Effects of scattering particles concentration on light propagation through turbid media

Alexey N. Bashkatov , Elina A. Genina, Vyacheslav I. Kochubey, Valery V. Tuchin

Saratov State University, Astrakhanskaya 83, Saratov 410026, Russia

ABSTRACT

Experimental study and computer simulation of light propagation in turbid media with different concentration of scattering particles are described. Gel phantoms with adding of Intralipid-20% as a model of living tissue have been investigated. Experimental results have shown existing of transmittance and reflectance saturation in dependence on volume fraction of the scatterers. The inverse adding-doubling method and Reyleigh-Gans approximation of the Mie theory were applied to describe the light propagation. The explanation of the experimental results is presented.

Keywords: phantoms, turbid media, scattering spectroscopy, inverse adding-doubling method, concentration effects

1. INTRODUCTION

One of the problem in clinical laser therapy is the prediction of light distribution in tissue. Wavelength range from 400 to 700 nm has a special significance because of its therapeutic applications. However, light propagation in tissue is complicated by the inhomogeneous and variable character of tissue. In addition, *in vitro* samples are expected to have different optical properties from *in vivo* samples. Nowadays, phantoms are widely used for study of light propagation in tissues.[1-12] Real tissues are usually densely packed systems of scatterers, therefore concentration effects should be accounted for.[3,13-22] In this paper we present the results of experimental study and computer simulation of effects of scattering particles concentration on light propagation through turbid media.

2. MATERIALS AND METHODS

In this study we used a commercially available computer-driven CARY-2415 spectrophotometer with integrating sphere to make total transmittance, and diffuse reflectance measurements in the 400-700 nm wavelength range for various turbid media (phantoms) which model living tissues. For each phantom diffuse reflectance R_d and total transmittance T_d were measured. The diffuse reflectance were calibrated on the basis of reflectance from standard reflectance plate (BaF_2).

We used transparent gel, prepared from 10% aqueous solution of food gelatin, as a ground of the phantoms. Structure of gelatin gel was described in Ref. 23 and presented in Fig. 1. Gel was made turbid by adding of various quantity of Intralipid-20% suspension.[1-3,6,8,9,12] Concentrations of Intralipid-20% within samples were 0, 5, 10, 15, 20, 25, 30, 35, and 40% (vol/vol). The samples were prepared as tablets with diameter 25 mm and height 4 mm. The samples were placed on thin glass plates with thickness of 0.17 mm.

Since we used the food gelatin, which has its own strong absorption band in visible spectral range, we measured absorption coefficient of gelatin gel. The spectrum of measured absorption coefficient is presented in Fig. 2. Mie theory provides an exact computation of the scattering coefficient and the anisotropy factor of perfect spheres of arbitrary size.[24,25] To use Mie theory we considered the gelatin particles as spherical particles of the same volume. Scattering coefficient and anisotropy factor of the gelatin were calculated using Mie theory algorithm,[24] as a result there was shown that the scattering of gelatin can be neglected, so, only absorption of gelatin should be accounted for.

Optical properties of the Intralipid suspension can be found is Refs. 9, 12, the anisotropy factor is described by the formula.

Address all correspondence to Alexey N. Bashkatov. Tel: 8452 514693; E-mail: bash@softhome.net

In *Optical Biopsy III*, Robert R. Alfano, Editor,
Proceedings of SPIE Vol. 3917 (2000) • 1605-7422/00/$15.00

$$g = 1.1 - 5.8 \cdot 10^{-4} \cdot \lambda[nm] \tag{1}$$

Refractive indices of the samples were estimated using the law of Gladstone and Dale

$$n = n_g \eta_g + n_s \eta_s \tag{2}$$

where n_g, n_s, and η_g, η_s are the refractive indices and volume fractions of the ground substance (gelatin matrix and water) and substance which was used as a scatterers (Intralipid-20%), respectively. Refractive indices of the gelatin matrix and Intralipid-20% were found experimentally using Abbe refractometer as n= 1.3525 and 1.335, respectively.

The refractive indices for various wavelengths of water were calculated using dispersion formula from Ref. 26:

$$n_{H_2O} = 1.31848 + \frac{6.662}{\lambda[nm] - 129.2} \tag{3}$$

It is well known that the scatterers of Intralipid suspension are soybean oil particles, which wavelength dependent refractive index can be calculated using [12]

$$n_{soybean} = 1.451 + \frac{1.154 \cdot 10^4}{(\lambda[nm])^2} - \frac{1.132 \cdot 10^9}{(\lambda[nm])^4} \tag{4}$$

The refractive index of the gelatin particles was determined in Ref. 27 as $n_{gp} = 1.533$.

We used the inverse adding-doubling method that was developed by *Prahl et al.*[28] to calculate the absorption and scattering coefficients of turbid media (phantoms) from measured values of total transmittance and diffuse reflectance. To obtain optical properties of the investigated phantoms we used a computer program of *S.A. Prahl* (Oregon Medical Laser Center, USA; www.omlc.ogi.edu).

To compare optical properties calculated using inverse adding-doubling method and Reyleigh-Gans approximation of the Mie theory, we determined the reduced scattering coefficient using the formula taken from Ref. 3.

$$\sigma_s' = \frac{9}{256 \cdot \pi}\left(\frac{m^2-1}{m^2+2}\right)^2 \cdot \left(\frac{\lambda}{n_{ex}}\right)^2 \cdot \int_0^{\pi} (\sin u - u\cos u)^2 \frac{(1+\cos^2\theta)\sin\theta\,(1-\cos\theta)}{\sin^6\left(\frac{\theta}{2}\right)} d\theta \tag{5}$$

where $\sigma_s' = \sigma_s(1-g)$, $u = 2\frac{2\pi a n_{ex}}{\lambda}\sin\left(\frac{\theta}{2}\right)$, σ_s is the scattering cross section, g is the average cosine of the scattering angle, a is the radius of the scattering particle, λ is wavelength of the scattered light in vacuum, $m = \frac{n_{in}}{n_{ex}}$ is the refractive index of the scatterers relative to the surrounding medium, and n_{in} and n_{ex} are refractive indices of the scattered particle and surrounding medium, respectively. Anisotropy factor g we calculated using Eq. 1.

In a multiple-scattering medium, the reduced scattering coefficient, μ_s', is related to σ_s' by[14, 15, 20, 22]

$$\mu_s' = N\sigma_s' \frac{(1-\eta)^4}{(1+2\cdot\eta)^2} \tag{6}$$

where σ_s' is given by Eq. 5, *N* is the total number of scattering particles per unit volume, i.e., the number density. *N* can be given as η/v_{par}, where η is the volume fraction of the particles relative to the total volume, and v_{par} is $(4/3)\pi a^3$. To account for the packing factor (Eq. 6) we should evaluate the volume fraction of the scatterers (soybean oil particles). For that the volume fraction of Intralipid (which was added to gelatin gel) was multiplied by 0.239. This coefficient accounts for real concentration of oil particles in Intralipid solution.[12]

3. RESULTS AND DISCUSSION

Figures 3-6 show the experimental results of optical properties of the investigated samples (phantoms) with various concentrations of the scatterers. Figure 3 presents the diffuse reflectance spectra of the gelatin phantoms with adding of various volume fractions of Intralipid-20% suspension. Figure 4 presents the total transmittance spectra of the gelatin phantoms with adding of various volume fractions of Intralipid-20% suspension. Figure 5 presents the Intralipid concentration dependence on the diffuse reflectance at three wavelengths. In this figure we see that diffuse reflectance has a slight saturation which depends on concentration (expressed in volume fraction) of the Intralipid suspension. Figure 6 shows concentration dependence of the optical density of the gelatin phantoms with adding of various volume fractions of Intralipid suspension. We define the optical density as $D = -\log(T_d)$. We see that the optical density saturates as concentration of Intralipid goes up. As was shown above the absorption properties of phantoms are defined by gelatin gel and scattering properties by Intralipid suspension. We assume that saturation of optical density and diffuse reflectance are connected with changes of scattering properties of phantoms. Using inverse adding-doubling method the scattering coefficients of phantoms were obtain. Anisotropy factor of the scatterers was calculated using Eq. 1. To obtain refractive indices of phantoms Eqs. 2-4 and data taken from Ref. 27 were used. Results of our calculations are presented in Figs. 7 and 8. Figure 7 shows that the scattering coefficients of the phantoms decrease with increasing of the wavelength. With increasing of Intralipid concentration the increasing of the scattering coefficients is observed. Figure 8 shows that determined scattering coefficient dependencies on concentration are saturated at high concentrations, which well correlate with saturation of measured optical density and diffuse reflectance which.

To compare data obtained using inverse adding-doubling method and Reyleigh-Gans approximation of the Mie theory, we used Eqs. 5, 6. Refractive index of the scatterers was calculated using Eq. 4. Refractive index of surrounding medium was estimated using Eqs. 2, 3 and data from Ref. 27. Anisotropy factor was calculated using Eq. 1. Different references present different values of scatterers radius of Intralipid suspension. For example, in Ref. 3 scatterers radius is about 250 nm, in Refs. 2, 12 it is 46.5 nm. Due to well fit to our experimental data we use value of scatterers radius equal to 34 nm.

The final result of our calculations is presented in Fig. 8. In general, a good fit of data obtained using inverse adding-doubling method and Reyleigh-Gans approximation (scatterers radius 34 nm) is received.

4. CONCLUSION

This paper discusses some aspects of tissue-like phantoms optical properties, especially phantoms with a high concentration of scatterers which corresponds to real tissues. Experimental study and computer simulation of light propagation in gelatin gel phantoms with adding of Intralipid-20% at high concentrations up to 40 % have been investigated. The saturation of transmittance and reflectance of phantoms in dependence on volume fraction of the scatterers was revealed. The inverse adding-doubling method and Reyleigh-Gans approximation of the Mie theory were applied to describe the light propagation.

It should be noted that transmission and reflectance spectra of the studied phantoms with a high concentration of scatterers are well correlate with corresponding spectra of real tissues, like the human eye sclera.[26]

5. ACKNOWLEDGMENTS

The research described in this publication was made possible in part by grant "Leading Scientific Schools" #96-15-96389 of the Russian Basic Research Foundation

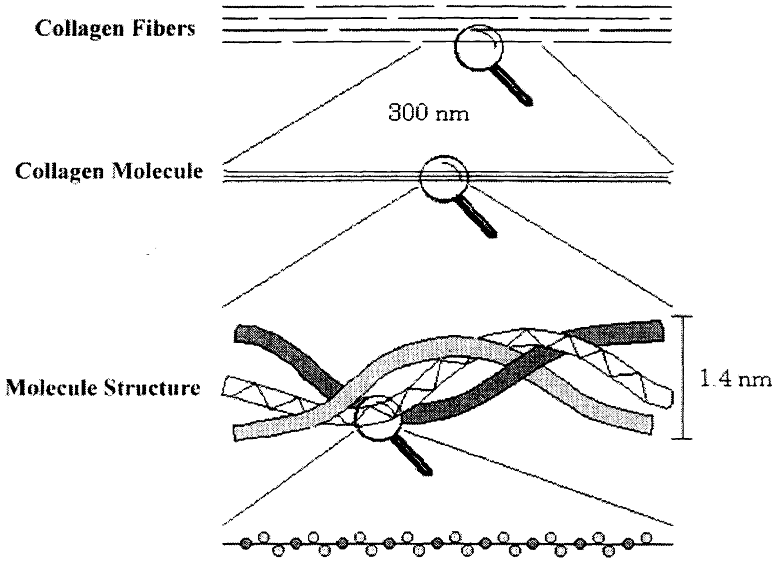

Figure 1. Structure of the gelatin particles

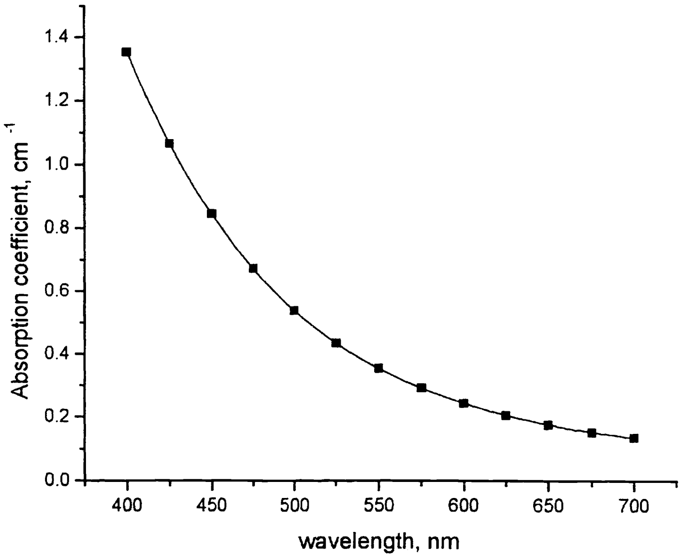

Figure 2. Absorption coefficient of the food gelatin gel.

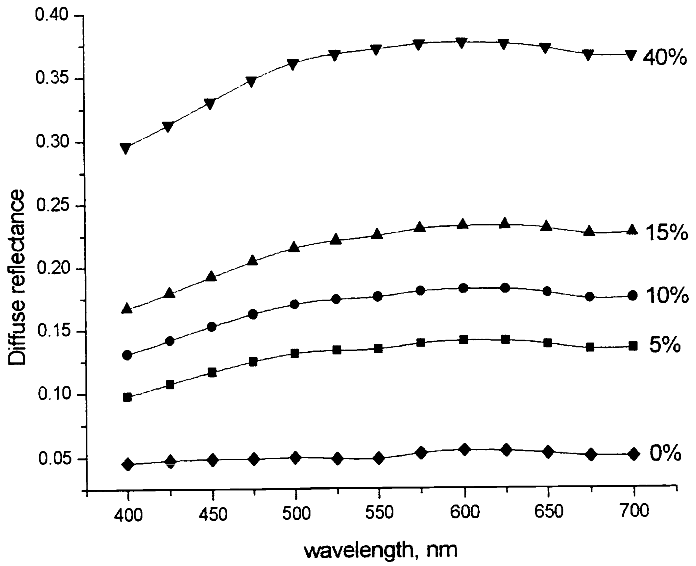

Figure 3. Diffuse reflectance spectra of the gelatin phantoms with adding of various volume fractions of 20%-Intralipid.

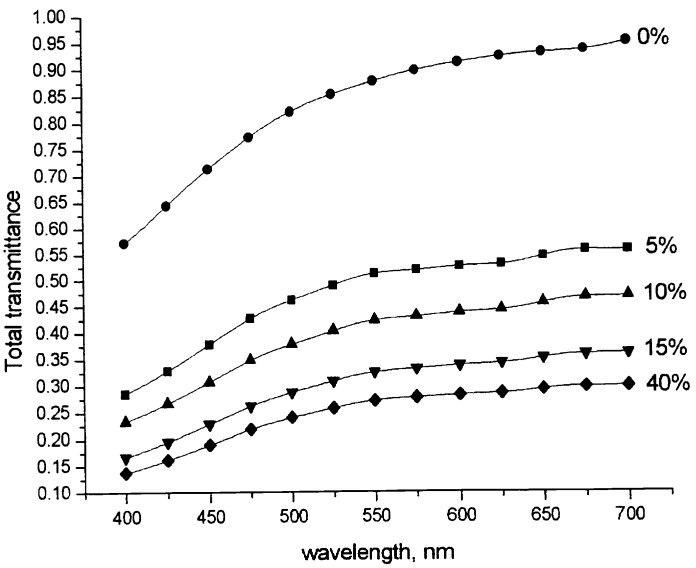

Figure 4. Total transmittance spectra of the gelatin phantoms with adding of various volume fractions of 20%-Intralipid.

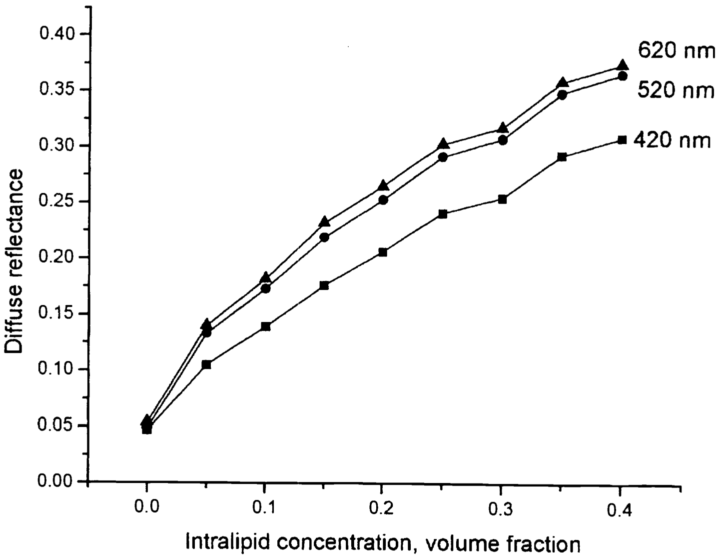

Figure 5. The diffuse reflectance of the gelatin phantoms with adding of various volume fractions of 20%-Intralipid.

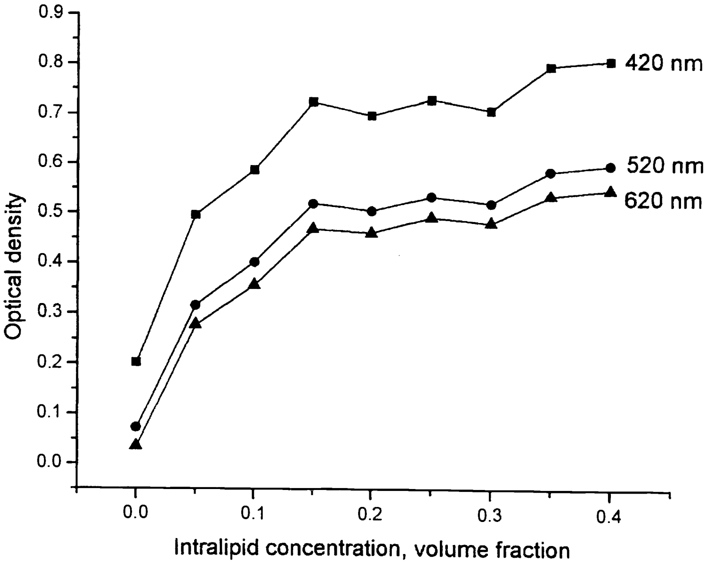

Figure 6. The optical density of the gelatin phantoms with adding of various volume fractions of 20%-Intralipid.

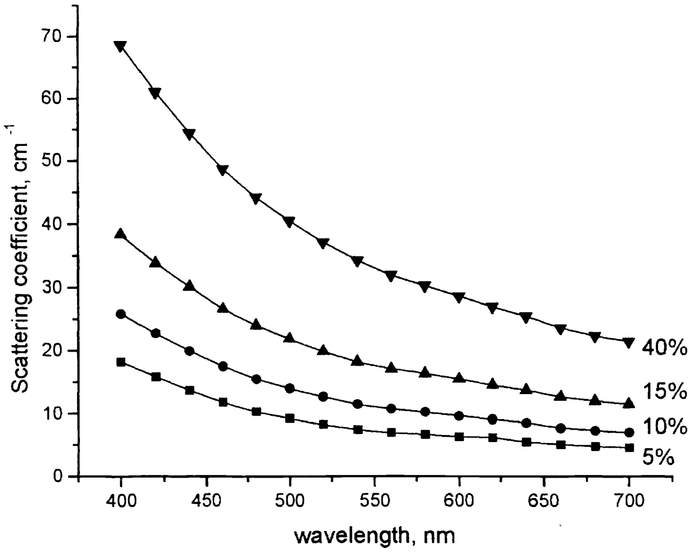

Figure 7. The scattering coefficient of the gelatin phantoms with adding of various volume fractions of 20%-Intralipid versus wavelength.

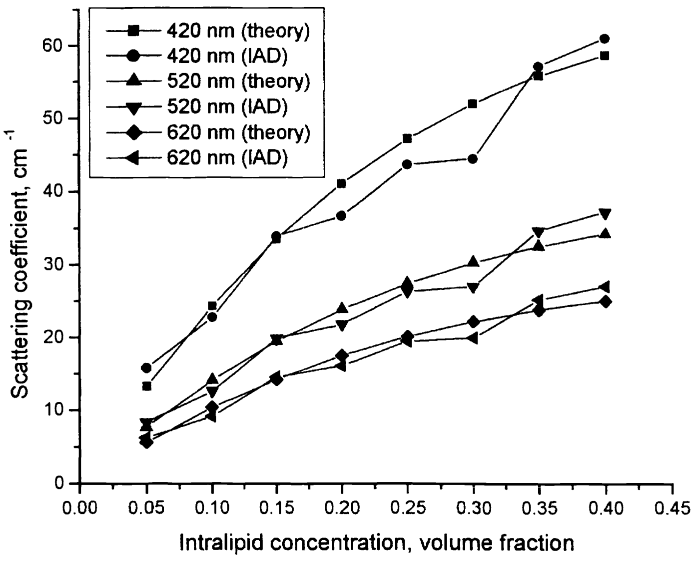

Figure 8. Dependencies of the scattering coefficient of the gelatin phantoms on Intralipid concentration calculated using inverse adding-doubling (IAD) method and Reyleigh-Gans approximation of the Mie theory (theory) at three wavelengths.

REFERENCES

1. C.J.M. Moes, M.J.C. van Gemert, W.M. Star, J.P.A. Marijnissen, S.A. Prahl, "Measurements and calculations of the energy fluence rate in a scattering and absorbing phantom at 633 nm," *Appl. Opt.* **28**(12), pp. 2292-2296, 1989.
2. J.R. Mourant, T. Fuselier, J. Boyer, T.M. Johnson, I.J. Bigio, "Predictions and measurements of scattering and absorption over broad wavelength ranges in tissue phantoms," *Appl. Opt.* **36**(4), pp. 949-957, 1997.
3. H. Liu, B. Beauvoit, M. Kimura, B. Chance, "Dependence of tissue optical properties on solute-induced changes in refractive index and osmolarity," *J. Biomed. Opt.* **1**(2), pp. 200-211, 1996.
4. L.P. Danilova, S.P. Chernova, A.B. Pravdin, "Tissue-like phantoms: fluorescence under 405 nm excitation," *Proc.* SPIE. **3726**, pp. 410-414, 1998.
5. K.E. Denisov, S.P. Chernova, A.B. Pravdin, "Fluorescence spectra of multilayered phantom of biotissue: Optimization of data collection," *Proc.* SPIE. **3726**, pp. 163-166, 1998.
6. M. Kohl, M. Esseupreis, M. Cope, "The influence of glucose concentration upon the transport of light in tissue-simulating phantoms," *Phys. Med. Biol.* **40**, pp. 1267-1287, 1995.
7. J.M. Schmitt, G. Kumar, "Spectral distortions in near-infrared spectroscopy of turbid materials," *Applied Spectroscopy* **50**(8), pp. 1066-1073, 1996.
8. D.D. Royston, R.S. Poston, S.A. Prahl, "Optical properties of scattering and absorbing materials used in the development of optical phantoms at 1064 nm," *J. Biomed. Opt.* **1**(1), pp. 110-116, 1996.
9. S.T. Flock, S.L. Jacques, B.C. Wilson, W.M. Star, M.J.C. van Gemert, "Optical properties of Intralipid: a phantom medium for light propagation studies," *Laser in Surgery and Medicine*, **12**, pp. 510-519, 1992.
10. A.A. Oraevsky, S.L. Jacques, F.K. Tittel, "Measurement of tissue optical properties by time-resolved detection of laser-induced transient stress," *Appl. Opt.*, **39**(1), pp. 402-415, 1997.
11. A.A. Oraevsky, R.O. Esenaliev, S.L. Jacques, F.K. Tittel, "Laser opto-acoustic tomography for medical diagnostics: principles," *Proc.* SPIE, **2676**, pp. 22-31, 1996.
12. H.J. van Staveren, C.J.M. Moes, J. van Marle, S.A. Prahl, M.J.C. van Gemert, "Light scattering in Intralipid-10% in the wavelength range of 400-1100 nm," *Appl. Opt.* **30**(31), pp. 4507-4514, 1991.
13. A.N. Bashkatov, E.A. Genina, Yu.P. Sinichkin, N.A. Lakodina, V.I. Kochubey, V.V. Tuchin, "Estimation of glucose diffusion coefficient in scleral tissue," *Proc.* SPIE **4001**, 1999.
14. A.P. Ivanov, V.A. Lojko, and V.P. Dik, *Light Transportation in Densely Packed Dispersive Media*, Nauka i Technika, Minsk, 1988.
15. J.M. Schmitt, G. Kumar, "Optical scattering properties of soft tissue: a discrete particle model," *Appl. Opt.* **37**(13), pp. 2788-2797, 1998.
16. E.K. Chan, B. Sorg, D. Protsenko, M. O'Neil, M. Motamedi., A.J. Welch, "Effects of compression on soft tissue optical properties," *IEEE Journal of selected topics in quantum electronics* **2**(4), pp. 943-950, 1996.
17. A.Ya. Khairullina, "About mechanism of coherent and diffuse transmittion monolayer of particles with different densities packing and optical properties," *Opt. and Spectr.* **53**(6), pp. 1043-1048, 1982.
18. A.N. Ponyavina, V.G. Vereshchagin, "Concentration effects during coherent scattering by big size particles with density packing," *J. Appl. Spectr.* **XL**(2), pp. 302-308, 1984.
19. A.N. Ponyavina, N.I. Silvanovich, A.A. Shevchenko, "About cooperating effects during radiation reflection from density packing scattering media," *J. Appl. Spectr.* **51**(4), pp. 670-675, 1989.
20. Ya.I. Granovsky, M. Ston, "Attenuation factor during light scattering by transparent particles," *J. Experimental and Theoretical Physics* **105**(5), pp. 1199-1207, 1994.
21. G.S. Dubova, A.Ya. Khairullina, "Diffuse transmittion and reflection of thick low absorbing layer with close particles packing," *J. Appl. Spectr.* **37**(5), pp. 832-836, 1982.
22. A.P. Ivanov, S.A. Makarevich, A.Ya. Khairullina, " Radiation propagation in tissues and liquids with close particle packing," *J. Appl. Spectr.* **47**(4), pp. 662-668, 1987.
23. S. Lipgens, *Sol-Gel Transition in Water-in-Oil Microemulsions. Investigation on the Dynamics of Gelatin-Containing Systems*, Ph.D. Thesis, Cologne, 1997.
24. C.F. Bohren and D.R. Huffman, *Absorption and Scattering of Light by Small Particles*, Willey, New York, 1983.
25. H.C. van de Hulst, *Light scattering by Small Particles*, Dover, New York, 1981.
26. V.V. Tuchin, I.L. Maksimova, D.A. Zimnyakov, I.L. Kon, A.H. Mavlutov, A.A. Mishin, "Light propagation in tissues with controlled optical properties," *J. Biomed. Opt.* **2**(4), pp. 401-417, 1997.
27. A. Seeboth, H. Hermel, "Gelatin films with embedded liquid crystals in the conoscopic ray," *Thin solid films*, **173**, pp. L119-L129, 1989.
28. S.A. Prahl, M.J.C. van Gemert, A.J. Welch, "Determining the optical properties of turbid media by using the adding-doubling method," *Appl. Opt.* **32**, pp. 559-568, 1993.