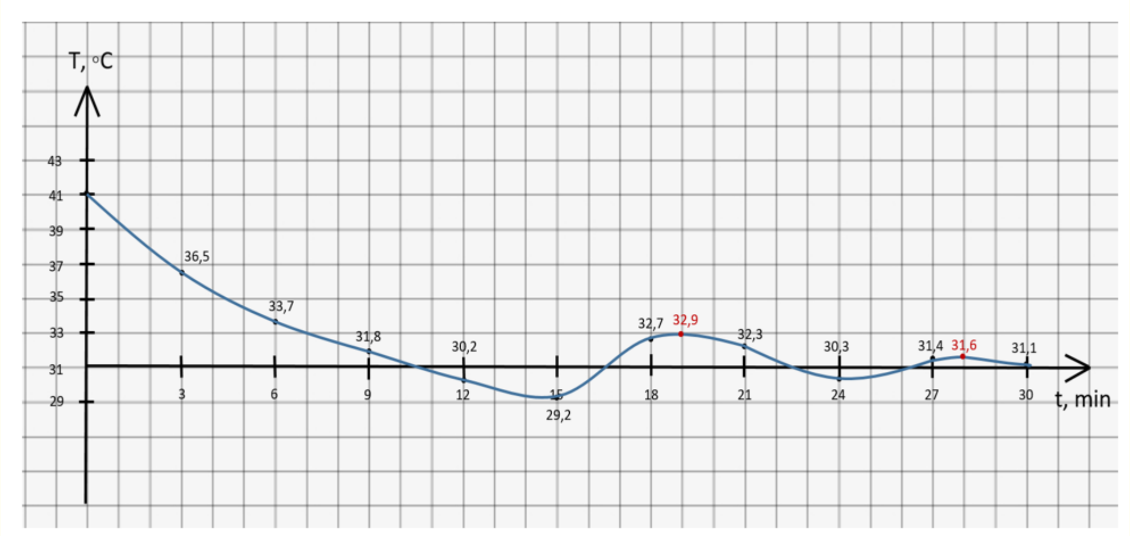

Figure 1: *The time dependence of the temperature relaxation of the human body.*

The obtained experimental data also show that the temperature relaxation of the thermal radiation of the human body in the infrared range of electromagnetic waves does not occur according to an exponential law with a gradual approach of the body temperature from above to the thermodynamically equilibrium and initial temperature $T=31^0C$. Just such an exponential temperature change with time should be expected on the basis of the solution of the differential equation for the heat conduction processes (see, for example, monograph [14]). At the same time, in the biological systems including the human body, there are non-linear feedback connections due, as in this case, to the presence of thermal receptors conjugated with heat conduction processes.

Thus, as a result of such non-linear feedback effects, the process of temperature relaxation is characterized by a gradual approach of temperature to its equilibrium value in the form of free damped temperature oscillations in a certain area of the human body.

Conclusion

In conclusion, it should be emphasized that the use of thermal radiation of the human body as a thermographic diagnostic method has a fundamental advantage over other diagnostic methods such as computer tomography (CT), magnetic resonance imaging (MRI), positron emission tomography (PET), etc. since thermography uses the body's own thermal radiation, and not external radiation, which can cause quite significant dose loads on the organs and tissues of the human body.

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