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Polarization Reflectance Spectroscopy: Application in Biophotonics

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ABSTRACT

Polarization Reflectance Spectroscopy (PRS) is an spectroscopic technique based on the multiple scattering of light in a homogeneous medium. PRS adds more to the information we obtain from original reflectance spectroscopy methods and it has been used in many biomedical fields using quantitative studies essential for biomedical diagnostics. PRS provides information about tissue chromophore concentration, chromophore depth distribution and is able to estimate sizes of the scattering object in tissue which could be used to detect neoplastic changes non-invasively. In this review paper, the basic concepts and principles of PRS from the point of view in biophotonics and its applications in biomedical field such as early diagnostics of cataracts and detection of precancer are presented.

Keywords: Polarization Reflectance Spectroscopy, Biophotonics, birefringence, optical properties, tissue, scattering, polarization-sensitive, Stokes vector

1. INTRODUCTION

Optical diagnostics and light based visualization of tissue structures play an important role in experimental and clinical medicine. They provide valuable information while they are not invasive, complicated and expensive. One of these promising methods is Polarization Reflectance Spectroscopy (PRS) of biological tissue that has an abundance of applications in medicine. PRS is capable of obtaining additional information about morphological structure and functional state of the tissue due to its highly sensitivity to the optical properties and dependence on the size of scatterers in the tissue.[1] Quantitatively estimation of the chromophore content in the tissue is possible by Diffuse Reflectance Spectroscopy[2] ,while PRS is capable of chromophore concentration estimation, chromophore depth distribution, and estimation of sizes of the scatterers using Mie theory.[3,4] (There are two types of major chromophores in the human tissue in the visible region of light: melanin and hemoglobin of blood. These chromophores are placed at different depths and have different absorbing band, thus their depth information is obtained using their specific absorbing bands on the differential polarization spectra that will be explained in the following.[5–7])

The depth at which an specific chromophore is located can be estimated through exposure of the tissue sample to the polarized light followed by the measurement of the co-and cross-polarized component of the backscattered light from the tissue.[6] To elaborate on this,[3] when the tissue under study is exposed to the linearly polarized light, three phenomenons in terms of scattering or reflection happen: 1- Specular reflection by the tissue surface. (It has the same polarization as incident light and is contributed to the 5% of all backscattered light.) 2-Reflection from subsurface tissues. (It also has the same polarization as incident light) 3-Diffuse reflection. (Remaining light that is not absorbed by the chromophores in the tissue undergoes several scattering events and it is

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completely randomly polarized with all possible polarization states). Therefore, using separate detection of two perpendicular polarized components of diffusely reflected light, it is possible to obtain the scattering from surface (polarization orientation same as the linearly polarized incident light) and deep layers of a tissue. (polarization orientation orthogonal to the linearly polarized incident light).[3] This is what exactly called polarization-sensitive spectroscopy of elastic scattering, or PRS.

PRS is based on the analysis of the transformations of the polarization state of light scattered by a tissue or medium. First, presence of the structures in tissue with dimensions much bigger than the light wavelength are responsible for large amount of scattering, while scattering randomizes the polarization state of light quickly. Second, existence of the absorbing chromophores in tissue at different depths leads to an increase in the degree of residual polarization of the backscattered light due to the shortening of photon migration trajectories at absorption. In fact, presence of absorbing chromophores lead to smaller average pathlengths of detected backscattered light with a higher degree of polarization.[7] Increased degree of residual polarization of the backscattered light is identified in spectral ranges corresponding to the absorption bands of the chromophores. And third, structural anisotropy in the tissue leads to an anisotropic birefringence effect that will change the polarization state of incident light.[8,9]

It should be mention that the same polarization technique (using linear polarization of incident light) can be used in tissue imaging. The co-polarized component carries information about shallow subsurface of tissue while information about deep tissue layers is obtained from the cross-polarized component. Using this method and further analysis enables to us to have a better image of the subsurface tissue structures.

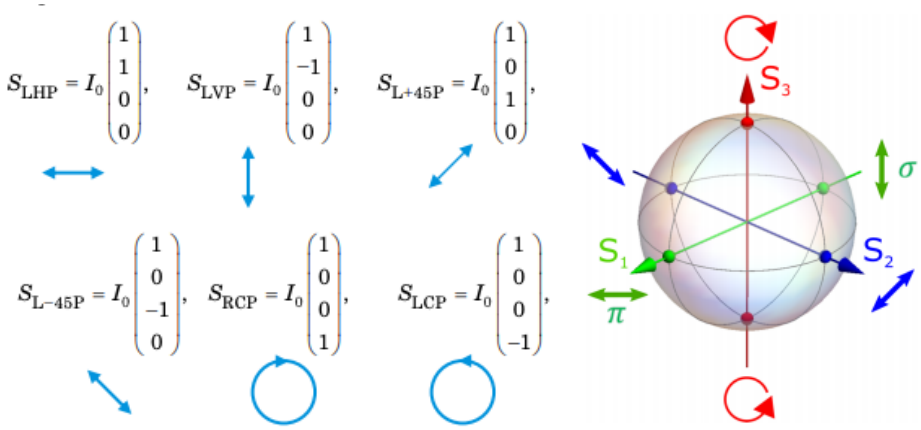
This review paper tries to provide an overview of the state of the art in PRS and its application in Biophotonics. In the following, we will introduce basic concepts and principle of for describing PRS, (section 2) and then, we will discuss applications of PRS in Biophotonics, (section 3) and its future prospects, (section 4).

2. BASIC CONCEPT OF POLARIZATION AND PRS FROM THE VIEWPOINT IN BIOPHOTONICS

The direction of electromagnetic field of light which is perpendicular to the propagation direction describes the polarization state of light. e_x and e_y are the complex-valued field along the x and y direction which describe polarization state of the transverse light which propagates in the z-direction.[10] Jones vector are these two complex-valued where a monochromatic plane wave travels in z-direction.[11]

Different polarization states will happen based on the amplitudes of e_x and e_y and on their respective phase delay δ. A linear polarization state is described by a Jones vector having a relative delay of 0° or 180° and there will be a horizontal or vertical linear state when it oscillates only in x-direction or only in y-direction, respectively. When the amplitude of e_x and e_y are equal, there will be a linear polarization state with an orientation of $+45^\circ$ for $\delta = 0^\circ$, a linear polarization state with an orientation of -45° for $\delta = 180^\circ$, and a right- or left-hand circular polarization state for $\delta = \pm 90^\circ$. Finally, there will be an elliptical polarization state for any arbitrary δ and amplitudes.[10]

Stokes vectors are another representation for the polarization state of light. Stokes vectors are described in a three-dimensional space spanned by horizontal/vertical linear state, $+45^\circ/-45^\circ$ linear state, and right-/left-hand circular state and they are defined by $[I\ Q\ U\ V]$ or $[S_1\ S_2\ S_3\ S_4]$,[12] where I corresponds to the intensity of light, and Q, U, and V are the components along the three axes mentioned above.[12] Stokes vectors for the degenerate polarization states[13] and Poincaré sphere for representation of three Stokes parameters[14] are shown in figure 3.



(a) (b)

Figure 1: (a): Stokes vectors for the degenerate polarization states[13] and (b): Representation of the Poincaré sphere. The coordinates refer to the three Stokes parameters S_1, S_2, and S_3.[14]

There are many papers about propagation of polarized light through the tissue.[15–17] As described before in section 1, polarization state of an incident light on the tissue sample is influenced by the multiple scattering events that happen in the highly scattering medium of the tissue. To put it simply, polarized light loses its original polarization as it propagate deep into the tissue. Aside from the part of the light that is absorbs by tissue chromophores and is multiply scattered deep into the tissue, a small portion of light in the upper epithelial layer preserves its polarization as it experience few scattering events.[4]
In other words, the multiple scattering events lead to a decrease in polarization degree P (equation 1), which is determined by the elements of the Stokes vector of backscattered light from the tissue.[10,18] Stokes vectors in fact characterize the depolarized light.

$$P = \frac{\sqrt{Q^2 + U^2 + V^2}}{I} \tag{1}$$

And in case of fully polarized light $P = 1$, I corresponds to the length of the vector $[Q\ U\ V]$:

$$I = \sqrt{Q^2 + U^2 + V^2} \tag{2}$$

In several cases, polarized based diagnostics of tissue can be done by using initial linear polarization for the incident light and assessment of the degree of polarization of linear backscattered light simply.[5]
Considering this, the degree of polarization will be equal to:

$$P_L = \frac{\sqrt{Q}}{I} = \frac{I_{\parallel} - I\perp}{I_{\parallel} + I\perp} \tag{3}$$

Where $I_{\parallel}$ and $I_{\perp}$ are the intensities of the co- and cross-polarized components of backscattered light, respectively.[5] The degree of polarization P_L depends on the wavelength of incident light, detection of backscattered light, and morphological structure of the biological tissue sample which means that the degree of polarization can be used as an important parameter for subsequent diagnostics and medical applications.[19,20]

Figure 2 shows a schematic of the experimental setup of the PRS to record the polarization spectra of a backscattered light for both tissue like phantom and for in vivo tissues samples (normal human skin and skin with erythema).[21] Illumination optical fiber 2 delivers the light form the light source 1 (a halogen lamp of power 200 W) to the sample 6. The incident light from the source is linearly polarized due to passing through wideband polarization filter 4, and the backscattered light from the tissue sample that reaches the optical multichannel spectrum analyzer 7 via the collection optical fiber 3 becomes linearly polarized after passing through polarization filter 5 (Orientation of backscattered polarized light can be parallel or orthogonal using the relevant polarization filter with respect to the polarization state of incident light).[21] In this way, $R_{\parallel}(\lambda)$ and $R_{\perp}(\lambda)$ of diffusely reflected light can be measured using described setup and using relevant polarization filters.
Difference polarization spectra $\Delta R(\lambda)$ and degree of residual polarization of light reflected from the sample $P_L^r(\lambda)$ will be expressed as follow:

$$\Delta R(\lambda) = R_{\parallel}(\lambda) - R_{\perp}(\lambda) \tag{4}$$

$$P_L^r(\lambda) = \frac{R_{\parallel}(\lambda) - R_{\perp}(\lambda)}{R_{\parallel}(\lambda) + R_{\perp}(\lambda)} \tag{5}$$

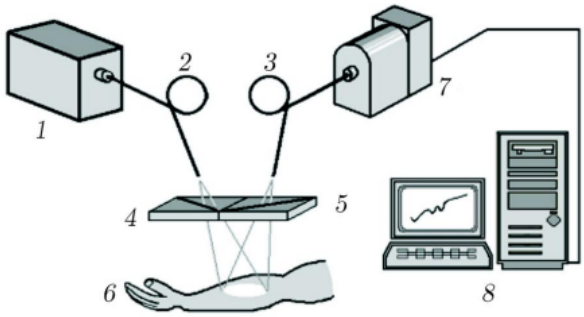
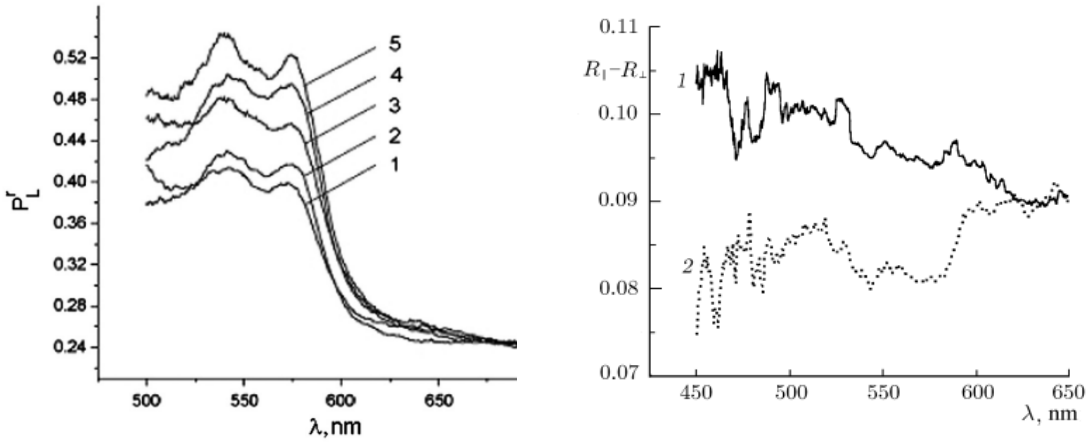


Figure 2: Scheme of the experimental setup of the PRS: 1, light source (halogen lamp); 2 and 3, the optical fiber; 4 and 5, the polarization filters; 6, tissue sample; 7, the optical multichannel analyzer; 8, the computer.[21]

It is discussed in detail in the Kiseleva et el's work,[21] but in this experiment, increased degree of residual polarization $P_L^r(\lambda)$ of the backscattered light along with increasing erythema grade is observed in the spectral ranges corresponding to the absorption bands of the blood chromophores and melanin (Figure 3a). This is a consequence of smaller average pathlengths of detected backscatteredlight while the light is absorbed by more chromophores as erythema index increases (Figure 3a).
Moreover, appearance of absorption bands of hemoglobin (at 545 and 575 nm) in the difference polarization spectrum $\Delta R(\lambda)$ during layer-by-layer removal of surface layers of epidermis is observed too (Figure 3b). This is also result of the thickening of the epidermis by removing its layers while absorption bands of hemoglobin is not observed in the difference polarization spectrum $\Delta R(\lambda)$ when the erythema is created by UV radiation while the erythema index is the same for two measurements (Figure 3b).



(a) (b)

Figure 3: (a): Degree of residual polarization spectra of linearly polarized incident light diffusely reflected by human skin with different erythema grades: 1 corresponds to the erythema index EI= 157, 2 – EI=223, 3 – EI=249, 4 – EI=275, and 5 – EI=290.[21] and (b): Difference polarization spectra $\Delta R(\lambda)$ of light diffusely reflected by epidermatose skin. Curve 1 corresponds to EI = 294, erythema is created by UV irradiation. Curve 2 corresponds to EI = 299, erythema appeared as a result of partial removal of epidermis.[5,21]

3. APPLICATIONS OF POLARIZATION REFLECTANCE SPECTROSCOPY IN BIOPHOTONICS

In general, there are abundance of works based on polarization measurements of biological structures, like early recognition of cataract,[22,23] polarimetry of transparent eye tissues for glucose concentration estimation.[24–26] It has also been shown that the quality of images of macroscopic inhomogeneities in a scattering medium improves when it is exposed to the linearly polarized light.[7,27–29]

PRS itself has many applications in biomedical field due to its ability to yield valuable data while is one of the easy methods of optical investigation without the need for tissue removal.

To begin, Precancerous lesions are identified by changes in structural tissue morphology and these changes will be shown in the polarization reflectance spectra of Precancerous tissues and cancerous changes. Most of the cancers are of epithelial origin and are characterized by increased nuclear size, increased nuclear/cytoplasmic ratio, hyperchromasia and pleomorphism. Early detection of epithelial neoplasia is crucial for the patient health. Scatterer sizes and refractive indices can be obtained using PRS and be used in biomedical diagnostics.[4]

Using suspensions of polystyrene spheres and Intralipid as a tissue like phantom, Mourant et al have shown that the sizes of scattering particles can be obtained from PRS spectra using Mie theory.[30] Backman et al. used single backscattering spectrum obtained from in situ method of probing the structure of living epithelial cells, based on the PRS to provide information about the epithelial cells such as their nuclei size distribution and refractive index.[31] Perelman et al. observed a fine structure component in backscattered light originated from Mie scattered light by surface epithelial cell nuclei from mucosal tissue which is normally covered by a diffusive background.[32] The density and size distribution of these nuclei can be important indicators of precancerous changes.

Assessment of tissue viability based on polarization spectroscopy also has been studied.[33] This viability method investigation could be useful in drug and skin care product development and many clinic case situations. More-

over, the size distribution of changes in refractive index structure of epithelial cells as well as in nuclei isolated from epithelial cells has been observed from measurements of the angular dependence of polarized light scattering.[34]

It also has been shown that a large amount of diffusive background and tissue chromophore absorption could be reduced using detection of parallel and perpendicular polarizations of reflectance spectra.[4]

Another interesting published report of using PRS is to find the effect of the optical anisotropy of scattering media like tissue (rat skin) on the polarization state of scattered light.[1] The result shows that surface tissues can be characterized by a high degree of orientational order of the local optical axis of a medium within large areas.[1]

Localization and visualization of structural inhomogeneities of tissues at different depths form the analysis of the polarized backscattered spectra has also been shown. It is reported that small changes in composition of tissue phantoms is identified in the wavelength-dependent polarization reflectance spectra.[15] It is been reported that subsurface polarization spectral imaging based on analysis of spectra of the polarization degree and polarization difference can be used to detect subsurface lesions and to evaluate their depth location.[21]

An example of using fiber optic probe in PRS for direct estimation of sizes and size distributions of nuclei in has been reported in reference.[35] Suspension of polystyrene spheres placed atop a diffusely scattering substrate and in vivo measurements of oral cavity mucosa have been investigated. This fiber based PRS with useful result about morphological parameters of nuclei paves the way for the clinical applications of PRS.

4. SUMMARY AND FUTURE PROSPECTS

In this review paper, we provided a brief description polarization of light followed by polarization-sensitive spectroscopy of elastic scattering or polarization reflectance spectroscopy, its basic principles and a few results from one of the published paper about polarization reflectance spectroscopy of human skin. PRS is actually an extension of diffuse reflectance spectroscopy and only some modifications in common diffuse reflectance spectroscopy system will make a polarization sensitive version of diffuse reflectance spectroscopy which is PRS. Moreover, the results of the mentioned paper are compatible with what is explained through the whole paper about powerful ability of PRS for detection of subsurface lesions and an increase of the polarization degree according to the higher amount of absorbance in tissue structure. Finally, applications of PRS in biomedical field both in vivo and vitro are described in the section 3. It is obvious that PRS is able to provide useful information about the tissue and can be helpful in diagnostics and identifying any abnormalities.

The future prospect of this method is to make the already existed fiber based PRS systems more robust and easy to use in the clinical situation. There should be some possibilities for assessment of other type of tissues and brain structure with PRS and obtain extra precious information. Moreover, almost all the works according to PRS has been done using linear polarization state of the light while using other polarization states like circular polarized light may be useful and lead to extra findings. Finally, there will be a lot of opportunities for simulations of PRS and validating its ability like using Monte Carlo simulation.

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