BACK-SCATTERED POLARIZED LIGHT AND ITS APPLICATION IN TISSUE AGING INVESTIGATION

Hamed Mohamed Abubaker

Doctoral Degree Programme (2), FEEC BUT

E-mail: xabuba00@stud.feec.vutbr.cz

Supervised by: Pavel Tománek

E-mail: tomanek@feec.vutbr.cz

Abstract: Optical sensing methods for real-time inspection of biological tissues are of considerable interest in investigating polarization properties of light backscattered from turbid media. Although tissue multiple scattering randomizes incident polarization states, linear, circular and elliptical polarization states are considered, and there are circumstances when appreciable degree of polarization can be observed in diffusive scattering. Our work has shown the sufficient degree of sensitivity to detect structural changes due to the aging of processed meat. Moreover, it demonstrated that the degree of polarization of the backscattered light is sensitive to the optical properties of specimen material and to its thickness.

Keywords: polarization degree, multiple back-scattering, biological tissue, aging, measurement

1. INTRODUCTION

The propagation of laser light in tissue is a question of growing concern in many, mainly medical applications. Numerous models that predict fluence rates in tissues, or reflection or transmission of light by tissue have been developed [1-3]. The accuracy of these models is ultimately depending upon how well optical properties of these tissues are known. Optical parameters are obtained by converting measurement of observable quantities (e.g. reflection) into parameters which characterize light propagation in tissue [4,5]. The conversion process is based on a particular theory of light transport in tissues [6].

In past years many different quantities have been reported [7-9], e.g. total attenuation coefficient, effective attenuation coefficient, the effective penetration depth, the absorption and scattering coefficients, and the anisotropy factor for variety of tissues for different light wavelengths. The majority of these results are based upon approximations to the radiative transfer theory (e.g., diffusion theory) [10]. Yet sufficient variations in model assumptions (isotropic-anisotropic scattering, or matched-mismatched boundaries), measurement techniques, experimental apparatus, calibration scheme, and biological heterogeneities exist that effort to extract average value for different tissue types is complicated.

The studies in the exact back-scattering direction are therefore attractive for two reasons – there is the expectation of non-vanishing polarization signals even in extremely thick turbid media, and this configuration is practically convenient, and sometimes unavoidable, for biomedical investigations. It is important to quantify the effect of tissue optics on the polarization properties of back-scattered light. For example, since the degree of polarization (DOP) surviving in a random media generally decreases as the optical path-length increases, one would assume that limiting light penetration by increasing tissue absorption would enhance polarization preservation, albeit at the expense of reducing the overall reflectance intensity. In this paper, a novel application of a polarization modulation method is used to investigate the aging dependence of DOP of the scattered polarized light in biological tissue post mortem.

2. MODIFIED PULSE VECTOR RADIATIVE TRANSFER EQUATION

A number of methods have been proposed for measuring optical properties of biological tissues. There can be divided into two groups: direct and indirect ones. In direct techniques, optical properties are found using nothing more complicated than Lambert-Beer's law [1,11]:

$$A = \log\left(\frac{I_0}{I_\ell}\right) = \alpha \ell C, \tag{1}$$

where A is absorbance, I_O incident light intensity, I_ℓ transmitted intensity, α absorptivity, ℓ optical path length, and C concentration of the medium.

The examples of direct methods are unscattered transmission measurements, effective attenuation measurements, and goniometric measurements of the single scattering function. In more complicated indirect methods, it is necessary to use a theoretical model of light scattering. Due to this fact, we distinguish iterative and non-iterative methods.

Non-iterative method uses equations in which optical properties are explicitly given in terms of the measured quantities. As example, the Kubelka-Munk [10] and three-flux [12] models are non-iterative, indirect methods. In indirect, iterative methods, the optical properties are implicitly related to measured qualities. The values for optical properties are iterated until the calculated reflection and transmission match the measured values [13]. These methods are much more cumbersome to use, but the optical model employed can be much more sophisticated than the non-iterative methods.

For a narrow band and plane-parallel medium case, the time-dependent vector radiative transfer equation is Fourier transformed to obtain the following modified frequency domain vector radiative transfer equation [14]:

$$\mu \frac{\partial}{\partial \tau}[I_d] + \left(1 - (\mu - 1) i \frac{\omega}{\tau_0}\right)[I_d] = \int_0^{2\pi}\int_1^1 S(\mu, \phi, \mu', \phi')[I_d]\, d\mu' d\phi' + F_0(\tau, \mu, \phi)\exp(-\tau), \quad \text{for } 0 \le \tau \le \tau_0, \tag{2}$$

where ω is the normalized frequency, the optical distance τ defined by $\tau = \rho \sigma_t z$, where ρ is the number density, σ_t is the total-cross section of a single particle, and z is the actual distance. Note that τ_o is the optical depth defined by $\tau_o = \rho \sigma_t L$ where L is length of the slab of the random medium, the scattering matrix [**S**] is calculated from Mie scattering [15, 16]. The time-domain diffuse Stokes vector [$\mathbf{I}_d$] is then given by

$$\left[I_d(t, \tau)\right] = \left[I_1 \;\; I_2 \;\; U \;\; V\right]^T = \frac{1}{2\pi}\int \left[I_d(\omega, \tau)\right] \exp\left(i \frac{\omega}{\tau_0}\tau - i\omega t\right) d\omega, \tag{3}$$

where t is normalized with respect to the propagation time. It is important to note that Eq. (2) is modified from the vector radiative transfer to obtain stable frequency-domain solutions. Eq. (2) is numerically solved using the discrete ordinate method and Fourier series decomposition in the azimuthal direction. For linear polarization, two Fourier components are needed while for circular polarization, one Fourier component with two separate equations is needed. The degree of polarization (DOP) and the cross-polarization discrimination (XPD) were defined from Stokes parameters [15] by

$$\text{DOP} = \frac{\sqrt{(I_1 - I_2)^2 + U^2 + V^2}}{I_1 + I_2}, \quad \text{and} \quad \text{XPD} = 10 \log\left[\frac{I_{co-pol}}{I_{x-pol}}\right]. \tag{4}$$

3. EXPERIMENTAL

There are several experimental systems capable of detecting weak polarization signals in the presence of large diffusive background for light scattered from a random biological medium [17]. For

our purpose the best setup is depicted in Fig.1 [18]. Its optical part consists of a He–Ne laser source (λ = 632.8 nm), a linear polarizer, a 50 kHz photoelastic modulator (PEM) to enable time-varying polarization states to impinge on the beam splitter and then onto the turbid sample, and an analyzer/photodetector combination to measure the scattered light intensity and the polarization properties of the scattered light. Electrical part then consists of the lock-in and transimpedance amplifiers enable sensitive synchronous measurement of the resultant photocurrent. A mechanical chopper in optical path operating at ~ 150 Hz is also used; when tuned to its rotation frequency, the lock-in measures the overall light intensity, and when tuned to the PEM's oscillation frequency (and its harmonics), the lock-in signal is sensitive to the polarization fraction that has survived the sample interactions. The beam splitter is present to enable detection of light that emerges from the sample centered on the exact backscattering direction.

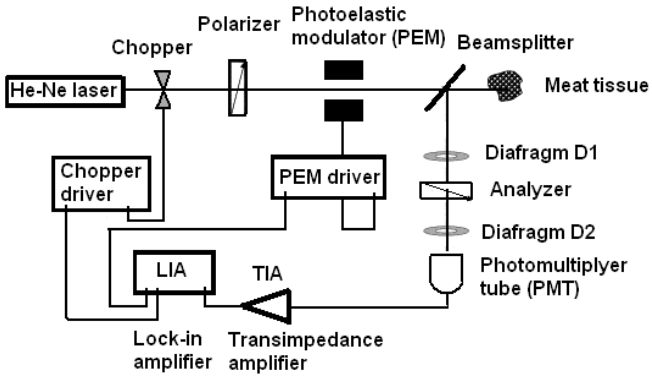

Figure 1: Schematic of the experimental system for measuring polarization properties of backscattered diffusely reflected light from a turbid biological sample.

The photoelastic modulator (oriented at 6° off normal incidence with respect to the incident beam direction, to negate the effects of modulated specular interference) oscillates in the plane of the optical table. The polarizer is at 45° with respect to the plane of the optical table, and the orientation of analyzer is set to rotate in the 0–360° range. D1 and D2 are pinhole diaphragms.

4. RESULTS

For a purpose of our investigation, we have used a porcine meat as a sample, cut in slices of 1.0-5.0 mm thick and sandwiched by a pair of microscope cover glasses. The slices were cut parallel or perpendicularly to the muscle fibers as normally made at the butcher´s shop. Due to the fact that meat as biological tissue is a chiral medium, it is optically active and curls a linear polarization plane. Therefore this rotation is one of the characteristics of aging process within muscle fibers.

Figure 2 displays an angular dependence of polarized light for samples of thickness 2.0 mm for measurement without turbid scattering sample and two parallel and perpendicular muscle orientations to the cutting plane. Following Fig.3 represents calculated DOP on a thickness of the meat layers. Next we have examined how polarization degree was related to the thickness of the sample. Figure 3 shows the result for slices with thickness of 3.0 mm where muscle fiber directions were aligned perpendicularly to the cover glass. The quantity of DOP was calculated from Eq.(4). Obviously, it is recognized that the polarization is changed with the meat thickness. This is caused by the multiple scattering which makes the polarization states more uniform. But it is surprising that although scattered light has almost random characteristics, the polarization degree > 40% at the thickness of 1.0 mm is maintained.

Finally, we investigated the relationship between the polarization changes and meat freshness. Figure 4 shows the result for the chicken breast meat of thickness 1.0 mm. Rotating characteristics of the light polarization were measured in Fig. 4 every 5 minutes during 180 minutes for a commer-

cial chicken sample with the muscle fiber orientation parallel to the cover glass. We can see that the degree of polarization decreases with time after slicing.

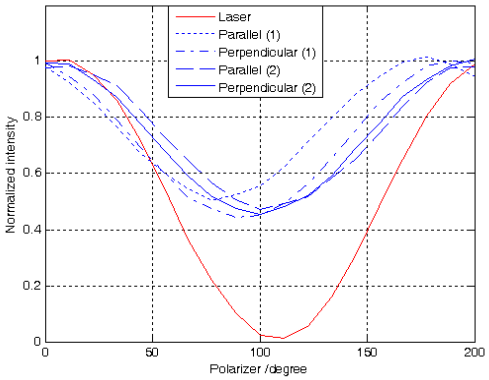

Fig.2: Angular dependence of polarization directions of diffused light for two meat samples sliced along the muscle fibers and orthogonally to them.

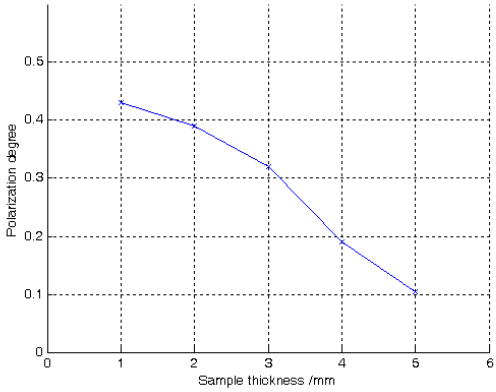

Fig. 3: Dependence of degree of polarization (DOP) on a thickness of meat slices (Eq.4).

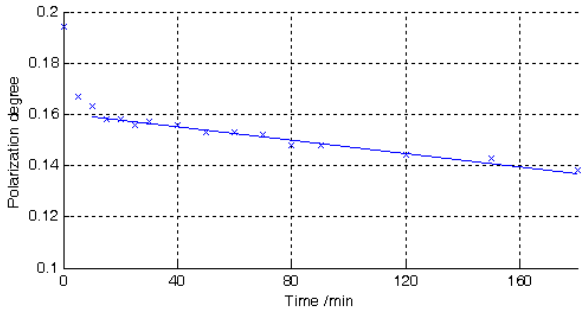

Fig. 4: Change of polarization degree vs. meat aging time after slice processing.

4. CONCLUSIONS

Optical properties of biological tissues are vital for the medical and food quality control investigations. We have found that the diffused light has the polarization depending on direction of muscle fiber. As the scattering coefficient of the porcine meat μ_s is about 27 mm^{-1}, the average free path of light without collision would of 37μm.

In such a case, the transmitting light would at least experience the scattering events over 30 times for the 1.0mm thick meat. The DOP tends to be reduced with the scattering times. On the other side, the polarization is partly maintained for 1.0mm thick meat. However a deviation from the sinusoidal intensity profile indicates various orientated polarizations. Further, from the polarization rotation profiles and DOP, we could guess the time passage from the processing time of meat for food estimated by the statistical method of PLS regression with the precision of 20.2 minutes.

ACKNOWLEDGEMENTS

This work has been supported by the Czech Ministry of Education in the frame of MSM 0021630503 Research Intention MIKROSYN “New Trends in Microelectronic System and Nanotechnologies”, by GAČR grant 102/11/0995 “ Transport of Electron Noise and Diagnostics of Schottky and Autoemitting Cathodes”, as well as by MŠMT grant KONTAKT LH 11060 “Local Optical and Electric Characterization of Optoelectronic Devices with Nanometer Resolution”.

REFERENCES

[1] Hulst, van de, H.C.: Light scattering by small particles, Dover Publications, New York, 1981, ISBN: 978-0-4866-4228-4.

[2] Tománek, P., Mikláš, J., Bajgar, A., Grmela, L., Dobis, P., Brüstlová, J., Sensor of back-scattered light polarization in body cells, *Proc. of SPIE*, 2009, vol. 7356, paper 735685, 9 p., ISSN 0277-786X.

[3] Ramachandran, H., Narayanan, A., Two-dimensional imaging through turbid media using a continuous wave light source, *Optics Comm.*, 1998, vol..154, p. 255–260, ISSN: 0030-4018

[4] Morgan,S.P., Khong, M.P., Somekh, M.G., Effects of polarization state and scatterer concentration on optical imaging through scattering media, *Appl. Opt.*, 1997, vol. 36, No. 7, p. 1560-1565, ISSN: 1559-128X.

[5] Vitkin, I.A., Hoskinson, E., Polarization studies in multiply scattering chiral media, *Opt. Eng*. 2000, vol. 39, p. 353-362, ISSN: 0091-3286

[6] Firdous, S, Ikram, M.: Polarized laser beam scattering through turbin medium for application in tissue imaging, *Science Asia*, 2005, vol. 31, p. 167-172, ISSN: 1445-8330

[7] Cheong, W.F., Pprahl, S.A., Welch, A.J. A review of optical properties of biological tissues, *IEEE J. Quant. Electron*., 1990, vol. 26, No. 12, 2166-2185, ISSN: 0018-9197

[8] Jary, G., Steimer, E., Damaschini, V., Epifanie, M., Jurczak, M., Kaiser, R., Coherence and polarization of light propagating through scattering media and biological tissues, *Appl. Opt.*, 1998, vol. 37, No. 1, p. 7357-7367, ISSN: 1559-128X.

[9] Hielscher, A.H., Bartel, S., Diffuse backscattering Mueller matrix analysis for tissue diagnostics with polarized light, *Proc. of SPIE*, 2000, vol. 3917, p. 43-53, ISSN 0277-786X.

[10] Tuchin, V.V., Tissue opics: light scattering methods and instruments for medical ddiagnosis, 2nd edition, SPIE Press, Bellingham, 2007, ISBN: 978-0-8194-6433-0.

[11] Mishchenko, M.I., L D Travis, L.D., Laris, A.A., S*cattering, absorption and emission of light by small particles*, Cambridge University Press, New York, 2002, ISBN: 052178252X.

[12] Ghosh, N., Patel, H. S., Gupta, P. K. Depolarization of light in tissue phantoms – effect of a distribution in the size of scatterers, *Opt. Express*, 2003, Vol. 11, No. 18, p. 2199-2205, ISSN: 1094-4087.

[13] Alexander, M., Dalgleish, D.G., Dynamic light scattering techniques and their applications in food science, *Food Biophys*., 2006, vol.1, No.1, p.2-13, ISSN: 1557-1858.

[14] Tatarskii, V. I., Theory of single scattering by random distributed scatterers, *IEEE Trans. Antenna and Propag.*, 2003, Vol. 51, No. 10, p. 2806-2813, ISSN: 0018-926X.

[15] Abubaker, H.M. Use of scattering matrix in body tissue investigation. In *Proceedings of the 16th Conference STUDENT EEICT 2010, Vol. 5.* Brno: Novpress, 2010. p. 54-58. ISBN: 978-80-214-4080- 7.

[16] Mujumdar, S., Ramachandran, H, Imaging through turbid media using polarization modulation: dependence on scattering anisotropy, *Opt. Comm*., 2004, vol. 241, No.1, p. 1–9, ISSN: 0030-4018.

[17] Damez, J-L., Clerjon, S., Meat quality assessment using biophysical methods related to meat structure, *Meat Sci*., 2008, Vol. 80, No.1, p. 132-149, ISSN: 0309-1740.

[18] Tománek, P., Mikláš, J., Abubaker, H. M., Grmela, L., Optical sensing of polarization states changes in meat due to the ageing. *AIP Conf. Proc*., 2010, Vol. 1288, No. 1, p. 127-131. ISSN: 0094- 243X.