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Towards skin polarization characterization using polarimetric technique

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Abstract: Measurement of optical properties of skin is an expanding and growing field of research. Recent studies have shown that the biological tissue, especially skin, changes the polarization state of the incident light. Using this property will enable the study of abnormalities and diseases that alter not only the light intensity but also its polarization state. In this paper we report an experimental study for measuring changes of polarization state of the light scattered from a phantom similar to a sample model of scattering skin. Using the notation of Stokes vector for the polarized light and Mueller matrix for the sample with its polarization properties, we have shown that some elements of the matrix were particularly sensitive to the changes of the polarization-altering physical properties of the scatterers within the phantom.

Key words: Polarization, Skin, Phantom, Scattering polarimetry, Mueller matrix, Stokes vector
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INTRODUCTION

Development of appropriate diagnostic techniques for measuring and monitoring skin abnormalities is currently one of the challenging areas of research (Sidorchuk, 2002; Andreassi *et al*., 2004; Matuszak and Radwanska, 2006; Beard, 2008). Most of diagnostic methods and evaluation methods for measuring the progress of skin disease are based on visual examination by dermatologists (Andreassi *et al*., 2004; Skvara *et al*., 2005; Celebi *et al*., 2008). Therefore, reliability and repeatability of such methods are almost questionable. Skin shows absorption and scattering properties when it is exposed to light. Most of available methods are based on measuring intensity of reflected, scattered or transmitted light. Techniques like microscopy or dermatoscopy are able to only diagnose physical parameters that make changes to the light intensity (Andreassi *et al*., 2004; Beard, 2008). Researches have shown that biological tissue can affect the polarization state of the incident light. The main polarization-altering agents of skin are scattering particles like nuclei cells and mitochondria, and collagen fibers that demonstrate birefringent effect (Amos and White, 2003). Development of skin abnormalities can also change the polarization state of the scattered light (Baba *et al*., 2002; Cerny *et al*., 2007). Therefore, the progress of such diseases could be measured and monitored by measuring the changes in the polarization state.

Polarized light can be represented mathematically by a 4×1 vector known as the Stokes vector (Perry *et al*., 1978; Azzam and Bashara, 1987; Bohren and Huffman, 1998). By measuring the Stokes vector of the scattered light from an object and comparing its elements with those of the incident light, we can obtain a 4×4 matrix known as the Mueller matrix characterizing the object under study. Each of the 16 elements of the Mueller matrix depends on the polarization-altering features of the object affecting the polarization state of the light. Polarization-altering components of skin could illustrate different polarization properties based on their shape, size, composition, structure, etc. The objective of this paper is to show the sensitivity of some elements of the matrix to the changes of physical properties of scatterers and collagen fibers, using the notation of Stokes vector for the polarized light and Mueller matrix for the skin.

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We have used a polarimetric experimental setup to measure the elements of the Mueller matrix of a phantom similar to the biologic skin with scattering and polarization properties. Our results have shown that polarimetry is a valuable technique that can be used for measuring the change in scattering and polarization properties of skin and can be developed as a suitable diagnostic tool for measuring skin abnormalities.

MATERIALS AND METHODS

Theory

In scattering polarimetry, a beam of light of arbitrary polarization is represented mathematically by a 4×1 column vector known as the Stokes vector. Its elements, the Stokes parameters, are usually labeled I, Q, U, and V, and defined in terms of electrical field amplitudes parallel $E_{\parallel}$ and perpendicular $E_{\perp}$ to the scattering plane (Perry *et al.*, 1978; Bohren and Huffman, 1998):

$$\begin{aligned} I &= \left\langle E_{\parallel}E_{\parallel}^{*} + E_{\perp}E_{\perp}^{*} \right\rangle = I_{\mathrm{H}} + I_{\mathrm{V}}, \\ Q &= \left\langle E_{\parallel}E_{\parallel}^{*} - E_{\perp}E_{\perp}^{*} \right\rangle = I_{\mathrm{H}} - I_{\mathrm{V}}, \\ U &= \left\langle E_{\parallel}E_{\perp}^{*} + E_{\perp}E_{\parallel}^{*} \right\rangle = I_{\mathrm{P}} - I_{\mathrm{M}}, \\ V &= i\left\langle E_{\parallel}E_{\perp}^{*} - E_{\perp}E_{\parallel}^{*} \right\rangle = I_{\mathrm{R}} - I_{\mathrm{L}}, \end{aligned} \tag{1}$$

where parameters are defined as follows: *, complex conjugate; $\langle\ \rangle$, time averaging over the interval long compared with the period; $E_{\parallel}$, amplitude of electric field parallel to the scattering plane; $E_{\perp}$, amplitude of electric field perpendicular to the scattering plane; I, light intensity; H, horizontal state of polarization; V, vertical state of polarization; P, +45° linear state of polarization; M, −45° linear state of polarization; R, right circular state of polarization; L, left circular state of polarization.

It can be shown that, in general, $I^2 \geq Q^2+U^2+V^2$. The equality holds if the light is strictly monochromatic or completely polarized. For unpolarized light, $Q=U=V=0$. In general, the degree of polarization (DOP), degree of linear polarization (DOLP) and degree of circular polarization (DOCP) can be calculated from Stokes elements (Azzam and Bashara, 1987):

$$\begin{aligned} DOP &= \sqrt{Q^2+U^2+V^2}\,/\,I, \\ DOLP &= \sqrt{Q^2+U^2}\,/\,I, \\ DOCP &= V\,/\,I. \end{aligned} \tag{2}$$

For a partially polarized beam the sign of V indicates the preferential handedness of the vibration ellipse traced out by the electric field vector (Yao and Wang, 2000).

In general, the polarization state of a light beam is changed on interaction with a polarization-altering object (for example, polarizer, retarder, reflector, and scatterer). It is possible to represent such an object by a 4×4 matrix known as the Mueller matrix. If the incident beam Stokes vector is denoted by $\boldsymbol{S}_{\mathrm{in}}$ and the Mueller matrix of the system by $\boldsymbol{M}$, the Stokes vector of outgoing beam $\boldsymbol{S}_{\mathrm{out}}$ is obtained by (Bohren and Huffman, 1998):

$$\boldsymbol{S}_{\mathrm{out}}=\boldsymbol{M}\boldsymbol{S}_{\mathrm{in}}. \tag{3}$$

The Mueller matrix representing a scattering medium is termed the scattering matrix. The Stokes vectors $\boldsymbol{S}_{\mathrm{in}}$ and $\boldsymbol{S}_{\mathrm{out}}$, representing the incident and scattered beams respectively, are then related by the following matrix equation:

$$\begin{bmatrix} I_{\mathrm{out}} \\ Q_{\mathrm{out}} \\ U_{\mathrm{out}} \\ V_{\mathrm{out}} \end{bmatrix} = \frac{1}{k^2r^2} \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \begin{bmatrix} I_{\mathrm{in}} \\ Q_{\mathrm{in}} \\ U_{\mathrm{in}} \\ V_{\mathrm{in}} \end{bmatrix}, \tag{4}$$

where parameters are defined as follows: S_{ij}, elements of the scattering Mueller matrix; k, wave number of the medium surrounding the particles; r, distance between the observation point and any scatterer in the medium.

Each element of the scattering matrix is angle-dependent function of wavelength, size, shape, and composition of the scatterers within the scattering medium. To measure all the 16 elements of the scattering matrix, a combination of a light source, polarizer and retarder in the incident path and a combination of polarizer (analyzer), retarder, and detector in the detecting path are required. A required polarization state can be generated using appropriate selection of the azimuth angle of the polarizer and retarder in the incident path. The polarization state of the beam emerging from the scattering medium can be measured by appropriate adjustment of the azimuth angles of the polarizer and retarder and noting the intensity of the detected signal in the detecting path.

It can be shown that using the following suggested positions for the polarization elements in the incident and detecting paths, all the elements of the scattering matrix can be calculated (Hariharan, 1992; Cameron *et al*., 1998; Roma and Dinescu, 2008):

$$\boldsymbol{M}=\begin{bmatrix} I_{HH}+I_{HV}+I_{VH}+I_{VV} & I_{HH}+I_{HV}-I_{VH}-I_{VV} & I_{PH}+I_{PV}-I_{MH}-I_{MV} & I_{RH}+I_{RV}-I_{LH}-I_{LV} \\ I_{HH}-I_{HV}+I_{VH}-I_{VV} & I_{HH}-I_{HV}-I_{VH}+I_{VV} & I_{PH}-I_{PV}-I_{MH}+I_{MV} & I_{RH}-I_{RV}-I_{LH}+I_{LV} \\ I_{HP}+I_{HM}-I_{VP}-I_{VM} & I_{HP}-I_{HM}-I_{VP}+I_{VM} & I_{PP}-I_{PM}-I_{MP}+I_{MM} & I_{RP}-I_{RM}-I_{LP}+I_{LM} \\ I_{HR}-I_{HL}+I_{VR}-I_{VL} & I_{HR}-I_{HL}-I_{VR}+I_{VL} & I_{PR}-I_{PL}-I_{MR}+I_{ML} & I_{RR}-I_{RL}-I_{LR}+I_{LL} \end{bmatrix}. \quad (5)$$

In Eq.(5), each element of the matrix is obtained by adding the detected intensities in response to different polarizer and retarder settings in the incident and detecting paths. For example, I_{HH} denotes the detected light intensity in responded to horizontal polarization setting in the incident path and horizontal polarization setting in the detecting path. I_{HV} represents a next experiment by changing the polarizer setting in the detecting path to vertical position. Table 1 shows the complete notations.

Table 1 Notations for Eq.(5)

Detecting path	Incident path					
	H	V	P	M	R	L
H	I_{HH}	I_{VH}	I_{PH}	I_{MH}	I_{RH}	I_{LH}
V	I_{HV}	I_{VV}	I_{PV}	I_{MV}	I_{RV}	I_{LV}
P	I_{HP}	I_{VP}	I_{PP}	I_{MP}	I_{RP}	I_{LP}
M	I_{HM}	I_{VM}	I_{PM}	I_{MM}	I_{RM}	I_{LM}
R	I_{HR}	I_{VR}	I_{PR}	I_{MR}	I_{RR}	I_{LR}
L	I_{HL}	I_{VL}	I_{PL}	I_{ML}	I_{RL}	I_{LL}

H: horizontal polarization; V: vertical polarization; P: +45° linear polarization; M: −45° linear polarization; R: right circular polarization; L: left circular polarization

Preparation of skin phantom

In some previously published studies, researchers have made use of water, epoxy resin, polyester, etc. to produce skin-like phantoms. The objective has been to generate a phantom with a homogenous matrix with an acceptable stability (Roma and Dinescu, 2008; Gangnus *et al*., 2004). The use of phantoms such as Intralipid in water, titanium dioxide in agar, glass microspheres in epoxy resin, epoxy resin with titanium dioxide, and glass microspheres in polyester has been recommended for optical and polarization study of skin (Gangnus *et al*., 2004; Meglinski and Matcher, 2002; Pogue and Patterson, 2006). In our study we used epoxy resin with titanium dioxide (TiO_2) as a stable phantom for our polarization measurements. The materials that we used were epoxy resin EM-8037 (Epoxiran, Iran), hardener (Epoxiran, Iran) and titanium particles (Kemira, Finland), which were added to epoxy resin to resemble skin scatterers.

Experimental setup

We set up a laboratory-based scattering polarimetric system using appropriate optical devices such as a laser source (HeNe laser, λ=632.8 nm, 7.5 mW), two wide band polarizer plates, two quarter (1/4) wave plates (retarders), two collimating lenses to focus laser on the sample and to collect the scattered light from the sample, and an optical detector. The block and schematic diagrams of the system are shown in Figs.1 and 2. A photograph of the system is shown in Fig.3. As shown, the light source, lens, polarizer and retarder form the polarization state generator (PSG) unit. The PSG unit generates the polarized light with arbitrary states of polarization. After interaction with the sample (skin-mimicking phantom), the scattered light is received by the polarization state detector (PSD) unit that consists of

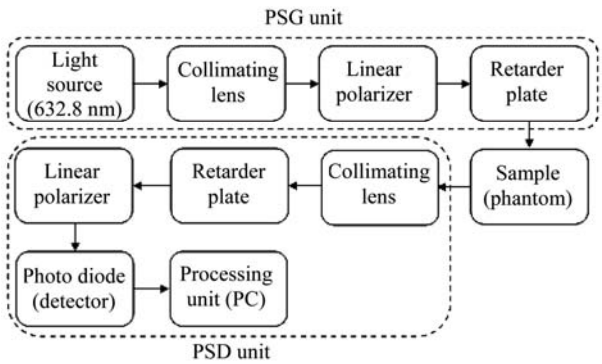

Fig.1 Block diagram of the prepared polarimetry system

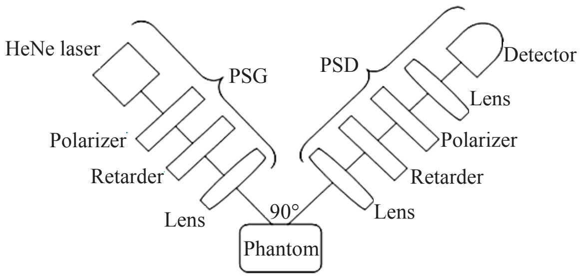

Fig.2 Schematic diagram of the prepared polarimetry system

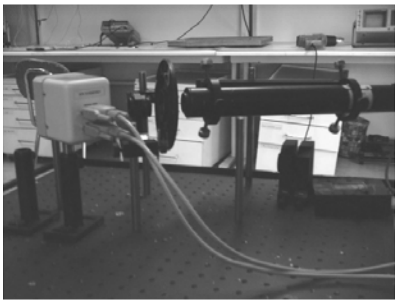

Fig.3 A photograph from the polarimetric experimental setup

lens, retarder, polarizer, and optical detector. The scattering angle for measurements was set to 90°.

By making comparison between polarization states of the incident light and scattered light, we can extract the polarization ellipse of the scattered light and elements of the Mueller matrix of the scattering phantom.

In our experiment we used a commercially available PSD module from Thorlabs (Thorlabs PA500, UK) to measure the polarization state of light being scattered from the sample. A number of different phantoms were prepared and used for the measurements. These included epoxy resins with and without the TiO_2 particles. We used two different quality types of TiO_2 scatterers. The first type of TiO_2 particles had non-spherical shape and the second type was near-spherical as observed by a scanning electron microscope (Philips XL30, Holland).

The objective of using the above particles was to study the presence of the scatterers resembling nuclei cells and mitochondria, and also check on the sensitivity of the technique to the change in shape of the scatterers. In order to study the birefringence properties of skin, in the next step, we prepared phantom of epoxy resin with TiO_2 spherical scatterers but added fiber glass threads to resemble collagen fibers in the skin. It is worth mentioning that during the formation process, the fiber glass is subjected to a high mechanical tension. Under such stress, the fiber material will become birefringent (Gupta, 1988; Onofri *et al.*, 2003).

According to Eq.(5), it is necessary to make the 16 independent measurements for calculating the elements of the Mueller matrix. So, we had to make 4 individual polarimetric measurements with 4 different incident polarized light states (vertical, horizontal, +45°, and right circular).

RESULTS

Initially, we carried out some calibration tests to evaluate the performance of the system. We used a polarizer and retarder, with known polarimetric properties, in place of the sample, and measured their Mueller matrices. The calibration tests were repeated and adjustments were made until we obtained their Mueller matrices in agreement with the references (Bohren and Huffman, 1998; Azzam and Bashara, 1987) within the instrumentation accuracy (±1.0%). As we mentioned before, we used a commercially available PSD module, which has its own calibration file provided by the manufacturer.

The measurements for the prepared phantoms were repeated 10 times to check the repeatability of the results. The results of the polarimetric measurements for obtaining the Mueller matrices of epoxy resins with and without near-spherical TiO_2 particles are shown in Table 2. All elements of the Mueller matrix are normalized to the first elements S_{11}. The comparison between the results of these two samples is shown in Fig.4.

From Table 2, S_{23}, S_{31}, S_{33}, S_{34}, S_{43}, and S_{44} show considerable sensitivity to the presence of the scatterers. It is clear from Fig.4 that S_{23} shows the highest sensitivity to the presence of scattering particles.

The results of the polarimetric measurements of epoxy resin with non-spherical TiO_2 particles compared with those of epoxy resin with near-spherical TiO_2 particles are shown in Table 3. A comparison between results is shown in Table 3 and Fig.5.

From Table 3, S_{23}, S_{24}, and S_{44} show considerable sensitivity to the change in shape between the two types of scatterers. Also from Fig.5 it is evident that S_{23} is the most sensitive marker for the shape of the scatterers.

Table 4 shows the results of the polarimetric measurements for obtaining the Mueller matrices of epoxy resin with near-spherical TiO_2 particles compared with the same type of scatterers but with added fiber glass threads to create birefringence property.

From the Table 4, S_{22}, S_{24}, S_{32}, S_{33}, and S_{34} show considerable sensitivity to the presence of fiber glass threads. From Fig.6 we can say that S_{24} is the most sensitive marker for the presence of fiberglass threads or birefringent activity of the phantom.

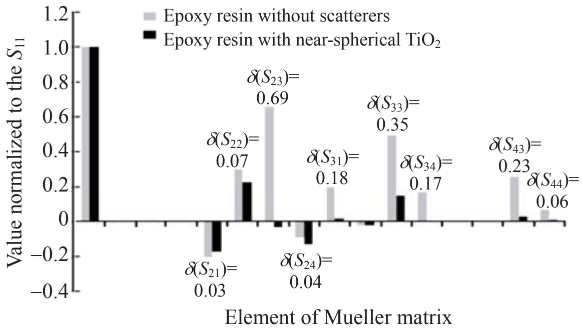

Fig.4 Comparison between the results of measurements from epoxy resins without and with the scatterers (Table 2); differences δ(S_{ij}) are shown on each chart

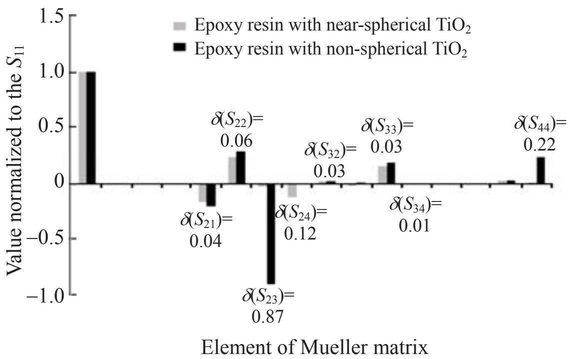

Fig.5 Comparison between the results of measurements from epoxy resins with near-spherical and non-spherical scatterers (Table 3); differences δ(S_{ij}) are shown on each chart

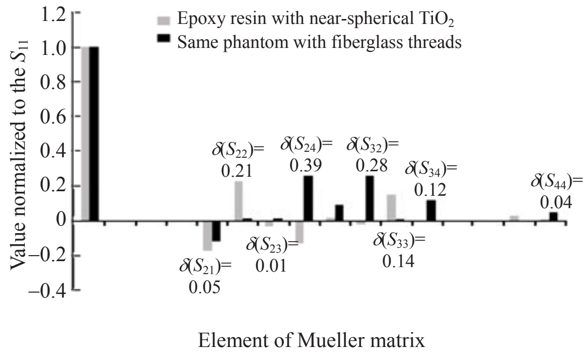

Fig.6 Comparison between the results of measurements from epoxy resin with near-spherical scatterers and the same phantom with added fiberglass threads (Table 4); differences δ(S_{ij}) are shown on each chart

Table 2 Elements of Mueller matrices obtained for epoxy resin without scatterers and epoxy resin with near-spherical TiO_2 particles

M_{resin}	S_{i1}		S_{i2}		S_{i3}		S_{i4}	
	ER1	ER2	ER1	ER2	ER1	ER2	ER1	ER2
S_{1j}	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
S_{2j}	−0.20	−0.17	0.30	0.23	0.66	−0.03	−0.09	−0.13
S_{3j}	0.20	0.02	−0.02	−0.02	0.50	0.15	0.17	0.00
S_{4j}	0.00	0.00	0.00	0.00	0.26	0.03	0.07	0.01

i, j=1~4. ER1: epoxy resin without scatterers; ER2: epoxy resin with near-spherical TiO_2 particles. The values of whole elements have been normalized to the values of S_{11}

Table 3 Elements of Mueller matrices obtained for epoxy resin with near-spherical TiO_2 and non-spherical TiO_2 scatterers

M_{resin}	S_{i1}		S_{i2}		S_{i3}		S_{i4}	
	ER2	ER3	ER2	ER3	ER2	ER3	ER2	ER3
S_{1j}	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
S_{2j}	−0.17	−0.21	0.23	0.29	−0.03	−0.90	−0.13	−0.01
S_{3j}	0.02	0.02	−0.02	0.01	0.15	0.18	0.00	−0.01
S_{4j}	0.00	0.00	0.00	0.00	0.03	0.03	0.01	0.23

i, j=1~4. ER2: epoxy resin with near-spherical TiO_2 particles; ER3: epoxy resin with non-spherical TiO_2 particles. The values of whole elements have been normalized to the values of S_{11}

Table 4 Elements of Mueller matrices obtained for epoxy resin with near-spherical TiO_2 and the same phantom with added fiberglass threads

$\boldsymbol{M}_{resin}$	S_{i1}		S_{i2}		S_{i3}		S_{i4}	
	ER2	ER4	ER2	ER4	ER2	ER4	ER2	ER4
S_{1j}	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
S_{2j}	−0.17	−0.12	0.23	0.02	−0.03	0.02	−0.13	0.26
S_{3j}	0.02	0.09	−0.02	0.26	0.15	0.01	0.00	0.12
S_{4j}	0.00	0.00	0.00	0.00	0.03	0.00	0.01	0.05

i, j=1~4. ER2: epoxy resin with near-spherical TiO_2 particles; ER4: epoxy resin of the same type with added fiberglass threads. The values of whole elements have been normalized to the values of S_{11}

DISCUSSION AND CONCLUSION

In this paper, we presented the potential application of polarimetric technique for measuring polarization properties of skin. We carried out measurements of elements of the Mueller matrices of epoxy resin samples with TiO_2 scatterers with and without birefringent fiber glass threads, resembling skin with scattering and birefringent properties.

The results presented are in good agreement with the theory that each element of the scattering matrix is dependent on the polarization-altering properties of the particulate medium including the presence of the scatterers, their size and shape, and the birefringence property. As mentioned, the sensitivity of elements is due to the orientation of the electrical field vector with respect to the assumed scattering plane within the particulate medium. Any change to such scattering medium will change the orientation of the electrical field vector. Also, the results presented are in good agreement with experimental results from previously published studies (Yang *et al*., 2003; Viktin *et al*., 2002; Ishimaru *et al*., 2001; Firdous and Ikram, 2005).

The results show that some elements of the matrix were particularly sensitive to the presence of scatterers and their shape. Also, the results demonstrate the sensitivity of some particular elements to the birefringent effect of the sample. It is evident that S_{24} is particularly sensitive to the birefringence property of skin phantom. Also S_{23} shows the maximum sensitivity to the presence and change in shape of the scatterers.

The choice of the scattering angle of 90° has been arbitrary. As mentioned earlier, the elements of the matrix are angle-dependent functions of the polarization-altering properties of the particulate medium. This means that other angles could be selected. However, the sensitive elements could vary in their sensitivity to the particular polarization-altering property. For example, instead of S_{23}, another element may have emerged with highest sensitivity to the presence of the scatterers within the medium. The choice of 90° scattering angle provides a practical setup with view of the development of a future compact system for skin measurement.

Although the introduction of fiber glass threads was meant to produce birefringence effect to the particulate medium, it is worth mentioning that the changes in elements of the Mueller scattering matrix, though highly dependent on the birefringence effect, can be due to the introduction of scattering by cylindrical fiber glass threads. This requires a future investigation, using appropriate experimental setup, to differentiate the effect of birefringence and scattering by cylindrical particles. The choice of a scattering angle can play a vital role in such an investigation. It is recommended to do such investigation over a number of scattering angles and use the theory, to find the appropriate angle that can differentiate these two effects.

The above results show the applicability of the polarimetric technique that can be developed by designing an appropriate system for measuring polarization properties of skin in a clinical laboratory. The sensitive elements of the Mueller matrix can represent biomarkers of polarization-dependent scattering and birefringent elements of the skin in such studies. Furthermore, the sensitivity of the elements of the Mueller matrix to the size and shape of the scatterers and birefringent properties of the skin can be employed for the measurement or monitoring of specific abnormalities in the skin such as parakeratosis, epithelial precancerous lesions, or skin cancer.

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