Effect of luminescence transport through adipose tissue on measurement of tissue temperature by using ZnCdS nanothermometers

Elena K. Volkova,[1,2] Irina Yu. Yanina,[1,2]Elena Sagaydachnaya,[1] Julia G. Konyukhova,[1]

Vyacheslav I. Kochubey,[1,2] Valery V. Tuchin[1,2,3]

[1]Optics and Biophotonics Department, Saratov State University (National Research University), 83 Astrakhanskaya Str., Saratov, 410012, Russia
[2]Interdisciplinary Laboratory of Biophotonics, Tomsk State University (National Research University), 36 Lenin Avenue, Tomsk, 634050, Russia
[3]Laboratory of Laser Diagnostics of Technical and Living Systems, Institute of Precise Mechanics and Control of the Russian Academy of Sciences, 24 Rabochaya Str., Saratov, 410028, Russia

Abstract

The spectra of luminescence of ZnCdS nanoparticles (ZnCdS NPs) were measured and analyzed in a wide temperature range: from room to human body and further to a hyperthermic temperature resulting in tissue morphology change. The results show that the signal of luminescence of ZnCdS NPs placed within the tissue is reasonably good sensitive to temperature change and accompanied by phase transitions of lipid structures of adipose tissue. It is shown that the presence of a phase transition in adipose tissue upon its heating (polymorphic transformations of lipids) leads to a nonmonotonic temperature dependence of the intensity of luminescence for the nanoparticles introduced into adipose tissue. This is due to a change in the light scattering by the tissue. The light scattering of adipose tissue greatly distorts the results of temperature measurements. The application of these nanoparticles is possible for temperature measurements in very thin or weakly scattering samples.

Keyword list: nanoparticles, ZnCdS, adipose tissue, nanothermometer, spectroscopy

*e-mail: volkovae87@gmail.com

1. INTRODUCTION

One of the fields of application of nanoparticles is their use as thermometers for accurate non-contact temperature determination with micron spatial resolution in real time. Precise non-contact temperature measurement at the micro level in real time is an important objective for many practical applications, including for biology and medicine. The temperature is determined by the temperature-dependent change in the luminescent characteristics of the nanoparticles. The change in the intensity of luminescence due to temperature quenching [1,2,3] and the shift of the spectral band can be used as such characteristics. This is due to the fact that for a number of nanoparticles the position and magnitude of a spectral peak of fluorescence depend on the ambient temperature. [4,5]

The use of semiconductor nanoparticles as nanothermometers today is not a new phenomenon. Semiconductor particles are stable in aqueous medium and retain their luminescent properties for a long time that is necessary for biological applications.

Dynamics and Fluctuations in Biomedical Photonics XV, edited by Valery V. Tuchin, Kirill V. Larin, Martin J. Leahy, Ruikang K. Wang, Proc. of SPIE Vol. 10493, 104931K · © 2018 SPIE
CCC code: 1605-7422/18/$18 · doi: 10.1117/12.2295620

Modern fluorescent nanothermometers allow accurately (up to tenths of a degree) to measure the local temperature in a thin layer of a biological object. [6] However, measurement of the thermal radiation of a biological object at the depth of a tissue is difficult. [7]

When luminescent nanoparticles are used for biological problems, it is necessary to take into account the fact that the interaction of radiation with a biological medium affects the result obtained. The recorded spectra of excitation, luminescence, and absorption of nanoparticles will be distorted due to the effects of multiple scattering and reabsorption of radiation in biological tissues. The absorption of the luminescence inside the sample depends both on the absorption coefficient and on the degree of scattering of the luminescence at given wavelength. These processes depend on wavelength, so the degree of radiation attenuation is different within a sufficiently wide spectral region, both for luminescence and for its excitation. Therefore, to obtain real information about the nanoparticle properties, it is necessary to correct the recorded spectra, taking into account the processes of light scattering and reabsorption.

An additional problem with the use of luminescent nanoparticles for biological tasks is the fact that the interaction of the surface of particles with the environment affects their optical characteristics. In this case, both the intensity and the position of the bands of luminescence can vary, which may affect the accuracy of the determination of temperature by means of nanoparticles.

To obtain real luminescence spectra and excitation of nanoparticles, it is of interest to develop a method for correcting the experimentally obtained spectra of samples to eliminate distortions introduced by the absorption of luminescence in the sample. [8,9] It is necessary to take into account the geometry of the experiment. Such correction methods can be used to obtain luminescence spectra of internal regions of scattering biological media. However, the available correction software, for example, IAD program used for obtaining the spectral dependence of the absorption and scattering coefficients, is absent. This forces us to create our own algorithm and software implementation of correction of spectra of luminescence and excitation.

The goal of the work is to study the behavior of the spectra of luminescence of nanoparticles both outside the biological medium and placed in it, with a change in temperature.

2. EXPERIMENTAL PROCEDURES

To determine the local temperature of biological tissue, the in-house synthesized heat-sensitive ZnCdS semiconductor nanoparticles (ZnCdS NPs) with an average size ~36 nm were used. The synthesis procedure and characteristics of these nanoparticles are described in articles. [10,11] To prevent aggregation and to evenly heat the particles, the ZnCdS NPs were placed into a film made on the basis of cellulose acetate (film thickness is 12 μm). As a biological object, thin (0.24 ± 0.6 mm) and thick (0.55 ± 0.6 mm) sections of human abdominal adipose tissue *in vitro*, obtained from frozen samples, were used.

The experimental setup is designed for the measurement of thermal fields of biological objects, shown in Figure 1.

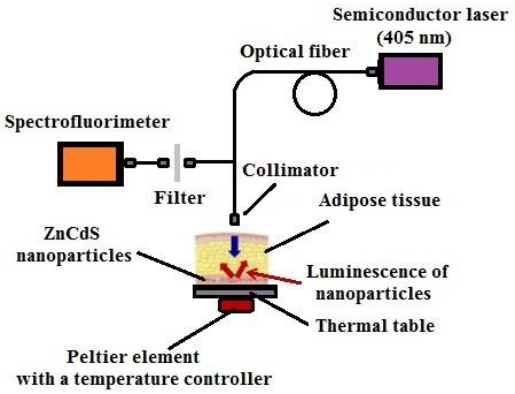


Figure 1. Scheme of the experimental setup used for the measurement of thermal fields of biological objects.

For non-contact measurement of the temperature of the upper surface of the samples, an IR thermal imager was used, and the temperature of the lower surface was controlled using a Peltier element with a control unit. The luminescence of the particles was excited by the emission of a semiconductor laser with wavelength 405 nm and a power of 300 mW (laser pointer Pen Style (HangZhou NaKu Technology Co., China)). The spectra of luminescence were recorded with a spectrometer (QE6500, OceanOptics, USA). To suppress the scattered laser radiation with wavelength 405 nm, a longwave LVF-H filter (OceanOptics, USA) was used, which was fixed between the receiving fiber and the sample. During the heating of the tissue, the semiconductor nanoparticles were periodically excited by laser radiation. The spectra of luminescence were measured with a 200-ms acquisition time. The excitation frequency is necessary to exclude the heating of the sample by exciting radiation.

The element temperature determined by a thermocouple varied from 25 °C to 70 °C and held at a predetermined temperature for 5 min. In the experiments, the placement of nanoparticles in the region of the near-surface tumor, i.e., inside a biological tissue, was simulated. ZnCdS NPs were deposited on the surface of adipose tissue, and then, to reconstruct the conditions for recording the signal from the depth of the tissue, a sample with deposited nanoparticles was covered with a similar layer.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 shows the spectra of luminescence of ZnCdS NPs at different temperatures.

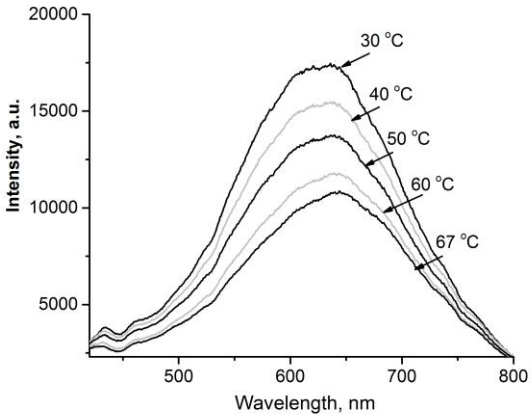
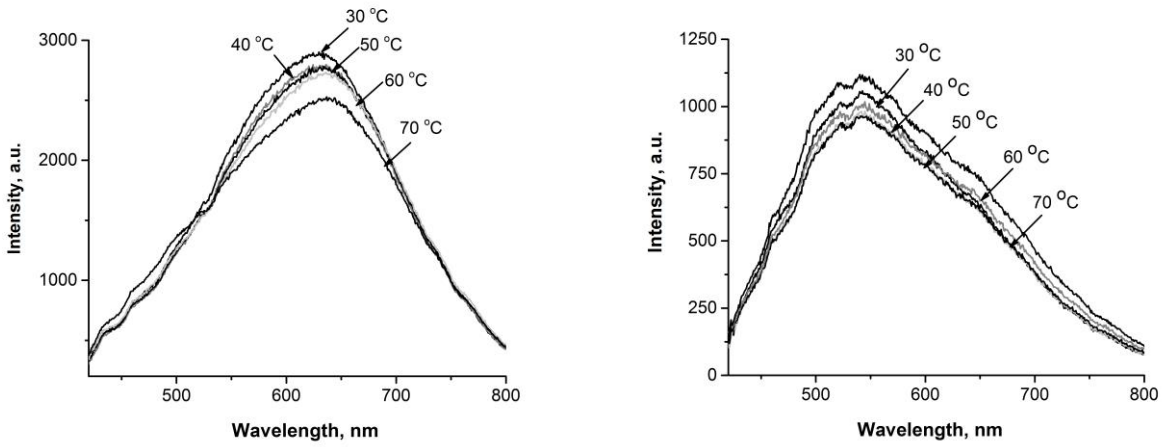


Figure 2. Spectra of luminescence of ZnCdS NPs at different temperatures.

As illustrated in Figure 2, when the temperature was raised, quenching of the ZnCdS NP luminescence was observed. The change is due to the distortion of the energy states of luminescent surface defects.

The temperature dependence of the intensity of luminescence of nanoparticles decreases linearly with increasing temperature in our experiments. [12]

Figure 3 a,b shows the spectra of luminescence of ZnCdS NPs placed into adipose tissue (thin layer (a) and thick layer (b)), at different temperatures. The normalized spectra of luminescence of ZnCdS NPs without adipose tissue and placed into adipose tissue (thin and thick layers), at a temperature of 30 °C, are shown in Fig. 4.



a) b)

Figure 3. Spectra of luminescence of ZnCdS NPs placed into adipose tissue (thin layer (a) and thick layer (b)), at different temperatures (excitation wavelength λ = 405 nm).

From Figure 3 it follows that when particles are placed into adipose tissue, the intensity of luminescence of ZnCdS NPs decreases due to the absorption of both the exciting radiation and luminescence in the adipose tissue. In addition, the luminescence of adipose tissue is observed, which leads to a shift in the peak position of the recorded spectrum (Figure 3, 4).

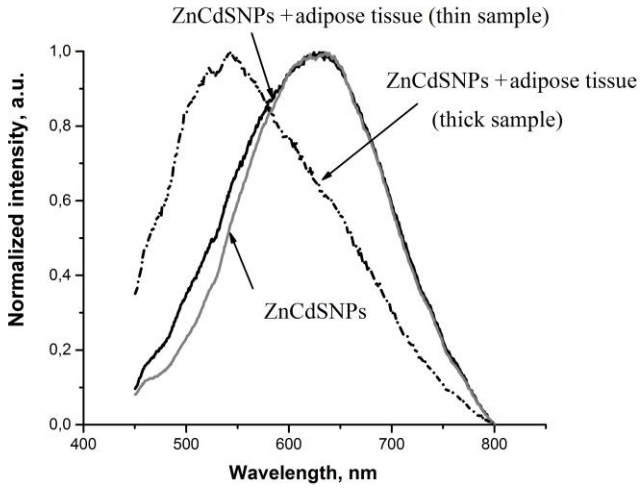


Figure 4. Normalized spectra of luminescence of ZnCdS NPs without adipose tissue and placed into adipose tissue (thin and thick layers), at a temperature of 30 °C (excitation wavelength λ = 405 nm).

Figure 5 shows the temperature dependences of the intensities of luminescence of ZnCdS NPs at wavelength 630 nm for nanoparticles without adipose tissue and placed into adipose tissue. As illustrated in Figure 5, for ZnCdS NPs this dependence is linear, the value of the slope coefficient B = -180.4 (A = 22642.04). For particles in adipose tissue, linearity is impaired due to a change in the optical properties of adipose tissue and the appearance of fat luminescence.

As the temperature in the adipose tissue increases, phase transformations (lipid transformations) occur, which leads to a decrease in light scattering in the tissue and, consequently, to a decrease in its absorption. The low-temperature phase transitions (22-35 ºC) could be associated with the fusible free fatty acid (FFA) of the fat droplet like oleic acid; the middle-temperature (40-44 ºC) – with cell membrane phospholipids, and the high-temperature (45-55 ºC) – with less fusible FFT of the fat droplet like palmitic acid. [13] For a thin layer, this effect leads to an increase in the intensity of the detected luminescence, starting at a temperature of 30-35ºC, despite the decrease in the emissivity of nanoparticles due to thermal quenching. After reaching a high-temperature phase transition, thermal quenching leads to a sharp decrease in the recorded intensity of luminescence. For a thick sample, the optical clearing occurs at a higher temperature (45 ºC), but it is clear that this effect is predominant, and as a result, the recorded intensity increases sharply with increasing temperature.

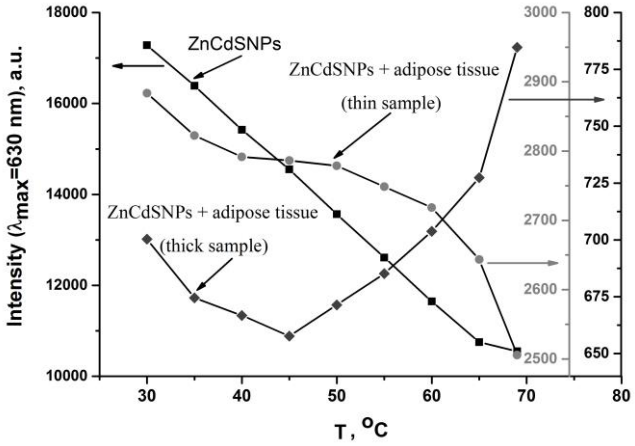


Figure 5. Temperature dependence of intensities of luminescence of ZnCdS NPs at wavelength 630 nm for nanoparticles without adipose tissue and placed into adipose tissue (excitation wavelength λ = 405 nm).

In the collimated-radiation approximation, which is permissible for a thin layer, the degree of attenuation of the detected luminescence can be obtained from the ratio P of the intensities luminescence of of ZnCdS NPs for experiments with adipose tissue (I_f) and without it (I_{np}): $P= I_f/I_{np}$. Such intensity ratio at wavelength 630 nm is shown in Figure 6. The obtained dependences characterize the radiation attenuation and, consequently, the change of the optical characteristics of the sample with increasing temperature.

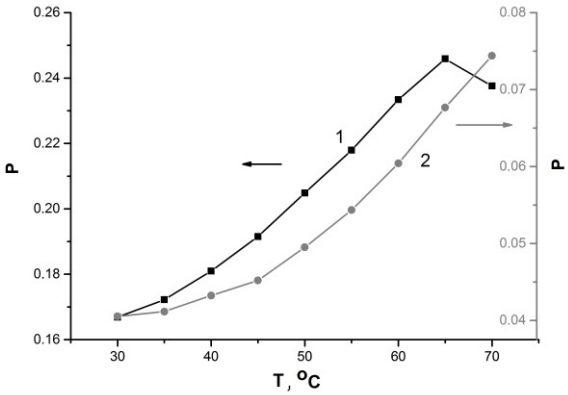


Figure 6. Temperature dependence of P for: (1) – thin layer, (2) - thick layer of the adipose tissue (excitation wavelength λ = 405 nm).

It should be noted that the dependences in Figure 5 for the particles and the thin sample have the same slope at low temperatures, at which the change in optical properties is small. It can be concluded that, if the optical characteristics are constant, it is possible to determine the relative change in the temperature of the sample from the change in the luminescence of the ZnCdS NPs. Their use is also possible for very thin samples, for example, inside cells or in non-absorbing light bio-samples.

Figure 7 shows the temperature dependence of the peak position of the band of luminescence of the nanoparticles. The peak position of the band of luminescence of the particles was determined from the first derivatives of the spectra.

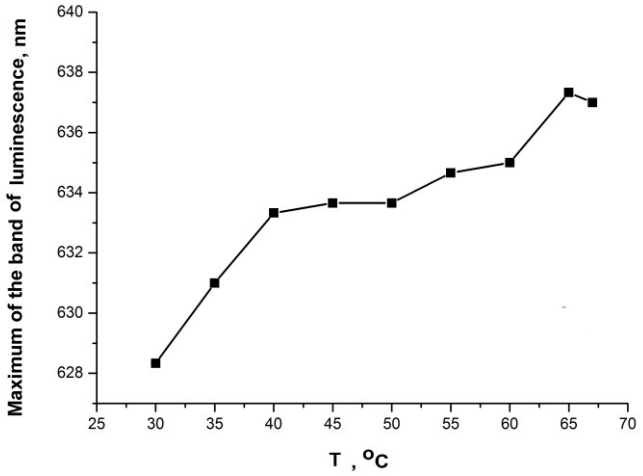


Figure 7. Temperature dependence of the peak position of the band of luminescence of the nanoparticles.

The temperature determination from the peak position of the band of luminescence is difficult because of the presence of additional luminescence of the tissue and distortion of the spectra. It follows from Figure 7 that the dependence in the region of phase transitions is nonmonotonic. At the same time, this means that it is possible to determine the presence of phase transitions in adipose tissue from the behavior of the intensity of the detected luminescence and the peak position of the spectral band.

4. CONCLUSIONS

The spectra of luminescence of ZnCdS NPs nanoparticles (ZnCdS NPs) were measured and analyzed in a wide temperature range: from room to human body and further to a hyperthermic temperature resulting in tissue morphology change. The results show that the signal of luminescence of ZnCdS NPs placed within the tissues is reasonably good sensitive to temperature change and accompanied by phase transitions of lipid structures of adipose tissue. We have shown that the phase transformations (lipid transformations) occurring in the fat tissue with increasing temperature lead to a deviation from the linear temperature dependence of the luminescence intensity of the particles introduced into the tissue. This is due to a change in the light scattering by the tissue. Therefore, determination of the relative changes in the temperature of a biological sample from the intensity of luminescence of ZnCdS NPs is possible only if the optical characteristics of the biological tissue are constant, i.e., in the absence of phase transitions and coagulation. It is shown that the determination of the temperature from the position of the band maximum of luminescence of nanoparticles is hampered by distortion of the spectra of luminescence of nanoparticles due to absorption in the biotissue and intrinsic luminescence of the biological tissue. The application of these nanoparticles is possible for very thin samples, for example, inside cells or in non-absorbing bio-samples.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support from Russian Federation President Grant for state support of young Russian scientists № MK-6009.2016.2 (IYuY and EKV), The National Research Tomsk State University Academic D.I. Mendeleev Fund Program (IYuY, EKV, VIK, and VVT).

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