Multiply Scattered Light Fields in Tooth Tissue

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***Abstract*—Optical characteristics of three tissue layers, namely of enamel, dentin, and pulp, are compiled over the wavelength range from the visible to the near infrared on the base of available publications and own calculations. These characteristics were used to analytically simulate the diffuse reflectance of multi-layered tooth tissue (usually measured by an integrating sphere) and the distributions of the fluence rate over tooth depth. The light penetration depth is computed to be on the order of 2 mm. The obtained results can be useful to design various optical methods to noninvasively diagnose tooth conditions.**

***Index Terms*—Light, scattering, absorption, tooth tissue, enamel, dentin, pulp.**

I. Introduction

To diagnose a biological tissue, noninvasive methods is of a special interest, becaise they enable one to study the conditions of normal and pathological tissues by a nondestructine means. One of such methods is optical one, and tissie is a tooth. For the latter, the noninvasine instrunebtal diagnostics is very important from the viewpoint, at least, of everyday practice, if one recalls the fear, which one has going to a dentist. A first step for designing optical diagnistic means is the investigation of multiply scattered light fields inside and outside a tooth. This is just the objective of this work.

II. Optical Properties of Tooth Tissue Layers

The tissue is assumed to be a three-layered medium composing of enamel (top layer), dentin (intermediate layer), and dental pulp (bottom layer). All these layers are highly turbid, so one can represent them as uniform infinite slabs in the direction perpendicular to the light incidence one. We will use this assumption in further simulations. One requires to know or to specify optical and geometrical characteristics of the multi-layered medium to describe light fields inside the tissue and backscattered by it. Unfortunately, there are no so much published data on scattering and absorption coefficients, μ_s and μ_a, and on phase function (or its integral parameters) of tooth tissue as the data concerning soft biotissues. We can mention several works, e.g. [1–9], devoted to experimental or model estimations of the said optical characteristics at several wavelengths λ. The data [5] concerning the enamel and dentin are shown in Table 1. The phase function of each layer is usually represented as the sum of the totally diffuse component (with relative weight f_d) and the Henyey – Greenstein function with relative weight $(1 - f_d)$. The latter has the asymmetry parameter g (or the mean cosine of the scattering angle) given in Table 1.

TABLE I. Spectral Characteristics of Enamel and Dentin [5]

Enamel				Dentin				
μ_s, cm^{-1}	μ_a, cm^{-1}	g	f_d	μ_s, cm^{-1}	μ_a, cm^{-1}	g	f_d	λ, nm
15±5	< 1	0.96±0.02	0.35±0.05	260±78	3 – 4	0.93 ±0.02	0– 0.02	1053
60±18	< 1	0.96±0.02	0.35±0.05	280±84	3 – 4	0.93 ±0.02	0– 0.02	632
105±30	< 1	0.96±0.02	0.60±0.10	280±84	3 – 4	0.93 ±0.02	0– 0.02	543

We used the compilation of data [2, 5, 7, 9] to simulate spectral light fields inside and outside tooth tissue. For intermediate wavelengths, where published results were absent, the literature data were extrapolated and interpolated, as needed. Note that the employed optical model is rough to make no account for the anisotropy of tissue scattering properties caused by the orientations of enamel prisms and dentinal tubules [10 – 13]. We ignored this effect for our estimations as many investigators really do while studying light propagation through biological tissue.

As to the dental pulp, it is the connective tissue. Its main optically-essential chromophores are blood, interstitial fluid, collagen bloodless tissue, and some other minor components. Optical properties of pulp were assumed below to be the same as those of soft biotissues. According to various their models (e.g. [14 – 16]), scattering and, especially, absorption properties of the soft tissue depend on blood volume fraction C_V (blood volume per tissue volume). Estimate concentration C_V by the following way. Let pulp volume be [17] $V_p = 0.02$ cm^3, pulp density (pulp consists of 75 to 80 % water [18]) $\rho_p = 1$ g/cm^3, and specific blood flow through pulp [19] $F_0 = 40 – 50$ mL/min per 100 g of pulp. Then blood volume $V_b = v_b \Delta t S C_V$ passes through pulp section area $S \approx (V_p)^{2/3}$ per time Δt, where v_b is the blood velocity in pulp. On the other hand,

$V_b = F_0\rho_p V_p \Delta t$. So one can estimate $C_V = 0.025/v_b$ for the specific F_0 value, where v_b is in mm/s. Velocity v_b depends on the blood vessel type and diameter. It approximately equals to [20] 0.08 – 0.36, 0.3 – 2.5, and 0.5 – 1 mm/s for capillaries, arterioles, and venules, respectively. Therefore, concentration C_V varies from 0.01 to 0.3. This range agrees rather well with measurements [21] and will be used below in the model calculations.

III. Light Fields inside and outside Multi-Layered Tooth Tissue

Consider here some examples of simulated light fields multiply scattered by tooth tissue. Let a tooth be illuminated by a light beam along the normal to its surface. We simulated the diffuse reflectance (usually measured by an integrating sphere) and depth distributions of fluence rate over three-layered tooth tissue. The calculation procedure to do so was published [1, 22, 23] earlier as applied to skin tissue. This method is based on the known analytical solutions to the radiative transfer equation [24] with accounting for multiple re-reflections between tissue layers and surface. The goals of the simulations are to evaluate, whether blood conditions will be seen in the reflected light, and to estimate the light penetration depth in tooth tissue.

Figure 1 shows the results of the simulations for spectral diffuse reflectance (Fig. 1*a*) and fluence rate distributions over depth z (Fig. 1*b*). Fig. 1*a* gives the calculations for varying enamel thickness d_e and a specific dentin thickness d_d = 4 mm. The similar results obtained for other d_d values show that dentin with d_d > 2 mm can be practically regarded as an infinitely thick layer with respect to light reflection. In other words, the diffuse reflectance in the visible to the near infrared is essentially independent of d_d in this case. This is apparently due to rather large optical thickness of dentin that can be treated as a semi-infinite layer with respect to reflection. Besides, diffuse reflection is independent of blood volume content C_V. Would one plot points to the graphs of Fig. 1*a* corresponding to varying values C_V of the above range, the points would practically coincide with the respective curves. This tells us that it is impossible to follow blood conditions by using stationary backscattered light or habitual spectral photometric measurements "by reflection". The situation is understood to be opposite, while one observes transmitted light. In such a case, this light can promote to monitor various blood parameters [20, 25]. Fig. 1*a* gives also the experimental data [2] on diffuse reflectance (symbols). One can see that the experimental results show the similar behavior as our theoretical simulations. This is surprisingly at the first glance, if one recalls that the base for the calculations is rather a rough optical model.

Depth dependences of fluence rate are shown in Fig. 1*b*. Here the ordinate data are dimensionless to be normalized by the incident power density. One can see that fluence rate near the tooth surface up to some fractions of mm is greater than unity. It is due to large backscattered light at the topical tooth region. Light attenuation with z increasing can be approximately represented as a weighted sum of several exponential functions with its own exponent for each tooth tissue layer. This enables one to analytically solve the problem on heat transfer through the medium and on tooth temperature regime under light irradiation by the known method [26].

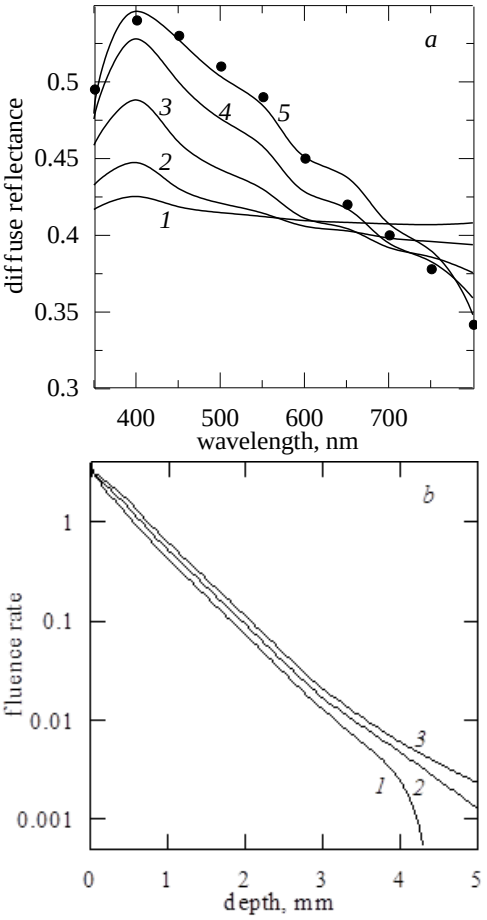

Fig. 1. (*a*) Spectral dependence of tooth diffuse reflectance, calculations (curves 1 – 5) and experiment[20] (symbols), d_e = 0.2 (*1*), 0.4 (*2*), 0.8 (*3*), 1.6 (*4*), and 3.2 mm (*5*), d_d = 4 mm; and (*b*) depth dependence of normalized fluence rate inside tooth tissue at λ = 450 (*1*), 632 (*2*), and 800 nm (*3*), d_e = 0.2 mm, d_d = 4 mm, C_V = 0.15, blood oxygen saturation 0.75.

Note two points with respect to Fig. 1*b*. First, fluence rate in the pulp at the blue – violet wavelengths attenuates quickly with depth, because of high blood absorption there. In the red to near infrared, blood absorption is lower, so the shown dependences do not practically change their slope. Second, one can roughly estimate the light penetration depth z_0 in tooth tissue, which is on the order of 2 mm in the visible to near-infrared. Here z_0 values are assumed to be the depths, where the fluence rate decreases by 10 times as compared with that incident to the tooth surface. It is understood also from the data of Fig. 1*b*, why blood optical characteristics do not show themselves in the diffuse reflectance. The point is that light reaches the pulp being highly attenuated (by 3 to 4 orders of magnitude depending on the dentin thickness) to make a negligible contribution to stationary backscattered fluxes.

IV. Conclusions

The theoretical evaluations based on a simple tooth tissue optical and geometrical model have showed that it is practically impossible to observe pulpal blood conditions by using stationary backscattered or reflected light. This is due to the high optical thicknesses of enamel and dentin layers shadowing light interaction with pulpal blood.

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References

[1] V.V. Barun et al., "Absorption spectra and light penetration depth of normal and pathologically altered human skin," J. Appl. Spectrosc, Vol. 74, pp. 430 – 439, 2007.

[2] D. Spitzer and J.J. ten Bosch, "The absorption and scattering of light in bovine and human dental enamel," Calcif. Tissue Res, vol. 17, pp. 129 – 137, 1975.

[3] J.R. Zijp and J.J. ten Bosch, "Angular dependence of hene laser light scattering by bovine and human dentine," Arch. Oral Biol, vol. 36, pp. 283 – 289, 1991.

[4] J.R. Zijp and J.J. ten Bosch, "Theoretical model for the scattering of light by dentin and comparison with measurements," Appl. Opt., vol. 32, pp. 411 – 415, 1993.

[5] D. Fried et al., "The Nature of light scattering in dental enamel and dentin at visible and near-IR wavelengths," Appl. Opt., vol. 34, pp. 1278 – 1285, 1995.

[6] J.R. Zijp, J.J. ten Bosch, and R.A. Groenhuis, "HeNe Laser light scattering by human dental enamel," J. Dental Res., vol 74, pp. 1891 – 1898, 1995.

[7] J. Vaartkamp, J.J. ten Bosch, and E.H. Verdonschot, "Light propagation through teeth containing simulated caries lesions," Phys. Med. Biol., vol. 40, pp. 1375 – 1387, 1995.

[8] J.R. Zijp, "Optical Properties of Dental Hard Tissues", PhD Thesis, Groningen, The Netherlands, 2001.

[9] D. Fried, M. Staninec, and C.L. Darling, "Near-infrared imaging of dental decay at 1310 nm," J. Laser Dent., vol. 18, pp. 8 – 16, 2010.

[10] G.B. Altshuler and V.N. Grisimov, "New optical effects in the human hard tooth tissues," SPIE Proc. 1353, pp. 97 – 102, 1989.

[11] V.M. Zolotarev and V.N. Grisimov, "Architectonics and optical properties of dentin and dental enamel," Optics Spectrosc., vol. 90, pp. 753 – 759, 2001.

[12] A. Kienle, R. Michels, and R. Hibst, "Magnification—a new look at a long-known optical property of dentin," J. Dent. Res., vol. 85, pp. 955 – 959, 2006.

[13] A. Kienle and R. Hibst, "Light guiding in biological tissue due to scattering," Phys. Rev. Lett., vol. 97, pp. 018104, 2006.

[14] V.V. Tuchin, "Light scattering study of tissues," Phys. – Uspekhi, vol. 40, pp. 495 – 515, 1997.

[15] V. V. Barun and A. P. Ivanov, "Thermal effects of a short light pulse on biological tissues. I. An optical and thermal model," Biophysics, vol. 49, pp. 1004 – 1012, 2004.

[16] S.L. Jacques, "Optical properties of biological tissues: a review," Phys. Med. Biol., vol. 58, pp. R37 – R61, 2013.

[17] http://en.wikipedia.org/wiki/Pulp_(tooth).

[18] http://www.uky.edu/~brmacp/oralhist/module4/lecture/oh4lect.htm.

[19] C. Yu and P.V. Abbott, "An overview of the dental pulp: its functions and responses to injury," Australian Dental J. Suppl., vol. 52, pp. S4 – S16, 2007.

[20] S. Kim et al., "Arteriovenous distribution of hemodynamic parameters in the rat dental pulp," Microvasc. Res., vol. 27, pp. 28 – 38, 1984.

[21] N. Vongsavan and B. Mattews, "The vascularity of dental pulp in cats," J. Dental Res., vol. 71, pp. 1913 – 1915, 1992.

[22] V.V. Barun and A.P. Ivanov, "Light and thermal fields in multilayer skin tissue exposed to laser irradiation," Optics Spectrosc., vol. 100, pp. 139 – 147, 2006.

[23] V.V. Barun and A. P. Ivanov, "Light absorption in blood during low-intensity laser irradiation of skin," Quant. Electron., vol. 40, pp. 371 – 376, 2010.

[24] E.P. Zege, A.P. Ivanov, and I.L. Katsev, "Image Transfer through a Scattering Medium", Springer-Verlag, Heidelberg, 1990.

[25] A.M. Diaz-Arnold, L.R. Wilcox, and M.A. Arnold, "Optical detection of pulpal blood," J. Endodontics, vol. 20, pp. 164 – 168, 1994.

[26] V.V. Barun and A.P. Ivanov, "Role of epidermis in the optics and thermal physics of human skin," Optics Spectrosc., vol. 107, pp. 909 – 916, 2009.