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# Using Mueller's formalism in differentiation of irradiate collagen from non-irradiate one based on polarimetric measurements

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In this paper, we propose a method to apply the polarimetry in biology using our single channel polarimetric system. We study the effect of irradiation on a class of protein – the collagen of the skin. Firstly, we present Mueller's formalism and the difficulties encountered in extracting information from Mueller's matrix due to the fact that all optical properties are mixed in it. Our solution is to globally characterize media through the Poincaré formalism, an index of depolarization and an index of entropy. Secondly, we briefly present our experimental setup and use these indexes to differentiate irradiate collagen from non-irradiate one.

Keywords: Mueller's matrices, depolarization index, Poincaré formalism.

## 1. Introduction

The principle of this method consits in studying several interactions between laser and matter following the different states of polarization for the input light. In fact, it is well known, for example, that a linearly polarized coherent light is less depolarized than a circularly polarized one in scattering media [2]. Taking this fact as a starting point, we proceed with the aim to propose an aid in medical diagnosis in dermatology. We based our protocol on the Stokes–Mueller formalism. Mueller's matrix is a 4×4 matrix which represents the transfer matrix between an incident Stoke's vector and the corresponding output vector. This Mueller's matrix may describe completely the optical polarimetric properties of the media. To obtain this matrix, we use a single channel polarimeter [13]. The intensity matrix (4×4) is obtained with combinations of input-output polarizers-analyzers. From this matrix, it is easy to find Mueller's matrix by linear combinations [10] of the components of the intensity matrix. The optical properties of the sample are mixed in the components of Mueller's matrix [1]. First, we establish Mueller's matrix of the sample. Second, we characterize this sample with indices calculated from it. Thus, we show an application to discriminate irradiate collagen from non-irradiate one (with X radiation).

# 2. Theoretical principle

## 2.1. Mueller's matrix

Our experimental process is the exploitation of the Stoke–Mueller formalism based on the following equation:

$$S_s = MS_e \tag{1}$$

with $S_s$ being the output vector and $S_e$ the input vector. Stoke's vectors present a general form given by Eq. (4). In our experiment only the first term of this vector is important, because it is the intensity measured by the sensor

$$S = \begin{bmatrix} E_x^2 + E_y^2 \\ E_x^2 - E_y^2 \\ 2E_x E_y \cos\varphi \\ 2E_x E_y \sin\varphi \end{bmatrix}. \tag{2}$$

The objective is to determine Mueller's matrix from this formalism. Due to our experimental setup, we have:

$$S_s = M_{\text{analyzer}} M_{\text{medium}} M_{\text{polarizer}} S_e. \tag{3}$$

The judicious combinations of polarizers at the input and analyzers at the output permit us to define sixteen equations between the components of the intensity measurement matrix and the components of Mueller's matrix from the previous equation. Concerning Mueller's matrix, it seems impossible to expose its sixteen terms one by one because the optical properties are mixed in several terms. Nevertheless, the literature data permits us to discriminate between the following terms [11] [9], as

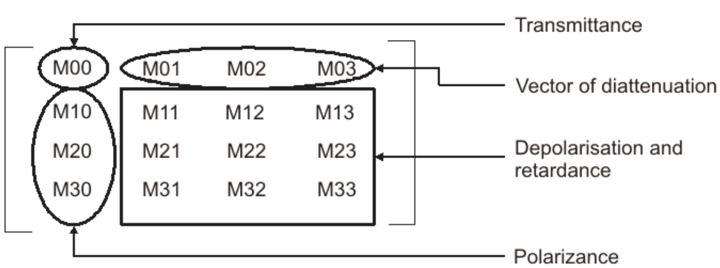


Fig. 1. Mueller's matrix and classification of its terms.

presented in Fig. 1. This is a more general form of Mueller's matrix which represents a depolarized medium.

Here, we define:

1. Diattenuation is the dependence of the transmittance following the incident states of polarization; we may express a diattenuation vector with three terms of Mueller's matrix; horizontal diattenuation (M01), 45° diattenuation (M02) and circular diattenuation (M03) [7]. The calculus of the norm of the vector of horizontal and 45° diattenuation (M01, M02) gives us a linear diattenuation which shows a linear dichroism. We see here an equivalence between the Mueller's matrix parameters and the optical properties of the medium.

2. Retardation characterises the dependence of the optic way relating to the incident states of polarization. It is equivalent to the properties of birefringence and optical activities of the media.

3. Depolarization is the ability of the sample to depolarize any polarized incident beam.

4. Polarization represents the capability of the media to polarize any unpolarized incident light.

Note that, from a theoretical point of view, contrary to Fig. 1, depolarization is statistically present in all the terms of the matrix but, currently, it is theoretically impossible to exactly extract the depolarization. That is the reason why, in Fig. 1, we expressed the terms of depolarization, which we are able to extract through several decompositions of Mueller's matrix [9], [11].

## 2.2. Theoretical explanation

At this point, considering an anisotropic depolarizing Mueller's matrix, which often represents the real case, it is not yet possible to extract all these optical properties because depolarization interacts with all the terms of the matrix. So we may discriminate medium only by a global vision of its optical response through the Poincaré formalism and by two indices: the index of depolarization and the index of entropy.

### 2.2.1. Poincaré formalism

Consider the representation of Poincaré. It is relatively easy to express Stoke's vector components as a function of the coordinate of Poincaré sphere in the particular case of the totally polarized light

$$\begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} 1 \\ \cos 2\varepsilon \cos 2\theta \\ \cos 2\varepsilon \sin 2\theta \\ \sin 2\varepsilon \end{bmatrix} \tag{4}$$

where $\varepsilon$ and $\theta$ represent the ellipticity and the azimuth of the ellipse of polarization, respectively. But, if the form of Eq. (4) is exact for any polarized light, it is not the case if the light is partially or totally depolarized. So, let us take again Eq. (1):

$$\begin{bmatrix} S_{s_0} \\ S_{s_1} \\ S_{s_2} \\ S_{s_3} \end{bmatrix} = \begin{bmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & m_{23} \\ m_{30} & m_{31} & m_{32} & m_{33} \end{bmatrix} \begin{bmatrix} S_{e_0} \\ S_{e_1} \\ S_{e_2} \\ S_{e_3} \end{bmatrix}. \tag{5}$$

To quantify the loss of polarization, we need to introduce the degree of polarization

$$P_d = \sqrt{\frac{S_{s_1}^2 + S_{s_2}^2 + S_{s_3}^2}{S_{s_0}^2}} \tag{6}$$

where $P_d$ is comprised between 0 and 1 ($P_d = 1$ for a totally polarized light and $P_d = 0$ for unpolarized light). So, after the experimental measurement of Mueller's matrix of the medium, it is possible to simulate all the outgoing normalized Stoke's vectors $S_s$ for all incident totally polarized ($P_d = 1$) light (*cf* Eq. (1)), they represent the global optical response of the system. Now, with all these outgoing vectors, it is possible to build a new Poincaré's sphere (deformed by the depolarized properties of the media) where the distance between a point of this new sphere and the center, represents the degree of polarization. This representation permits us to globally visualize the optical modification generated by the medium.

**2.2.2. Index of depolarization**

The second method of characterization of the media consists in using the depolarization index. Its value is directly calculated from Mueller's matrix in the following terms [8]:

$$P = \sqrt{\frac{\sum_{i,j=1}^{3} M_{ij}^2 - M_{00}^2}{3M_{00}^2}} \tag{7}$$

where $P = 0$ for a pure depolarizer and $P = 1$ for a pure polarizer.

Note that $P$ globally characterizes the power of the medium to depolarize the light contrary to $P_d$ which quantifies the loss of polarization of one and only one Stoke's vector.

#### 2.2.3. Index of entropy

The third method of characterization uses the index of entropy, based on a statistical optic calculus [6] of the eigenvalues of the coherency matrix expressed by Eq. (8)

$$C_{\text{coherency}} = \frac{1}{2}\sum\sum M_{ij}(\sigma_i \otimes \sigma_j^*) \tag{8}$$

where the $\sigma$ are Pauli's matrix. The coherency matrix is a 4×4 Hermitian matrix. So, it presents four eigenvalues and four eigenvectors. Consider $\lambda$ to be the eigenvalues of this coherence matrix. Thus, these four eigenvalues statistically represent a Bernouilli process with four parameters. From this fact, we may calculate an index of entropy

$$p_i = \frac{\lambda_i}{\sum \lambda_j}, \qquad S = -\sum p_i \log p_i. \tag{9}$$

This index may be explained with Shannon's information theory. Note that a polarizing system has only one non-null eigenvalue of its coherency matrix and the corresponding index of entropy is null. On the other hand, if the system depolarizes in the same way any of the input signals, all the eigenvalues of the coherency matrix are equal and the entropy index is equal to 1. All these particular cases may be found in [4]–[6]. The index of entropy quantifies the deterministic properties of the diffusion process such as defined by CLOUDE [4]–[6].

## 3. Materials and methods

Our experimental setup is presented in Fig. 2 and is composed of:

– HeNe laser (2 mW, 632.8 nm);

– optical devices to chop the signal for FFT signal processing (and treatment) and spatial extension of the pencil of rays;

– three polarizers in input (two linear and one circular) and three analyzers (two linear and one circular) at the output, which permit us to control the polarization at input-output in front of and behind the sample under study. Moreover, vacuum at input -output offers a fourth combination in input-output. We thus have four possibilities at the input and four at the output of the sample;

– step by step motors which assume the movement of the polarizers and analyzers;

– the receptor which is simply a photodiode.

So, an acquisition starts from the intensity matrix obtained by sixteen combinations (four at the input and four at the output) of the input-output polarizers. With these

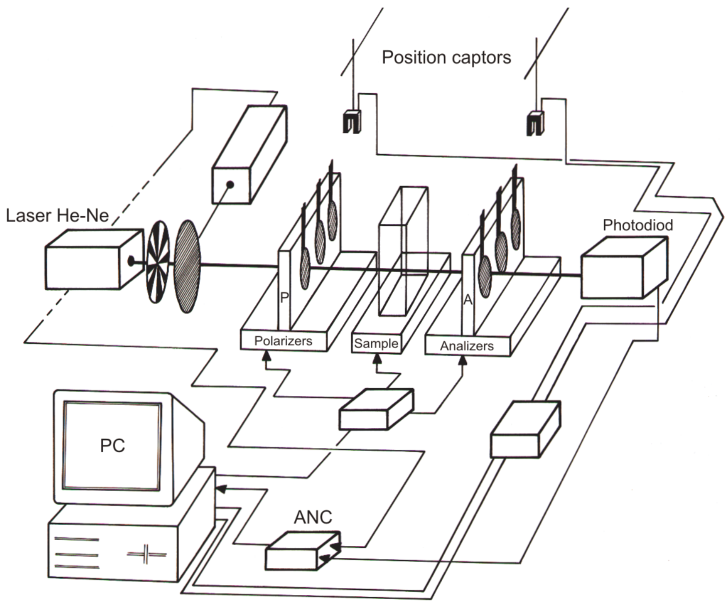


Fig. 2. Experimental setup.

sixteen numerical values obtained, it is possible by linear combinations to obtain Mueller's matrix of the sample. We present an example of this calculus.

Imagine the vacuum at the input and a linear polarizer at the output. Mathematically, we obtain:

$$\begin{bmatrix} I_{\mathrm{mes}} \\ \cdots \\ \cdots \\ \cdots \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} M_{00} & \cdots & \cdots & \cdots \\ M_{10} & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{10}$$

$I_{\mathrm{mes}} = \frac{1}{2}(M_{00} + M_{10})$ ($I_{\mathrm{mes}}$ denotes the photodiode measures).

So, with the sixteen input-output combinations, we obtain a system of sixteen equations, sixteen unknowns. After its resolution, we can obtain Mueller's matrix from intensity matrix. For more details, the reader may refer to paper [15].

## 4. Applications to the collagen

Our first application is to differentiate non-irradiate collagen from RX irradiate collagen (about 20 grays) by the modification of its optical properties. Indeed, collagen is one of the main constituents of the skin [3]. We characterized it by the indices of

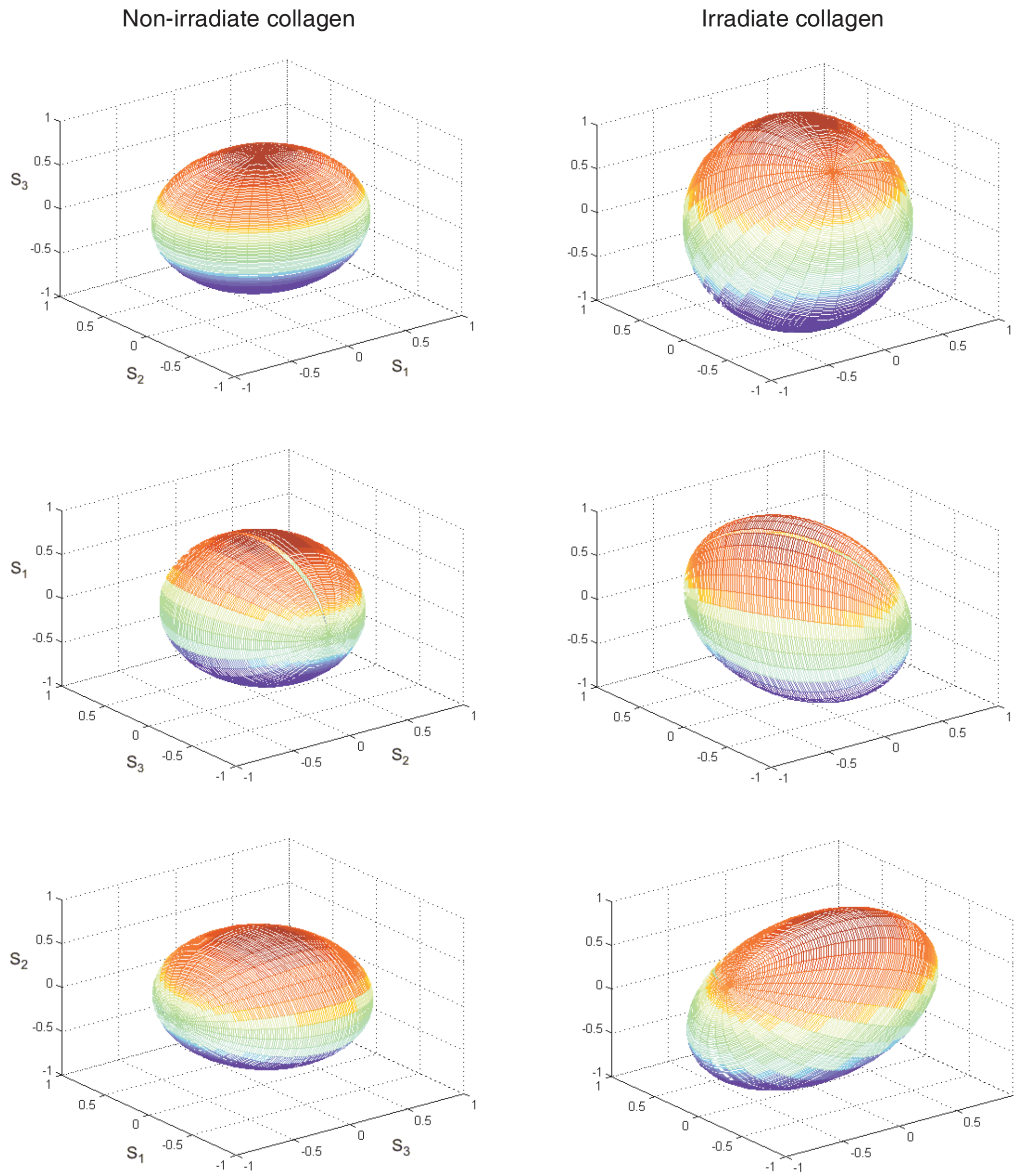


Fig. 3. Results of the discrimination within the Poincaré formalism (each row is in the same plan).

entropy and depolarization, and by Poincaré's formalism, too, as previously presented in Sec. 2.2.

It is well known that post-radiation diseases involve disfunctions of extracellular matrix (including collagen) produced in turn-over metabolism of fibroblasts in the dermal layers. Let us present our results in the Table.

T a b l e. Entropy and depolarization indexes.

| | Entropy indexes | Depolarization indexes |
|---|---|---|
| Non-irradiate collagen | $0.50 \pm 0.04$ | $0.73 \pm 0.03$ |
| Irradiate collagen | $0.32 \pm 0.04$ | $0.89 \pm 0.04$ |

The results confirm that radiation affects organisation of the system, which leads to a decline of the entropy and an increase of the index of depolarization. These variations may correspond to a modification of reticulation degree between helical structures and/or partial destruction of the helical structure of this protein. Collagen may lose its organisation, and hence its information.

The second method which would allow us to differentiate between the global optical properties is the Poincaré formalism. Figure 3 gives our results, each row represents one of the three possible points of view of this sphere for non-irradiate (left column) and irradiate collagen (right column). Let us recall that these spheres were simulated from the experimental Mueller's matrix by considering all the possible totally polarized incident light.

So, these representations allow a global vision of the optical modifications introduced by the sample on the polarization of the incident beam, and allow us to differentiate irradiate collagen from non-irradiate one, which was our aim. Now, we think that the use of Mueller's formalism in 1D may be improved by its extension to 2D. We hope to be able to characterize dermatological pathologies in the near future.

## 5. Conclusions

Our experimental protocol shows a modification of the optical properties of collagen after X absorption through the formalism of Mueller and radiobiological applications. It would be interesting to study the evolution of entropy as a function of irradiation, but our objective was to demonstrate that polarimetric measurements permit discrimination of irradiate collagen from non-irradiate one. The further step is to see the effect of these differences for the skin. Nevertheless, in the biomedical domain which interests us, it seemed indispensable to use our protocol in 2D in order to exploit the multitude of optical properties of the observed media and their variations [12]. This protocol will permit the contrast of the image to be based on the optical properties of the sample because each 4×4 Mueller matrix will be simply extend to 4 pictures×4 pictures. Now, we think that further work in 2D is necessary to differentiate irradiate skin from non-irradiate one. It will permit us to locate in a skin, irradiate area from non irradiate one, through differences in the contrast. It would be interesting to determine irradiation dose which would permit us the discrimination by these methods in 2D. Our hope for the future is to find a non-invasive method of diagnosing different skin pathologies through an imagery system where contrasts would be based on the optical properties of the media such as diattenuation, retardation or depolarization.

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