TISSUE OPTICS
Light Scattering Methods and Instruments for Medical Diagnosis
SECOND EDITION

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To My Grandkids
Dasha, Zhenya, and Stepa
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Nomenclature

2l separation between two point light sources formed in the nodal plane
2Ra diameter of circular aperture
A = \log \frac{1}{R} apparent absorbance
\bar{a} numerical coefficient depending on the form of the diffusion equation
a radius of a scatterer (particle), nm or \( \mu \)m
A signal amplitude in the frequency-domain measuring technique
A acoustic amplitude
A = \langle i \rangle^2 square of the mean value of the photocurrent (the base line of the autocorrelation function)
a' the largest dimension of a nonspherical particle, nm or \( \mu \)m
A0 initial amplitude due to the instrumental response
Aac ac component of the amplitude of the photon-density wave
Adc dc component of the amplitude of the photon-density wave
am more probable scatterer radius, \( \mu \)m
an and bn Mie coefficients
A(r) describes the optical absorption properties of the tissue at r
aT thermal diffusivity of the medium, \( m^2/s \)
Bd detection bandwidth
bs accounts for additional irradiation of upper layers of a tissue due to backscattering (photon recycling effect)
c velocity of light in the medium, \( cm/c \)
c0 velocity of light in vacuum, \( cm/c \)
C1 and C2 concentrations of molecules in two spaces separated by a membrane
Ca(x, t) concentration of the agent
Ca0 initial concentration of the agent
ca concentration of absorber in \( \mu \)mol, mmol, or mol
cb blood specific heat, \( J/kg K \)
CHb hemoglobin concentration
Cf(x, t) fluid concentration
cp specific heat capacity for a constant pressure, \( J/kg K \)
cs relative concentration of the scattering centers
\overline{C}_S average concentration of dissolved matter in two interacting solutions
c$_V$ specific heat capacity for a constant volume, J/kg K
$
C_\alpha^n$
Gegenbauer polynomials
$\langle C \rangle$
average blood concentration
$\langle C \rangle$$_{V_{rms}}$
blood flux or perfusion
$D = z\lambda/\pi L_d^2$
wave parameter
$D$
photon diffusion coefficient, cm$^2$/c
$D_\Lambda$
diattenuation (linear dichroism)
$D_a$
agent diffusion coefficient, cm$^2$/c
$D_B$
coefficient of Brownian diffusion, cm$^2$/c
$D_f$
fluid coefficient of diffusion, cm$^2$/c
$d$
sample (tissue layer or slab) thickness, cm
$D^{-1}$
inverse of the measurement matrix
$D_\perp$
dimension of incident light beam across the area where the total radiant energy fluence rate is maximal (determined from the $1/e^2$ level), cm
$D_\parallel$
dimension of incident light beam along the area where the total radiant energy fluence rate is maximal (determined from the $1/e^2$ level), cm
$d\Omega$
unit solid angle about a chosen direction, sr
$d_{av}$
average size of a speckle in the far-field zone
$D_f$
fractal (volumetric) dimension
$D_I$
structure function of the fluctuation intensity component
$d_p$
length of the space where the exciting and the probe laser beams are overlapped, cm
$d_s$
mean distance between the centers of gravity of the particles
$D_T$
coefficient of translation diffusion
$D_{Tf}$
coefficient of translation diffusion for fast process
$D_{Ts}$
coefficient of translation diffusion for slow process
$D_V$
diameter of a microvessel
d$\tilde{n}$/d$\lambda$
material dispersion, 1/nm
$dn/dT$
medium (tissue) refractive index temperature gradient, 1/$^\circ$C
DPF
differential path length factor accounting for the increase in photon migration paths due to scattering
dS
thermoelastic deformation, cm
$E$
incident pulse energy, J
electron charge
$E_0$
incident laser pulse energy at the sample surface (J/cm$^2$)
$E_{0j}$
scattering amplitude of an isolated particle, V/m
$\tilde{E}_{\perp,i}$
electric field component of the incident light perpendicular to the scattering plane, V/m
$\tilde{E}_{\parallel,i}$
electric field component of the incident light parallel to the scattering plane, V/m
$E_{\parallel,s}$
electric field component of the scattered light parallel to the scattering plane, V/m
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\perp s}$</td>
<td>electric field component of the scattered light perpendicular to the scattering plane, V/m</td>
</tr>
<tr>
<td>$\vec{E}_s$</td>
<td>scattered electric field vector, V/m</td>
</tr>
<tr>
<td>$\tilde{E}_s$</td>
<td>amplitude of a scattered wave, V/m</td>
</tr>
<tr>
<td>$E_T$</td>
<td>absorbed pulse energy, J</td>
</tr>
<tr>
<td>$E(\theta)$</td>
<td>subsurface irradiance (J/cm²)</td>
</tr>
<tr>
<td>$F(\text{Hct})$</td>
<td>packing function of RBC</td>
</tr>
<tr>
<td>$F(\tilde{r})$</td>
<td>radiant flux density or irradiance, W/cm²</td>
</tr>
<tr>
<td>$f(t,t')$</td>
<td>describes the temporal deformation of a $\delta$-shaped pulse following its single scattering</td>
</tr>
<tr>
<td>$f_{1,2}$</td>
<td>volume fractions of tissue components</td>
</tr>
<tr>
<td>$f_a$</td>
<td>frequency of acoustic oscillations, Hz</td>
</tr>
<tr>
<td>$f_c$</td>
<td>volume fraction of the collagen in tissue</td>
</tr>
<tr>
<td>$f_{cp}$</td>
<td>volume fraction of the fluid in the tissue contained inside the cells</td>
</tr>
<tr>
<td>$f_{cyl}$</td>
<td>surface fraction of the cylinders’ faces</td>
</tr>
<tr>
<td>$f_D$</td>
<td>Doppler frequency</td>
</tr>
<tr>
<td>$f_{Ds}$</td>
<td>Doppler frequency shift</td>
</tr>
<tr>
<td>$f_f$</td>
<td>volume fraction of the fibers in the tissue</td>
</tr>
<tr>
<td>$f_{ge}$</td>
<td>oscillator strength of transition between the ground and excited states</td>
</tr>
<tr>
<td>$F_{\text{int}}(\theta)$</td>
<td>interference term taking into account the spatial correlation of particles</td>
</tr>
<tr>
<td>$f_n = g^n$</td>
<td>$n^\text{th}$ order moment of the phase function</td>
</tr>
<tr>
<td>$f_{nc}$</td>
<td>volume fraction of the nuclei in the tissue contained inside the cells</td>
</tr>
<tr>
<td>$f_{or}$</td>
<td>volume fraction of the organelles in the tissue contained inside the cells</td>
</tr>
<tr>
<td>$f_p$</td>
<td>pulse repetition rate</td>
</tr>
<tr>
<td>$f_r$</td>
<td>fixed reference (lock-in) frequency</td>
</tr>
<tr>
<td>$f_{RBCi}$</td>
<td>volume fraction of RBCs</td>
</tr>
<tr>
<td>$f_s$</td>
<td>volume fraction of scatterers</td>
</tr>
<tr>
<td>$f_f$</td>
<td>focal length of the “thermal lens,” cm</td>
</tr>
<tr>
<td>$F_v$</td>
<td>total volume fraction of the particles</td>
</tr>
<tr>
<td>$f_\sigma$</td>
<td>material fringe value</td>
</tr>
<tr>
<td>$g_1(\tau)$</td>
<td>first-order autocorrelation function (normalized autocorrelation function of the optical field)</td>
</tr>
<tr>
<td>$g_2(\Delta \xi)$</td>
<td>autocorrelation function of intensity fluctuations</td>
</tr>
<tr>
<td>$G$</td>
<td>domain where radiative transport is examined</td>
</tr>
<tr>
<td>$g$</td>
<td>scattering anisotropy parameter (the mean cosine of the scattering angle $\theta$, $\langle \cos(\theta) \rangle$)</td>
</tr>
<tr>
<td>$G_1(\tau)$</td>
<td>autocorrelation function of the scalar electric field, $E(t)$, of the scattered light</td>
</tr>
<tr>
<td>$G(f)$</td>
<td>power spectrum with a Gaussian envelope</td>
</tr>
</tbody>
</table>
### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g(r) )</td>
<td>radial distribution function of scattering centers (local-to-average density ratio for scattering centers)</td>
</tr>
<tr>
<td>( G(r) )</td>
<td>binary density-density correlation function</td>
</tr>
<tr>
<td>( \tilde{g}_2 )</td>
<td>autocorrelation function of the fluctuation intensity component</td>
</tr>
<tr>
<td>( g_d )</td>
<td>scattering anisotropy factor of dermis</td>
</tr>
<tr>
<td>( g_e )</td>
<td>scattering anisotropy factor of epidermis</td>
</tr>
<tr>
<td>( G_s )</td>
<td>attenuation factor accounting for scattering and geometry of the tissue</td>
</tr>
<tr>
<td>( G_V )</td>
<td>gradient of the flow rate</td>
</tr>
<tr>
<td>( H )</td>
<td>blood hematocrit</td>
</tr>
<tr>
<td>( H )</td>
<td>tissue hydration</td>
</tr>
<tr>
<td>( h )</td>
<td>Planck’s constant</td>
</tr>
<tr>
<td>( h )</td>
<td>apparent energy transfer coefficient</td>
</tr>
<tr>
<td>( H(r, \vec{r}) )</td>
<td>heating function defined as the thermal energy per time and volume deposited by the light source in the close proportion to the optical absorption coefficient of interest</td>
</tr>
<tr>
<td>( h\nu )</td>
<td>photon energy</td>
</tr>
<tr>
<td>( h(x, y) )</td>
<td>spatial variations in the thickness of the RPS</td>
</tr>
<tr>
<td>( I(\theta)/I(0) )</td>
<td>normalized scattering indicatrix, 1/sr</td>
</tr>
<tr>
<td>( I(\theta) )</td>
<td>scattering indicatrix (angular dependence of the scattered light intensity), W/cm² sr ( i = (-1)^{1/2} )</td>
</tr>
<tr>
<td>( I_{AS}, I_S )</td>
<td>intensity of the anti-Stokes and Stokes Raman lines for a given vibration state</td>
</tr>
<tr>
<td>( I_F )</td>
<td>fluorescence intensity</td>
</tr>
<tr>
<td>( I_i )</td>
<td>irradiance or intensity of the incident light beam, W/cm²</td>
</tr>
<tr>
<td>( \langle I \rangle )</td>
<td>mean value of the intensity fluctuations</td>
</tr>
<tr>
<td>( I )</td>
<td>refers to the irradiance or intensity of the light, W/cm²</td>
</tr>
<tr>
<td>( I_{\bot}(t) )</td>
<td>intensity of the scattered light polarized orthogonal to the incident light</td>
</tr>
<tr>
<td>( I(\vec{r}, \vec{s}) )</td>
<td>radiance (or the specific intensity)—average power flux density at a point ( \vec{r} ) in the given direction ( \vec{s} ), W/cm² sr</td>
</tr>
<tr>
<td>( I(\vec{r}, \vec{s}, t) )</td>
<td>time-dependent radiance (or the specific intensity), W/cm² sr</td>
</tr>
<tr>
<td>( I(0) )</td>
<td>intensity at the center of the beam</td>
</tr>
<tr>
<td>( I(d) )</td>
<td>intensity of light transmitted by a sample of thickness ( d ) measured using a distant photodetector with a small aperture (on line or collimated transmittance), W/cm²</td>
</tr>
<tr>
<td>( I, Q, U, \text{ and } V )</td>
<td>Stokes parameters</td>
</tr>
<tr>
<td>( I_H, I_V, I_{+45^\circ}, )</td>
<td>are the light intensities measured with a horizontal linear polarizer, a vertical linear polarizer, a ( +45^\circ ) linear polarizer, a ( -45^\circ ) linear polarizer, a right circular analyzer, and a left circular analyzer in front of the detector, respectively</td>
</tr>
<tr>
<td>( I_{-45^\circ}, I_R, \text{ and } I_L )</td>
<td></td>
</tr>
<tr>
<td>( I_{\text{in}}(\eta_c) )</td>
<td>incident radiance angular distribution</td>
</tr>
</tbody>
</table>
\( I_\Sigma(\theta) \) angular distribution of the scattered intensity of a system of \( N \) particles

\( I_\Sigma(x,y) \) intensity of light transmitted by an RPS

\( I_\parallel \) and \( I_\perp \) intensities of the transmitted (scattered) light polarized in parallel or perpendicular to linear polarization of the incident light, respectively

\( I(\theta) \) angular distribution of the scattered light by a particle, W/cm\(^2\) sr

\( I(2\omega) \) SHG signal intensity

\( I_0(\lambda) \) spectrum of the incident light

\( I_0 \) incident light intensity, W/cm\(^2\)

\( I_b \) intensity of the uniform background light

\( I_c(x,y) \) intensity of light transmitted in the forward direction (the specular component)

\( I_{F\parallel} \) and \( I_{F\perp} \) fluorescence intensities of light polarized in parallel or perpendicular to the exciting electric field vector

\( I_{par} \) and \( I_{per} \) intensity images for light polarized in parallel or perpendicular to linear polarization of the incident light, respectively

\( I_r(r) \) and \( I_s(r) \) intensity distributions of the reference and signal fields

\( I_{\text{rest}} \) and \( I_{\text{test}} \) light intensity detected when an object is at rest (brain tissue, skeletal muscle, etc.) and test (induced brain activity, cold or visual test, training, etc.)

\( I_s(x,y) \) intensity of the scattered component

\( I_{sp} \) mean intensity of speckles

\( J \) flux of matter, mol/s/cm\(^2\)

\( J_0 \) zero-order Bessel function

\( J_1 \) first-order Bessel function

\( J_S \) dissolved matter flux

\( J_W \) water flux

\( k = 2\pi/\lambda \) wavenumber

\( k_a \) acoustic wave vector

\( k_F \) rate constant of the fluorescence transition to the ground state \( S_0 \) (including its vibrational states)

\( k_{\text{ET}} \) rate constant of non-radiative energy transfer to adjacent molecules

\( K, S \) Kubelka–Munk parameters

\( K_\phi(\Delta x) \) correlation coefficient of phase fluctuations of the boundary field

\( k_B \) Boltzmann constant

\( k_{b\text{vvo}} \) modification factor for reducing the crosstalk between changes of blood volume and oxygenation

\( k_G \) gas heat conductivity, W/K

\( k_i(\omega) \) imaginary part of the photon-density wave vector, 1/cm

\( k_r(\omega) \) real part of the photon-density wave vector, 1/cm

\( k_{IC} \) rate constant of internal conversion to the ground state \( S_0 \)
$k_{\text{ISC}}$ rate constant of intersystem crossing from the singlet to the triplet state $T_1$

$k_T$ heat conductivity, W/K

$L$ total mean path length of a photon

$L$ tissue slab thickness

$L = D\lambda/2l$ period of interferential fringes ($D$ is the mean distance between eye nodal plane and retina)

$L_D$ phenomenological coefficient characterizing the interchange flux induced by osmotic pressure

$L_\phi$ correlation length of the phase fluctuations of the scattered field

$l_0$ amplitude of longitudinal harmonic vibrations

$L_c$ correlation length of the inhomogeneities (random relief)

$l_c$ coherence length of a light source

$l_d = \mu_{\text{eff}}^{-1}$ diffusion length, cm

$l_e$ depth of light penetration into a tissue

$L_p$ phenomenological coefficient indicating that the volumetric flux can be induced by rising hydrostatic pressure

$L_{pd}$ phenomenological coefficient indicating on the one hand the volumetric flux that can be induced for the membrane by the osmotic pressure, and on the other, the efficiency of the separation of water molecules and dissolved matter

$l_{ph} = \mu_t^{-1}$ photon mean free path, cm

$l_s = l/\mu_s$ scattering length, cm

$l_t = (\mu_s' + \mu_a)^{-1}$ photon transport mean free path (MFP), cm

$l_T$ length of thermal diffusivity (thermal length), cm

$M$ molecule weight

$m \equiv n_s/n_0$ relative refractive index of the scatterers

$M = I_1/I_0$ intensity modulation depth defined as the ratio between the intensity at the fundamental frequency $I_1$ and the unmodulated intensity $I_0$

$M$ normalized $4 \times 4$ scattering matrix (intensity or Mueller’s matrix) (LSM)

$M_0$ zero-moment of the power density spectrum $S(\nu)$ of the intensity fluctuations

$M_1$ first-moment of the power density spectrum $S(\nu)$ of the intensity fluctuations

$m_1$ intensity modulation depth of the incident light

$M_{ij}$ LSM elements, $i, j = 1–4$, 16 elements

$\bar{M}_{ij}$ LSM element normalized to the first one

$M^0_{ij}$ LSM elements of an isolated particle

$m_{RBC}$ relative index of refraction of RBC

$m_t$ amount of dissolved matter at the moment $t$

$m_\infty$ amount of dissolved matter at the equilibrium state
m_U ≡ AC_{detector}/ DC_{detector} \quad \text{modulation depth of scattered light intensity}

n \quad \text{relative mean refractive index of tissue and surrounding media}

n'' \quad \text{imaginary part of index of refraction}

\bar{n} \quad \text{mean refractive index of the scattering medium}

N \quad \text{number of scatterers (particles)}

N = \theta/2\pi \quad \text{fringe order (\theta is the optical phase)}

N_0 \quad \text{number of scatterers in a unit volume}

N_1(z) = z \times \mu_{s}^{ex} \quad \text{average number of scattering events experienced by the excitation light before it reached the fluorophore (z is the distance of fluorophore location)}

N_2(z) = z \times \mu_{s}^{em} \quad \text{average number of scattering events experienced by the emitted light before it exited the medium (z is the distance of fluorophore location)}

\bar{N} \quad \text{outside vector normal to } \partial G

n_{2f} \quad \text{rate of two-photon excitation}

n_0 \quad \text{refractive index of the ground matter}

\bar{n}_0 \quad \text{average background index of refraction}

n_c \quad \text{refractive index of collagen fibers}

n_{cp} \quad \text{refractive index of the cytoplasm}

n_e \quad \text{extraordinary refractive index}

n_f \quad \text{refractive index of tissue fibers (collagen and elastin)}

n_{g0} \quad \text{refractive index of the ground material of a tissue}

\bar{n}_{g1} \quad \text{effective (mean) group refractive index of a tissue}

n_{g2} \quad \text{group refractive index of the homogeneous reference medium (air)}

n_g \quad \text{group refractive index}

n_{gs} \quad \text{group refractive index of the scatterers}

n_{H_2O} \quad \text{refractive index of water}

N_i = f_{RBCi}/ V_{RBCi} \quad \text{number of RBC in a unit volume of blood}

N_{int} = [\arcsin(\lambda/2l)]^{-1} \quad \text{density of interferential fringes per a degree of the view angle (an angular resolving power of the eye or retinal visual acuity)}

n_{is} \quad \text{refractive index of the interstitial fluid}

n_{nc} \quad \text{refractive index of cell nucleus}

n_o \quad \text{ordinary refractive index}

n_{or} \quad \text{refractive index of cell organelles}

N_p \quad \text{number of particle diameters}

n_s \quad \text{refractive index of the scattering centers}

\bar{n}_s \quad \text{refractive index of a scattering particle received by averaging of refractive indices of tissue components}

\bar{n}_{sc} \quad \text{average refractive index of eye sclera}

N_{sp} \quad \text{number of speckles within the receiving aperture}
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>numerical aperture of the objective or fiber</td>
</tr>
<tr>
<td>( n(x, y) )</td>
<td>spatial variations in the refractive index of the RPS</td>
</tr>
<tr>
<td>( \bar{n}_t )</td>
<td>average refractive index of the tissue</td>
</tr>
<tr>
<td>OD</td>
<td>optical density</td>
</tr>
<tr>
<td>osm</td>
<td>osmolarity</td>
</tr>
<tr>
<td>( p )</td>
<td>packing dimension</td>
</tr>
<tr>
<td>( p )</td>
<td>porosity coefficient</td>
</tr>
<tr>
<td>( P )</td>
<td>laser beam power, W</td>
</tr>
<tr>
<td>( P_i )</td>
<td>induced polarization</td>
</tr>
<tr>
<td>( P_a )</td>
<td>coefficient of permeability</td>
</tr>
<tr>
<td>( P_0 )</td>
<td>average incident power, W</td>
</tr>
<tr>
<td>( P_C = \frac{V}{I} = \frac{[Q^2 + U^2]^{1/2}}{I} )</td>
<td>degree of circular polarization</td>
</tr>
<tr>
<td>( P_{FL} = \frac{(I_{F\parallel} - I_{F\perp})}{(I_{F\parallel} + I_{F\perp})} )</td>
<td>degree of linear polarization of fluorescence</td>
</tr>
<tr>
<td>( P_L = \frac{(I_\parallel - I_\perp)}{(I_\parallel + I_\perp)} )</td>
<td>degree of linear polarization</td>
</tr>
<tr>
<td>( P_r^r(\lambda) )</td>
<td>residual polarization degree spectra</td>
</tr>
<tr>
<td>( P_{min} )</td>
<td>minimal detectable signal power</td>
</tr>
<tr>
<td>( p(I) )</td>
<td>intensity probability density distribution function</td>
</tr>
<tr>
<td>( p(s) )</td>
<td>distribution function of photon migration paths in the medium</td>
</tr>
<tr>
<td>( p(\bar{s}, \bar{s}') = p(\theta) )</td>
<td>scattering phase function (the probability density function for scattering in the direction ( \bar{s}' ) of a photon travelling in the direction ( \bar{s} )), 1/sr</td>
</tr>
<tr>
<td>( p_gk(\theta) )</td>
<td>Gegenbauer kernel phase function (GKPF)</td>
</tr>
<tr>
<td>( p_{hg}(\theta) )</td>
<td>Heney-Greenstein phase function (HGPF)</td>
</tr>
<tr>
<td>( PI )</td>
<td>polarization degree image</td>
</tr>
<tr>
<td>( P_n^1(\cos \theta) )</td>
<td>Legendre polynomials</td>
</tr>
<tr>
<td>( p(\Delta L) )</td>
<td>probability density distribution function of relief variations</td>
</tr>
<tr>
<td>( p(r, \bar{r}) )</td>
<td>the acoustic wave</td>
</tr>
<tr>
<td>( \vec{q} )</td>
<td>scattering vector</td>
</tr>
<tr>
<td>(</td>
<td>\vec{q}</td>
</tr>
<tr>
<td>( q(\vec{r}) )</td>
<td>source function (i.e., the number of photons injected into the unit volume)</td>
</tr>
<tr>
<td>( Q, U, ) and ( V )</td>
<td>represent the extent of horizontal linear, 45° linear, and circular polarization, respectively</td>
</tr>
<tr>
<td>( Q_a )</td>
<td>asymmetry parameter of the intensity fluctuations</td>
</tr>
<tr>
<td>( q_b )</td>
<td>blood perfusion rate (1/s), defined as the volume of blood flowing through unit volume of tissue in one second</td>
</tr>
<tr>
<td>( Q_s )</td>
<td>factor of scattering efficiency</td>
</tr>
<tr>
<td>( r )</td>
<td>transverse spatial coordinate</td>
</tr>
<tr>
<td>( r = \frac{I_\parallel - I_\perp}{I_\parallel + 2I_\perp} )</td>
<td>polarization anisotropy</td>
</tr>
</tbody>
</table>
\[ r_F = \frac{(I_{F\parallel} - I_{F\perp})}{(I_{F\parallel} + 2I_{F\perp})} \]  

fluorescence polarization anisotropy

\[ R(\phi) \]  

Stokes rotation matrix for angle \( \phi \)

\( \vec{r} \)  

radius vector of a scatterer or of a given point where the radiance is evaluated, cm

\( r_{\perp\parallel}(\tau) \)  

cross-correlation function (correlation coefficient) for two polarization states

\( R_{\parallel}(\lambda) \) and \( R_{\perp}(\lambda) \)  

reflectance spectra at in parallel and perpendicular orientations of polarization filters

\( \hat{R} \)  

reflection operator

\( \bar{R} \)  

4 \times 1 response vector corresponding to the four retarder/analyzer settings

\( R_d \)  

reflectance from the backward surface of the sample impregnated by an agent

\( R_0(\lambda) \)  

spectrum of light scattered under the angle \((\theta + d\theta)\)

\( r_0 \)  

radius of the incident light beam, cm

\( R_{bd} \)  

distance between the axis of exciting laser beam and the acoustic detector, cm

\( R_d \)  

diffuse reflectance

\( R_F = \frac{(n - l)}{(n + l)} \)  

coefficient of Fresnel reflection

\( \bar{R}_G \)  

gas cell radius, cm

\( r_h \)  

hydrodynamic radius of a particle

\( R_o \)  

dimension (radius for a cylinder form) of a bioobject, cm

\( r_p \)  

radius of the pinhole

\( r_{RBC} \)  

radius of RBC

\( r_s \)  

radius of the scattered beam in the observation plane

\( R_s \)  

reflectance from the backward surface of the control sample

\( r_{sd} \)  

distance between light source and detector at the tissue surface (source-detector separation), cm

\( R(\eta'_c, \eta_c) \)  

reflection redistribution function

\( RT\Delta C_S \)  

osmotic pressure

\( \hat{R}(z) \)  

optical backscattering or reflectance

\( s \)  

total photon path length (or mean path length of a photon)

\( S \)  

hemoglobin oxygen saturation

\( S \)  

heat source term, W/m³

\( S \)  

sample area

\( S_D \)  

surface of detection

\( S \)  

Stokes vector

\( \hat{S} \)  

Stokes vector calculated on the basis of experimental data

\( S_s \)  

Stokes vector of the scattered light

\( S_i \)  

Stokes vector of the incident light

\( \bar{s} \) and \( \bar{s}' \)  

directions of photon travel or unit vectors for incident and scattered waves
Nomenclature

$|\vec{s}| = 2k \sin(\theta/2)$  magnitude of the scattering wave vector $k = 2\pi\vec{n}/\lambda_0$

$\vec{S}_0$  unit vector of the direction of the incident wave

$\vec{S}_1$  unit vector of the direction of the scattered wave

$S(\vec{r}, \vec{s})$  incident light distribution at $\partial G$

$S(f)$  power spectrum of intensity fluctuations of the speckle field

$S(q)$  structure factor

$S_3(\theta)$  3-D structure factor

$S_2(\theta)$  2-D structure factor

$S(\omega)$  spectrum of intensity fluctuations

$S_{1-4}$  elements of the amplitude scattering matrix (S-matrix) or Jones matrix

$S_r(t)$  surface radiometric signal

$S(\vec{r})$  describes the shape of the irradiating pulse

$T_a$  acoustic period

$T_\theta(\lambda)$  transmission spectrum when a measuring system with a finite angle of view is used (the collimated light beam with some addition of a forward-scattered light in the angle range 0 to $\theta$ is detected)

$t_0$  spatially independent amplitude transmission of the RPS

$t_1$  the first moment of the distribution function $f(t, t');$ time interval of an individual scattering act, s

$t_2 = 1/(\mu c)$  average interval between interactions, s

$T$  absolute temperature

$T$  exposure time, s

$T(r)$  change in tissue temperature at point $r$

$T(\eta_c', \eta_c)$  transmission redistribution function

$T_a$  arterial blood temperature, K

$t_b$  blood temperature

$T_c(\lambda)$  collimated transmission spectrum

$T_c$  collimated transmittance

$T_d$  diffuse transmittance

$T_s$ and $T_e$  temperature of the tissue surface and environment, respectively

$t_s(x, y)$  amplitude transmission coefficient of an RPS

$T_l = T_c + T_d$  total transmittance

$T_l(\lambda)$  total transmission spectrum

$t$  time, s

$U(\vec{r})$  total radiant energy fluence rate, W/cm$^2$

$\langle U \rangle$  averaged amplitude of the output signal of the homodyne interferometer

$U_m$  maximum of the total radiant energy fluence rate, W/cm$^2$

$V$  illuminated volume

$V$  volume of the tissue sample

$v$  velocity of motion of the object with respect to the light beam

$V_C$  volume of collagen fibers
$V_e$ volume of an erythrocyte
$V_M$ molecular volume
$\bar{V}(z)$ contrast of average-intensity fringes
$V_\Phi$ phase velocity of a photon-density wave, cm/s
$V_0$ contrast of the interference pattern in the initial laser beam
$v_a$ velocity of acoustic waves in a medium, m/s
$V_I$ contrast of the intensity fluctuations
$v_p$ radius (in optical units) of conjugate pinholes of a confocal microscopic system
$V_P$ contrast of the polarization image
$V_{RBC}$ RBC volume, μm$^3$
$V_{rms}$ root-mean-square speed of moving particles
$V_s$ velocity of a moving particle
$\bar{V}_S$ partial mole volumes of dissolved matter
$v_{sh}$ shear rate
$V_V$ parameter directly proportional to the flow velocity
$\bar{V}_W$ partial mole volumes of water
$w$ laser (Gaussian) beam radius (or radius of a cylinder illuminated by a laser beam), cm
$w_p$ probing laser beam radius, cm
$w_0$ radius of the Gaussian beam waist
$x_0$ fixed point at the plane where speckles are observed
$x = 2\pi a/\lambda$ size (diffraction) parameter
$z$ linear coordinate (depth inside the medium), cm
$\bar{Z}$ normalized phase matrix $z_0 = (\mu'_s)^{-1}$, cm

**Greek**
$\alpha(z)$ reflectivity of the sample at the depth of $z$
$\alpha_{Hb}$ spectrally-dependent coefficient of proportionality of hemoglobin imaginary refractive index on its concentration
$\alpha_i$ incidence angle of the beam, angular degrees
$\beta$ coefficient of volumetric expansion, 1/K
$\bar{\beta}$ modulation depth of photoelectric signal of the interferometer
$\langle \bar{\beta} \rangle$ orientation averaged first molecular hyperpolarizability
$\beta_{sb}$ parameter of self-beating efficiency
$\Gamma$ Grüneisen parameter (dimensionless, temperature-dependent factor proportional to the fraction of thermal energy converted into mechanical stress)
$\Gamma_{eff}$ effective shear rate
$\Gamma_T$ relaxation parameter
$\gamma = c_p/c_V$ ratio of specific heat capacities
$\gamma_{11}(\Delta t)$ degree of temporal coherence of light
$\Delta \psi$ phase shift in a measuring interferometer, degrees
\( \Delta a \) halfwidth of the radii distribution
\( \Delta E_{vib} = h\nu_{vib} \) energy of the molecular vibration state
\( \Delta F \) width of the averaged spectrum
\( \Delta \tilde{k} \) wavenumber shift
\( \Delta L = \Delta (nh) \) optical length (relief) variations
\( \Delta n \) refractive indices difference
\( \Delta n_{oe} \) refractive indices difference due to birefringence of form
\( \Delta p \) change of pressure, Pa
\( \Delta R'(\lambda) \) differential residual polarization spectra
\( \Delta V \) change of illuminated volume caused by local temperature increase, m³
\( \Delta w \) change of radius of a cylinder illuminated by a laser beam caused by local temperature increase, cm
\( \Delta x \) linear shift of the center of maximal diffuse reflection, cm
\( \Delta z \) longitudinal displacement of the object
\( \Delta T \) local temperature increase, °C
\( \Delta T_{opt} \) optical clearing (enhancement of transmittance)
\( \Delta x_{T} \) amplitude of mechanical oscillations, cm
\( \langle \Delta n \rangle \) mean refractive index variation
\( \Delta \Phi_{0} \) initial phase due to the instrumental response
\( \Delta \theta \) angular width of the coherent peak in backscatter, angular degrees
\( \Delta \lambda \) bandwidth of a light source
\( \Delta \xi \) change in variable
\( \Delta \Psi_{I}(r) \) deterministic phase difference of the interfering waves
\( \Delta \Phi \) phase shift relative to the incident light modulation phase (phase lag), degrees
\( \langle \Delta r^{2}(\tau) \rangle \) mean-square displacement of a particle within time interval \( \tau \)
\( \Delta \Phi_{I}(r) \) random phase difference
\( \Delta T_{S} \) temperature change of a sample, °C
\( \Delta T_{G} \) temperature change of a surrounding gas, °C
\( \Delta t \) time shift of the transmitted pulse peak
\( \Delta \Phi_{I}(r) \) time-dependent phase difference related to the motion of an object
\( \delta = 2\pi d\Delta n/\lambda_{0} \) phase delay (retardance) of optical field
\( \delta_{n} \) and \( \delta_{d} \) parameters related to the average contributions per photon free path and per scattering event, respectively, to the ultrasonic modulation of light intensity
\( \delta_{oe} = 2\pi d\Delta n_{oe}/\lambda_{0} \) phase delay of optical field due to birefringence
\( \delta p(\omega) \) amplitude of harmonically modulated pressure, Pa
\( \delta p(t) \) time-dependent change of pressure, Pa
\( \partial G \) boundary surface of the domain \( G \)
\(\partial n / \partial p\) adiabatic piezo-optical coefficient of the tissue
\(\Delta z_{\text{opt}}\) optical path length
\(\varepsilon_{ab}\) absorption coefficient measured in \(\text{mol}^{-1} \text{ cm}^{-1}\)
\(\varepsilon_d\) extinction coefficient of deoxyhemoglobin measured in \(\text{mol}^{-1} \text{ cm}^{-1}\)
\(\varepsilon_o\) extinction coefficient of oxyhemoglobin measured in \(\text{mol}^{-1} \text{ cm}^{-1}\)
\(\varepsilon_{\lambda}\) extinction coefficient at the wavelength \(\lambda\) in \(\text{mol}^{-1} \text{ cm}^{-1}\)
\(\eta\) absolute viscosity of the medium
\(\eta(a)\) or \(\eta(2a)\) radii \((a)\) or diameter \((2a)\) distribution function of scatterers
\(\eta_c\) cosine of the polar angle
\(\eta_F\) fluorescence quantum yield
\(\eta_q\) quantum efficiency of the detector
\(\eta'(2a)\) correlation-corrected distribution \(\eta(2a)\)
\(\theta\) scattering angle, angular degrees
\(\theta_I\) angle between the wave vectors of the interfering fields
\(\theta_{\text{GK}}\) GKPF random scattering angle
\(\theta_{\text{HGPF}}\) HGPF random scattering angle
\(\Lambda = \frac{\sigma_{\text{sa}}}{\sigma_{\text{ext}}} = \frac{\mu_s}{\mu_t}\) albedo for single scattering (characterizes the relation of scattering and absorption properties of a tissue)
\(\Lambda' = \frac{\mu'_s}{\mu_a + \mu'_s}\) transport albedo
\(\Lambda_{\Phi}\) photon-density wavelength, cm
\(\Lambda_I\) spacing of interference fringes
\(\lambda = \lambda_0 / \bar{n}\) wavelength in the scattering medium, nm
\(\lambda_0\) wavelength of the light in vacuum, nm
\(\lambda_p\) wavelength of the probe beam, nm
\(\mu_a\) absorption coefficient at the thermal radiation emission wavelength, 1/cm
\(\mu_{\text{eff}} = [3\mu_a(\mu'_s + \mu_s)]^{1/2}\) effective attenuation coefficient or inverse diffusion length, 1/cm
\(\mu_{ge}\) change in dipole moment between the ground and excited states
\(\mu_n\) \(n\) order statistical moment \((n = 1, 2, 3 \ldots)\)
\(\mu_s = (1 - g)\mu_s\) reduced (transport) scattering coefficient, 1/cm
\(\mu_s\) scattering coefficient, 1/cm
\(\mu_{\text{ex}}\) scattering coefficient of the excitation light, 1/cm
\(\mu_{\text{em}}\) scattering coefficient of the emitting light, 1/cm
\(\mu_t = \mu_a + \mu_s\) extinction coefficient (interaction or total attenuation coefficient), 1/cm
\(\mu'_t = \mu_a + \mu'_s\) transport coefficient
\(|\mu(z)|\) modulus of the transverse correlation coefficient of the complex amplitude of the scattered field
\( \nu_I \)  

exponential factor of the spatial intensity fluctuations  

\( \xi \equiv x \text{ or } t \)  

spatial or temporal variable  

\( \xi_I \)  

characteristic depolarization length for linearly \((i = L)\) and circularly \((i = C)\) polarized light  

\( \rho \)  

medium density, kg/m\(^3\)  

\( \rho \)  

polarization azimuth  

\( \rho_a \)  

volume density of absorbers, 1/cm\(^3\)  

\( \rho_b \)  

blood density (kg/m\(^3\))  

\( \rho_G \)  

gas density, kg/m\(^3\)  

\( \rho_s \)  

volume density of the scatterers, 1/cm\(^3\)  

\( \rho(s) \)  

probability density function of the optical paths  

\( \sigma \)  

halfwidth of the particle size distribution  

\( \sigma = -(L_{pd}/L_p) \)  

molecular reflection coefficient  

\( (\sigma_1 - \sigma_2) \)  

difference in the in-plane principle stress  

\( \sigma_{\text{abs}} \)  

absorption cross-section of a particle, cm\(^2\)  

\( \bar{\sigma}_{\text{abs}} \)  

specific absorption coefficient, cm\(^{-1}\)  

\( \sigma_{\text{ext}} \)  

extinction cross section of a particle, cm\(^2\)  

\( \sigma_f \)  

photon absorption cross-section  

\( \sigma_h \)  

standard deviation of the altitudes (depths) of inhomogeneities  

\( \sigma_I \)  

standard deviation of the intensity fluctuations  

\( \sigma_L \)  

standard deviation of relief variations (in optical lengths)  

\( \sigma_m \)  

width of the skewed logarithmic distribution function for the volume fraction of particles of diameter \(2a_i\)  

\( \sigma_s(2a_i) \)  

optical cross-section of an individual particle with diameter \(2a_i\) and volume \(v_i\), cm\(^2\)  

\( \sigma_{\text{sca}} \)  

scattering cross-section of a particle, cm\(^2\)  

\( \bar{\sigma}_{\text{sca}} \)  

specific scattering coefficient, cm\(^{-1}\)  

\( \Sigma_{\text{sca}} \)  

scattering cross-section for the system of particles, cm  

\( \sigma_{\phi} \)  

standard deviation of the phase fluctuations of the scattered field  

\( \sigma^2_I \)  

variance of the intensity fluctuations  

\( \sigma^2_s \)  

spatial variance of the intensity in the speckle pattern  

\( \sigma^2_U \)  

variance of the output signal of the homodyne interferometer  

\( \tau \)  

delay time  

\( \tau \)  

lifetime of the excited state  

\( \tau = \int_{0}^{s} \mu ds \)  

optical thickness  

\( \tau_a = 1/\mu_a c \)  

average travel time of a photon before being absorbed, s  

\( \tau_c \)  

correlation time of intensity fluctuations in the scattered field  

\( \tau_d \)  

time delay between optical and acoustical pulses, s  

\( \tau_L \)  

duration of a laser pulse, s  

\( \tau_p \)  

pulse duration  

\( \tau_r \)  

time constant of rotational diffusion  

\( \tau_{\text{th}} \)  

time delay for the “thermal lens” technique, s  

\( \tau_T \)  

thermal relaxation time of the photoacoustic cell, s
\[ \tau^{-1}_B \equiv \Gamma_T \] characterizes the random (Brownian) flow
\[ \tau^{-1}_S \equiv \frac{0.18 G_V |\bar{q}| l_i}{\Phi_1(x,y)} \] characterizes the directed flow
\[ \Phi(x, y) \] random phase shift introduced by the RPS at the \((x, y)\) point
\[ \Phi_p(\omega) \] phase-lag of harmonically modulated pressure, degrees
\[ \phi(t) \] phase shift defined by a scatterer position
\[ \varphi \] angle of observation and azimuthal angle, angular degrees
\[ \varphi_d \] deflection angle of a probe laser beam, angular degrees
\[ \Omega \] solid angle, sr
\[ \Omega_v \] frequency of harmonic vibrations
\[ \omega = 2\pi f \] modulation frequency, 1/s
\[ \omega_a \] fundamental acoustic frequency
\[ \omega_{ge} \] energy difference between the ground and excited states
\[ \omega_p \] packing factor of a medium filled with a volume fraction \(f_s\) of scatterers
\[ (\omega t - \theta) \] phase of the photon-density wave
\[ \chi^{(n)} \] the \(n\)th order nonlinear susceptibility
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ac</td>
<td>alternating current</td>
</tr>
<tr>
<td>ADC</td>
<td>amplitude-digital convertor</td>
</tr>
<tr>
<td>AF</td>
<td>autocorrelation function</td>
</tr>
<tr>
<td>AF</td>
<td>autofluorescence</td>
</tr>
<tr>
<td>AHA</td>
<td>α-hydroxy acid</td>
</tr>
<tr>
<td>AO</td>
<td>acoustooptical</td>
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<tr>
<td>AOM</td>
<td>acoustooptic modulator</td>
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<tr>
<td>AOT</td>
<td>AO tomography</td>
</tr>
<tr>
<td>APD</td>
<td>avalanche photodetector</td>
</tr>
<tr>
<td>ALA</td>
<td>δ-aminolevulenic acid</td>
</tr>
<tr>
<td>ATR-FTIR</td>
<td>attenuated total reflectance Fourier transform infrared</td>
</tr>
<tr>
<td>AW</td>
<td>acoustic waves</td>
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<tr>
<td>BEM</td>
<td>boundary-element method</td>
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<tr>
<td>BSA</td>
<td>bovine serum albumin</td>
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<tr>
<td>BW</td>
<td>birefringent wedges</td>
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<tr>
<td>CBF</td>
<td>cerebral blood flow</td>
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<tr>
<td>CCD</td>
<td>charge-coupled device</td>
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<tr>
<td>CDI</td>
<td>coherent detection imaging</td>
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<tr>
<td>CFD</td>
<td>constant-fraction discriminator</td>
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<tr>
<td>CIE</td>
<td>Commission Internationale de l’Eclairage which is the French title of the International Commission on Illumination</td>
</tr>
<tr>
<td>CIN</td>
<td>cervical intraepithelial neoplasia</td>
</tr>
<tr>
<td>CIS</td>
<td>carcinoma in situ</td>
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<tr>
<td>CM</td>
<td>confocal microscopy</td>
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<tr>
<td>CMOS</td>
<td>complementary metal-oxide-semiconductor</td>
</tr>
<tr>
<td>CP OCT</td>
<td>cross-polarization OCT</td>
</tr>
<tr>
<td>CPU</td>
<td>central processing unit</td>
</tr>
<tr>
<td>CSF</td>
<td>cerebrospinal fluid</td>
</tr>
<tr>
<td>CT</td>
<td>computed tomography</td>
</tr>
<tr>
<td>CW</td>
<td>continuous wave</td>
</tr>
<tr>
<td>DBM</td>
<td>double-balanced mixer</td>
</tr>
<tr>
<td>dc</td>
<td>direct current</td>
</tr>
<tr>
<td>DG</td>
<td>delay generator</td>
</tr>
<tr>
<td>DIS</td>
<td>double integrating sphere</td>
</tr>
<tr>
<td>DMSO</td>
<td>dimethyl sulfoxide</td>
</tr>
<tr>
<td>DNA</td>
<td>deoxyribonucleic acid</td>
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<tr>
<td>Acronyms</td>
<td>Definition</td>
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<tr>
<td>----------</td>
<td>------------</td>
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<tr>
<td>DOCP</td>
<td>degree of circular polarization</td>
</tr>
<tr>
<td>DOLP</td>
<td>degree of linear polarization</td>
</tr>
<tr>
<td>DOP</td>
<td>degree of polarization</td>
</tr>
<tr>
<td>DOPA</td>
<td>3,4-dihydroxyphenylalanine</td>
</tr>
<tr>
<td>DOPE</td>
<td>dioleylphosphatidylethanolamine</td>
</tr>
<tr>
<td>DPF</td>
<td>differential path length factor</td>
</tr>
<tr>
<td>DPS OCT</td>
<td>differential phase-sensitive OCT</td>
</tr>
<tr>
<td>DT</td>
<td>diffusion theory</td>
</tr>
<tr>
<td>DWS</td>
<td>diffusion wave spectroscopy</td>
</tr>
<tr>
<td>EDL</td>
<td>extensor digitorum longus</td>
</tr>
<tr>
<td>EDTA</td>
<td>ethylenediaminetetraacetic acid</td>
</tr>
<tr>
<td>EEM</td>
<td>excitation-emission map</td>
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<tr>
<td>ESR</td>
<td>erythrocyte sedimentation rate</td>
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<tr>
<td>FAD</td>
<td>flavin dinucleotide</td>
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<tr>
<td>FD</td>
<td>frequency domain</td>
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<tr>
<td>FDA</td>
<td>Food Drug Administration</td>
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<tr>
<td>FD-LUM</td>
<td>frequency-domain luminescence</td>
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<tr>
<td>FD-OTR</td>
<td>frequency-domain OTR</td>
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<tr>
<td>FDPM</td>
<td>frequency-domain photon migration</td>
</tr>
<tr>
<td>FDTD</td>
<td>finite-difference time-domain</td>
</tr>
<tr>
<td>FFT</td>
<td>fast Fourier transform</td>
</tr>
<tr>
<td>FG</td>
<td>function generator</td>
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<tr>
<td>FMN</td>
<td>flavin mononucleotide</td>
</tr>
<tr>
<td>FRAP</td>
<td>fluorescence recovery after photobleaching</td>
</tr>
<tr>
<td>FWHM</td>
<td>full width half maximum</td>
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<tr>
<td>GHb</td>
<td>glycated hemoglobin</td>
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<tr>
<td>GK</td>
<td>Gegenbauer kernel</td>
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<td>GKPF</td>
<td>Gegenbauer kernel phase function</td>
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<td>GPM</td>
<td>goniophotometric measurements</td>
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<td>GRIN</td>
<td>gradient index</td>
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<tr>
<td>Hb</td>
<td>hemoglobin</td>
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<td>HEM</td>
<td>human epidermal membrane</td>
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<tr>
<td>HCM</td>
<td>human cervical mucus</td>
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<tr>
<td>Hct</td>
<td>hematocrit</td>
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<tr>
<td>HPD</td>
<td>hematoporphirin derivative</td>
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<tr>
<td>HG</td>
<td>Henyey-Greenstein</td>
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<tr>
<td>HGPF</td>
<td>Henyey-Greenstein phase function</td>
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<td>HWHM</td>
<td>half width half maximum</td>
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<tr>
<td>IAD</td>
<td>inverse adding–doubling</td>
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<tr>
<td>ICG</td>
<td>indocyanine green</td>
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<tr>
<td>IF</td>
<td>intermediate frequency</td>
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<tr>
<td>IFS</td>
<td>interfibrillar spacing</td>
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<tr>
<td>IMC</td>
<td>inverse Monte Carlo</td>
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<tr>
<td>IMS</td>
<td>intermolecular spacing</td>
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</tbody>
</table>
IC25  Infracyanine 25
IQ    in-phase quadrature
IR    infrared
IS    integrating sphere
KDP   kalium dihydrophosphate
KMM   Kubelka-Munk model
LASCA laser speckle contrast analysis
LD    laser diode
LDA   laser Doppler anemometer
LDI   laser Doppler imaging
LDM   laser Doppler microscope
LED   light-emitting diode
LID   lattice of islet damage
LIPT  laser-induced pressure transient
LITT  laser-induced interstitial thermal therapy
LO    local oscillator
LPF   low-pass filter
LSI   laser speckle imaging
LSM   light-scattering matrix
LSMM  laser scattering matrix meter
LSS   light scattering spectroscopy
LVDS  low-voltage differential signaling
MAR   modified amino resin
MB    methylene blue
MBG   mean blood glucose
MC    Monte Carlo
MCA   multichannel analyzer
MCP-PMT multichannel plate-photomultiplier tube
MED   minimal erythema dose
MFP   mean free path length
MIM   multispectral imaging micropolarimeter
MIR   middle infrared
MO    microobjective
MONSTIR multichannel optoelectronic near-infrared system for
time-resolved image reconstruction
MPS   maximum permissible exposure
MR    magnetic resonance
MRI   MR imaging
MTT   meal tolerance test
NA    numerical aperture
NAD   nicotinamide adenine dinucleotide
NAD+  oxidized form of NAD
NADH  reduced form of NAD
NIR   near infrared
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tr>
<td>OA</td>
<td>optoacoustic</td>
</tr>
<tr>
<td>OAT</td>
<td>OA tomography</td>
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<tr>
<td>OCA</td>
<td>optical clearing agent</td>
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<tr>
<td>OCI</td>
<td>optical coherence interferometry</td>
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<tr>
<td>OCM</td>
<td>optical coherence microscopy</td>
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<tr>
<td>OCP</td>
<td>optical clearing potential</td>
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<tr>
<td>OCT</td>
<td>optical coherence tomography</td>
</tr>
<tr>
<td>OD</td>
<td>optical density</td>
</tr>
<tr>
<td>OGTT</td>
<td>oral glucose tolerance test</td>
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<tr>
<td>OMA</td>
<td>optical multichannel analyzer</td>
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<tr>
<td>OT</td>
<td>optothermal</td>
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<tr>
<td>OTR</td>
<td>optothermal radiometry</td>
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<tr>
<td>PA</td>
<td>photoacoustic</td>
</tr>
<tr>
<td>PAM</td>
<td>photoacoustic microscopy</td>
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<tr>
<td>PBS</td>
<td>phosphate buffered saline</td>
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<tr>
<td>PC</td>
<td>personal computer</td>
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<tr>
<td>PD</td>
<td>photodetector</td>
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<tr>
<td>PDF</td>
<td>probability distribution function</td>
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<tr>
<td>PDMD</td>
<td>phase-delay measurement device</td>
</tr>
<tr>
<td>PDT</td>
<td>photodynamic therapy</td>
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<tr>
<td>PDWFCS</td>
<td>photon-density wave-fluctuation correlation spectroscopy</td>
</tr>
<tr>
<td>PEG</td>
<td>polyethylene glycol</td>
</tr>
<tr>
<td>PG</td>
<td>propylene glycol</td>
</tr>
<tr>
<td>PHA</td>
<td>pulse-height analysis</td>
</tr>
<tr>
<td>PM</td>
<td>polarization-maintaining</td>
</tr>
<tr>
<td>PMT</td>
<td>photomultiplier tube</td>
</tr>
<tr>
<td>POS</td>
<td>polyorganosiloxane</td>
</tr>
<tr>
<td>PPG</td>
<td>polypropylene glycol</td>
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<tr>
<td>PRS</td>
<td>polarized reflectance spectroscopy</td>
</tr>
<tr>
<td>PS OCT</td>
<td>polarization-sensitive OCT</td>
</tr>
<tr>
<td>PS-OLCR</td>
<td>phase-sensitive optical low-coherence reflectometer</td>
</tr>
<tr>
<td>PT</td>
<td>photothermal</td>
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<tr>
<td>PTFC</td>
<td>PT flow cytometry</td>
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<td>PTM</td>
<td>PT microscopy</td>
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<tr>
<td>PTR</td>
<td>PT radiometry</td>
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<tr>
<td>PVDF</td>
<td>polyvinylidene fluoride</td>
</tr>
<tr>
<td>PY</td>
<td>Percus-Yevick</td>
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<tr>
<td>QELS</td>
<td>quasi-elastic light scattering</td>
</tr>
<tr>
<td>RBC</td>
<td>red blood cell</td>
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<tr>
<td>RC</td>
<td>relative contrast</td>
</tr>
<tr>
<td>RCM</td>
<td>reflection confocal microscopy</td>
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<tr>
<td>RF</td>
<td>radio frequency</td>
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<tr>
<td>RGA</td>
<td>Rayleigh-Gans approximation</td>
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<tr>
<td>rms</td>
<td>root mean square</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>RNA</td>
<td>ribonucleic acid</td>
</tr>
<tr>
<td>RNFL</td>
<td>retinal nerve fiber layer</td>
</tr>
<tr>
<td>ROI</td>
<td>region of interest</td>
</tr>
<tr>
<td>RPS</td>
<td>random phase screen</td>
</tr>
<tr>
<td>RSODL</td>
<td>rapid scanning optical delay line</td>
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<tr>
<td>RTE</td>
<td>radiative transfer equation</td>
</tr>
<tr>
<td>RTT</td>
<td>radiation transfer theory</td>
</tr>
<tr>
<td>SC</td>
<td>stratum corneum</td>
</tr>
<tr>
<td>SEM</td>
<td>standard error of the mean</td>
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<tr>
<td>SERS</td>
<td>surface-enhanced Raman scattering</td>
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<tr>
<td>SHG</td>
<td>second harmonic generation</td>
</tr>
<tr>
<td>SMF</td>
<td>skeletal muscle fibers</td>
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<tr>
<td>SL</td>
<td>sonoluminescence</td>
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<tr>
<td>SLD</td>
<td>superluminescent diode</td>
</tr>
<tr>
<td>SLT</td>
<td>SL tomography</td>
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<tr>
<td>SMLB</td>
<td>spatially-modulated laser beam</td>
</tr>
<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
</tr>
<tr>
<td>SPR</td>
<td>spatially resolved reflectance</td>
</tr>
<tr>
<td>SSB</td>
<td>single sideband</td>
</tr>
<tr>
<td>SRR</td>
<td>spatially resolved reflectance</td>
</tr>
<tr>
<td>ST</td>
<td><em>Staphylococcus</em> toxin</td>
</tr>
<tr>
<td>TAC</td>
<td>time-to-amplitude convertor</td>
</tr>
<tr>
<td>TD</td>
<td>time-domain</td>
</tr>
<tr>
<td>TDM</td>
<td>time division multiplex</td>
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<tr>
<td>TDM</td>
<td>transillumination digital microscopy</td>
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<tr>
<td>TEWL</td>
<td>transepidermal water loss</td>
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<tr>
<td>TGS</td>
<td>thermal gradient spectroscopy</td>
</tr>
<tr>
<td>THb</td>
<td>total hemoglobin</td>
</tr>
<tr>
<td>TMP</td>
<td>trimethylolpropanol</td>
</tr>
<tr>
<td>TOAST</td>
<td>time-resolved optical absorption and scattering tomography</td>
</tr>
<tr>
<td>TRS</td>
<td>time-resolved spectroscopy</td>
</tr>
<tr>
<td>US</td>
<td>ultrasound</td>
</tr>
<tr>
<td>UV</td>
<td>ultraviolet</td>
</tr>
<tr>
<td>VOA</td>
<td>variable optical attenuator</td>
</tr>
<tr>
<td>WP</td>
<td>Wollaston prism</td>
</tr>
<tr>
<td>VRTE</td>
<td>vector radiative transfer equation</td>
</tr>
<tr>
<td>VTW</td>
<td>virtual transparent window</td>
</tr>
<tr>
<td>WDM</td>
<td>wavelength division multiplex</td>
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<tr>
<td>WHO</td>
<td>World Health Organization</td>
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</table>
Preface to First Edition

Many up-to-date medical technologies are based on recent progress in physics, including optics.\textsuperscript{1–102} An interesting example relevant to the topic of this tutorial is provided by computer tomography.\textsuperscript{1,4} X-ray, magnetic resonance, and positron-emission imaging techniques are extensively used in high-resolution studies of both anatomical structures and local metabolic processes. Another safe and technically simple tool currently in use is diffuse optical tomography.\textsuperscript{1,3,4,6,15,28,71}

From the viewpoint of optics, biological tissues and fluids (blood, lymph, saliva, mucus, gastric juice, urine, aqueous humor, semen, etc.) can be separated into two large classes.\textsuperscript{1–69,92–97,101} The first class includes strongly scattering (opaque) tissues and fluids, such as skin, brain, vessel walls, eye sclera, blood, and lymph. The optical properties of these tissues and fluids can be described within the framework of the model of multiple scattering of scalar or vector waves in a randomly nonuniform absorbing medium. The second class consists of weakly scattering (transparent) tissues and fluids, such as cornea, crystalline lens, vitreous humor, and aqueous humor of the front chamber of the eye. The optical properties of these tissues and fluids can be described within the framework of the model of single scattering (or low-step scattering) in an ordered isotropic or anisotropic medium with closely packed scatterers with absorbing centers.

The vector nature of light waves is especially important for transparent tissues, although much attention has been recently focused also on the investigation of polarization properties of light propagating in strongly scattering media.\textsuperscript{3,5,6,8–10,23,28,43,59–64,69,70} In scattering media, the vector nature of light waves is manifested as polarization of an initially nonpolarized light beam or as depolarization (generally, the change in the character of polarization) of an initially polarized beam propagating in a medium. Similar to coherence properties of a light beam reflected from or transmitted through a biological object, polarization parameters of light can be employed as a selector of photons coming from different depths in an object.

The problems of optical diagnosis and spectroscopy of tissues are concerned with two radiation regimes: continuous wave and time-resolved.\textsuperscript{1,3,4,6,12,14,15,28,31,71,92} The latter is realized by means of the exposure of a scattering object to short laser pulses (\(~10^{-10}~\) to \(~10^{-12}~\) s) and the subsequent recording of scattered broadened pulses (the time-domain method), or by irradiation with modulated light, usually in the frequency range 50 MHz to 1000 MHz and recording the depth of modulation of scattered light intensity and the corresponding phase shift at modulation frequencies (the frequency-domain or phase
method). The time-resolved regime is based on the excitation of the photon-density wave spectrum in a strongly scattering medium, which can be described in the framework of the nonstationary radiation transfer theory (RTT). The continuous radiation regime is described by the stationary RTT.

Many modern medical technologies employ laser radiation and fiber-optic devices.1–7 Since the application of lasers in medicine has both fundamental and technical purposes, the problem of coherence is very important for the analysis of the interaction of light with tissues and cell ensembles. On the one hand, this problem can be considered in terms of the loss of coherence due to the scattering of light in a randomly nonuniform medium with multiple scattering, or the change in the statistics of speckle structures of the scattered field. On the other hand, this problem can be interpreted in terms of the appearance of an amplified, coherent, sharply directed component in backscattered radiation under conditions when a tissue is probed with an ultrashort laser pulse.1,3,73,74 The coherence of light is of fundamental importance for the selection of photons that have experienced a small number of scattering events or none, as well as for the generation of speckle-modulated fields from scattering phase objects with single and multiple scattering.1,3,75–77 Such approaches are important for coherent tomography, diffractometry, holography, photon-correlation spectroscopy, laser Doppler anemometry, and speckle interferometry of tissues and fluxes of biological fluids.1,3,15,22,28,76–83 The use of optical sources with a short coherence length opens up new opportunities in coherent interferometry and tomography of tissues, organs, and blood flows.1,3,8,17,18,77,84

The transparency of tissues reaches its maximum in the near infrared (NIR), which is associated with the fact that living tissues do not contain strong intrinsic chromophores that would absorb radiation within this spectral range. Light penetrates into a tissue for several centimeters, which is important for the transillumination of thick human organs (brain, breast, etc.). However, tissues are characterized by strong scattering of NIR radiation, which prevents one from obtaining clear images of localized inhomogeneities arising in tissues due to various pathologies, e.g., tumor formation, a local increase in blood volume caused by a hemorrhage or the growth of microvessels. Strong scattering of NIR radiation also imposes certain requirements on the power of laser radiation, which should be sufficient to ensure the detection of attenuated fluxes. Special attention in optical tomography and spectroscopy is focused on the development of methods for the selection of image-carrying photons or detection of photons providing the information concerning the optical parameters of the scattering medium. These methods employ the results of fundamental studies devoted to the propagation of laser beams in scattering media.1,3,4,6,15,28,31,71,92

Another important area in which deep tissue probing is practiced is reflecting spectroscopy, e.g., optical oxymetry for the evaluation of the degree of hemoglobin oxygenation in working muscular tissue, the diseased neonatal brain, or the active brain of adults.1,3,4

This tutorial is primarily concerned with light-scattering techniques recently developed for quantitative studies of tissues and optical cell ensembles. It discusses
the results of theoretical and experimental investigations into photon transport in
tissues and describes methods for solving direct and inverse scattering problems
for random media with multiple scattering and quasi-ordered media with single
scattering, in order to model different types of tissue behavior. The theoretical con-
sideration is based on stationary and nonstationary radiation transfer theories for
strongly scattering tissues, the Mie theory for transparent tissues, and the numeri-
cal Monte Carlo method, which is employed for the solution of direct and inverse
problems of photon transport in multilayered tissues with complicated boundary
conditions.

These are general approaches extensible to the examination of a large number
of abiological scattering media. It is worthwhile to note that many known methods
of scattering media optics (e.g., the integrating sphere technique) were brought to
perfection when used in biomedical research. Concurrently, new measuring sys-
tems and algorithms for the solution of inverse problems have been developed that
are useful for scattering media optics in general. Moreover, the improvement of
certain methods was undertaken only because they were needed for tissue studies;
this is especially true of the diffuse photon-density waves method, which is promis-
ning for the examination of many physical systems: aqueous media, gels, foams, air,
aerosols, etc.

Based on such fundamental optical phenomena as elastic and quasi-elastic (sta-
tic and dynamic) scattering, diffraction, and interference of optical fields and pho-
ton density waves (intensity waves), we will discuss optical methods and instru-
ments offering much promise for biomedical applications. Among these are spec-
trophotometry and polarimetry; time-domain and frequency-domain spectroscopy
and imaging systems; photon-correlation spectroscopy; speckle interferometry; co-
herent tomography and tomography; phase, confocal, and heterodyne microscopy;
and partial coherence interferometry and tomography.

I am grateful to Terry Montonye, Donald O’Shea, Alexander Priezzhev, Barry
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I. L. Kon, E. I. Zakharova, A. A. Bednov, A. A. Chaussky, S. Yu. Kuz’min,
K. V. Larin, I. V. Meglinsky, A. A. Mishin, I. S. Peretochnik, and A. N. Yaros-
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My joint chairing with Halina Podbielska, Ben Ovryn, and Joe Izatt of the SPIE Conference on Coherence Domain Optical Methods in Biomedical Science and Clinical Applications also was very helpful.

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I would like to say a few words in memory of Pascal Rol, my good friend and colleague with whom I have organized many SPIE meetings. Pascal died suddenly on January 10, 2000. The reader will find many of his excellent results on scleral tissue optics in this tutorial. He has made many outstanding contributions to biomedical optics, and I will always remember him as a good scientist and friendly person.

I am very thankful to Ruth Haas, Erika Wittmann, and Sue Price for their assistance in editing and production of the book, and to S. P. Chernova and E. P. Savchenko for their help in the preparation of the figures.

Last, but not least, I express my gratitude to my wife, Natalia, and all my family for their support, understanding, and patience.
Preface to the Second Edition

This is the second edition of the tutorial *Tissue Optics: Light Scattering Methods and Instruments for Medical Diagnosis* first published in 2000. The last seven years, since the printing of the first edition, have seen intensive growth of research and development in tissue optics, particularly in the field of tissue diagnostics and imaging.\(^{103–147}\) Further developments of light-scattering techniques for the quantitative evaluation of optical properties of normal and pathological tissues and cell ensembles have occurred. New results on theoretical and experimental investigations into light transport in tissues and methods for solving direct and inverse scattering problems for random media with multiple scattering and quasi-ordered media have been found. A few specific fields, such as optical coherence tomography (OCT)\(^{108–111,115,116,126,127,129,130,136,142}\) and polarization-sensitive technologies,\(^{129,130,135,136,138,139}\) which are very promising for optical medical diagnostics and imaging, have developed rapidly over the last few years. The optical clearing method, based on reversible reduction of tissue scattering due to refractive index matching of scatterers and ground matter, has also been of great interest for research and application since the last edition.\(^{129,132,136,139,140}\) Further developments of Raman and vibrational spectroscopies\(^{104,105,123,130,132,136,143}\) and multiphoton microscopy\(^{114,119,122,130,132,136,137}\) applied to morphology and the functioning of living cells and tissues have been provided by many research groups. This new edition of this book is conceptually the same as the first one. It is also divided into two parts: Part I describes tissue optics fundamentals and basic research, and Part II presents optical and laser instrumentation and medical applications. The author has corrected misprints, updated the references, and added some new results mostly on tissue optical properties measurements (Chapter 2) and polarized light interaction with turbid tissues (Section 1.4). Recent results on polarization imaging and spectroscopy techniques (Chapter 7), as well as on OCT developments and applications (Chapter 9) are also overviewed. Materials on controlling tissue optical properties (Chapter 5) and optothermal and optoacoustic interactions of light with tissues (Section 1.5) are updated. Brief descriptions of fluorescent, nonlinear, and inelastic light scattering spectroscopies are provided in Chapter 1.

I am grateful to Sharon Streams for her suggestion to prepare the second edition of the tutorial and for her assistance in editing of the book. I also would like to thank Merry Schnell for her assistance on the final stage of book editing and production. I am very thankful to attendees of my short courses “Coherence, Light Scattering, and Polarization Methods and Instruments for Medical Diagnosis,” “Tissue Optics and Spectroscopy,” “Tissue Optics and Controlling of Tissue Optical Properties,” and “Optical Clearing of Tissues and Blood,” which I have given during
SPIE Photonics West Symposia, SPIE/OSA European Conferences on Biomedical Optics, and OSA CLEO/QELS Conferences over last seven years, for their stimulating questions, fruitful discussions, and critical evaluations of presented materials. Their responses were very valuable for preparation of this edition. My joint chairing with Joseph A. Izatt and James G. Fujimoto of the SPIE Conference on Coherence Domain Optical Methods and Optical Coherence Tomography in Biomedicine also was very helpful.

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I express my gratitude to my wife, Natalia, and all my family, especially to my daughter, Nastya, and grandchildren, Dasha, Zhenya, and Stepa, for their indispensable support, understanding, and patience during my writing this book.

Valery Tuchin
June 2007