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Study of Scattering and Polarization of Light in Biological Tissues

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STUDY OF SCATTERING AND POLARIZATION OF LIGHT IN BIOLOGICAL TISSUES

Studium rozptylu a polarizace světla v biologických tkáních

Short version of Dissertation thesis

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KLÍČOVÁ SLOVA

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1 INTRODUCTION

The objects or structures existing in the nature and forming object fields can be divided into deterministic (regular), random (statistic) and fractal (self-similar) ones. As a consequence, the set of parameters used to characterize such the structures, would differ considerably. As a good example, the biological tissues or food materials display large compositional variations, inhomogeneities, and anisotropic structures. Tissue optics is a rapidly expanding field of great interest to those involved mainly in the development of optical medical technologies and food control. The composition of tissue can be affected by process conditions and material history. It is difficult to define what exactly constitutes an engineering property of a certain food. In general, however, any attribute affecting the processing or handling of a food can be defined as engineering properties [1].

Traditionally, these properties are divided into the following categories:
- **mechanical** (structural, geometrical, and strength),
- **thermal** (specific heat, thermal conductivity, and diffusivity),
- **electrical** (conductivity and permittivity),
- **optical** (color, gloss, and translucency) properties.

Since the topics of the thesis deal with optical properties of postmortem processed meat, we targeted them, particularly the scattering and polarization of light in interaction with matter.

So, the optical imaging is a powerful approach for visualizing tissue structure and function across spatial scales ranging from micrometers to centimeters. Tissue optical imaging technologies are generally discussed in two broad regimes, microscopic and macroscopic, which are based on controlling and measuring coherent and diffuse light-tissue interactions, respectively.

Light scattering and polarization are widely used in biological research to determine particle numbers, particle sizes, axial ratios, size distributions, particle mobility, and indices of refraction. Light scattering in biological tissues originates from the tissue inhomogeneities such as cellular organelles, extracellular matrix, blood vessels, etc [2]. This often translates into unique angular, polarization, and spectroscopic features of scattered light emerging from tissue, and therefore information about tissue macroscopic and microscopic structure can be obtained from the characteristics of scattered light [3]. Recognition of this fact has led to a long history of the studies of light scattering by biological structures such as cells and connective tissues.

1.1 STATE OF-THE-ART

Polarized light plays important roles in the understanding of the nature of electromagnetic waves [4], elucidating the three-dimensional characteristics of chemical bonds [5], uncovering the asymmetric (chiral) nature of biological molecules [6], determining sugar concentrations in industrial processes, quantifying protein properties in solutions, supplying a variety of nondestructive evaluation methods [7], developing advanced concepts such as polarization entropy, contributing to remote sensing in meteorology and astronomy [8], and differentiating between normal and precancerous cells in superficial tissue layers, as well as other biomedical applications [9].

The biological tissue is a turbid medium where significant depolarization is provided due to strong multiple scattering effects, inhomogeneities in the media cause scattering which may alter the direction of propagation, polarization and phase of the light. The propagation of light through such media may be analyzed either by means of the wave or the photon theory, respectively [4]. Photons travel in straight line paths until they encounter an inhomogeneity, where they are scattered in random directions (Fig.1).

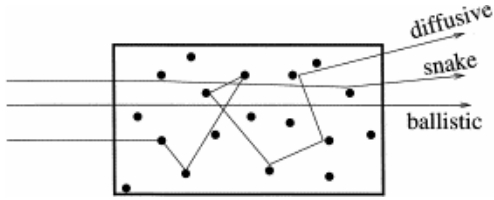


Fig. 1 Trajectories of photons in a random medium.

Most of studies measure only the small-angle differential scattered light intensity even though much more additional information is contained in the polarization states of the differentially scattered light.

Traditional optical spectroscopic techniques are rigorous and are well established in simple, homogeneous, optically thin samples. On the other hand, diffuse optical imaging and spectroscopy aims to investigate tissue physiology millimeters to centimeters below the tissue surface [10]. Traditional optical spectroscopy can not be used for this purpose, since light is strongly scattered in tissue.

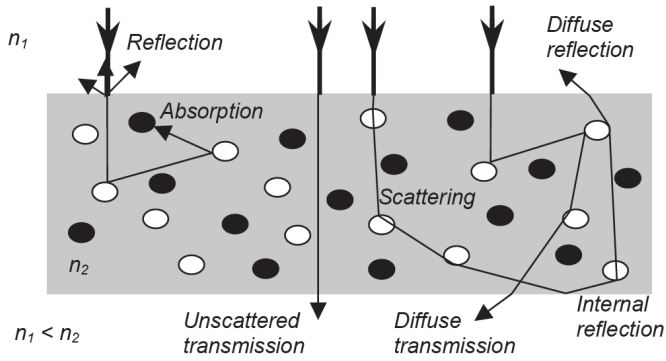


Fig. 2 Schematic diagram for the interaction of light with matter.

The multiple scattering of light within a material (Fig.2) is an area of considerable interest [11]. In medical diagnostics, the analysis of scattered laser light from tissue samples is increasingly being used as a diagnostic tool. Some attemps in biomedical polarimetry have been made in the context of optical imaging, specifically using polarization gating to separate out and potentially remove the multiply scattered (depolarized) component of the light beam in order to enhance contrast and to improve tissue imaging resolution [12]. This has proven moderately successful in selected applications, provided that proper attention is paid to the optimal choice of incident polarization states (e.g., linear versus circular), polarization detection schemes (e.g., Stokes versus Mueller polarimetry) [13], geometry of detection (e.g., transmission versus reflection) [7], etc.

Early physical property analyses of food products required constant uniform values and were often oversimplified and inaccurate. Unfortunately, the biological tissue is a complex medium, so some simulation is necessary. Nowadays, computational engineering techniques, such as the finite element or Monte Carlo methods [14, 15], are much more sophisticated and can be used to evaluate non-uniform properties (for example, thermal properties) that change with time, temperature, and location in food products that are heated or cooled when stored.

Mathematical models have been fitted to data as a function of one or several experimental parameters, such as temperature, water content, porosity, or other food characteristics [15]. Both modern and more conventional measurement methods allow computation of these properties, which can provide information about the macrostructural effects of processing conditions in fresh and manufactured foods.

1.2 OBJECTIVE OF THE DISSERTATION

In this dissertation we want to characterize the bio-materials (different kinds of meat) going to the ageing with Stokes and Mueller matrix optical polarimetry. To seriously tackle the problem we need first to examine the physical nature of the scattering of polarized light and to see how multiple scattering affects the degree of polarization. Knowledge of this fact would aid in determining the validity of using scalar theories in analyzing the multiple scattering of polarized light.

The images and matrix elements with Mueller calculus provides a comprehensive information of samples due to which it is possible to combine all the necessary parameters for describing a beam of light into a single image. The resultant describing the light beam is simply the four-parameter Stokes vector and determined by measuring a flux transmitted through a set of polarization optics: polarization generating optics provide linear and/or circular polarized light to sample and polarization analyzing optics collect polarized output light from sample to detecting devices. The characteristic Mueller matrix in all experiments contains 16 elements, having total 49 intensity measurements at different polarization states. In practice, all 16 elements may not be independent. Only seven of sixteen Mueller matrix elements are independent and others depending on the symmetry and certain properties of the optical medium.

Therefore objectives of the dissertation are to provide

- better understanding of nature of various physical phenomena (polarization, scattering, birefringence) in turbid media and in biological tissue, and
- measurement of temporal changes of polarization states due to multiple scattering of light in biological tissues going to ageing.

These objectives also include a detailed study of:

1. complicated nature of polarization effects in tissue, including simultaneous multiple effects,
2. depolarization of signal generated by tissue multiple scattering,
3. difficulties in measuring typically small tissue polarization signals,
4. analysis and quantification of measured signals or images, and mainly
5. complexity in understanding and interpreting tissue polarimetry results.

2 SELECTED METHODS OF INVESTIGATION

2.1 MODELING OF PHOTON TRANSPORT IN TISSUE

To understand the propagation of light in biotissue and to aid tissue polarimetry for quantitative determination of intrinsic tissue polarimetry characteristics, an accurate forward modeling is enormously useful. This helps in gaining physical insight, designing, and optimizing experiments, and analyzing/interpreting the measured data.

2.1.1 Radiative transfer equation

Radiative transfer equation (RTE) [16] treats a light as composed of distinct particles (photons) propagating through a medium. The model is restricted to interactions between light particles themselves and is derived by considering changes in energy flow due to incoming, outgoing, absorbed and emitted photons within an infinitesimal volume dV in the medium (energy balance).

The model considers a small packet of light energy defined by its position **r**, direction of propagation $\hat{s}$, over a time interval dt, and with propagation speed c (Fig. 3).

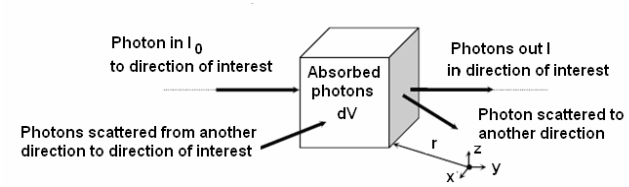


Fig. 3 Model for RTE.

The change in energy radiance $I(r,t,\hat{s})$ is equal to the loss in energy due to absorption and scattering out of $\hat{s}$, plus the gains in energy from light scattered into the $\hat{s}$-directed packet from other directions and from any local source of the light at r. This energy balance is represented by the individual terms in the RTE:

$$\frac{1}{c}\frac{\partial I(r,t,\hat{s})}{\partial t}+\hat{s}\nabla I(r,t.\hat{s})= \\ =-\left[(\mu_a+\mu_s^{'}).I(r,t,\hat{s})\right]+\mu_s^{'}\int_{4\pi}p(\hat{s},\hat{s}^{'}).I(r,t,\hat{s}^{'}).d^2\hat{s}^{'}+q(r,t,\hat{s}) \qquad (2.1)$$

Each term in equation (2.1) represents in time domain a certain quantity (Fig.3). So

$$\frac{1}{c}\frac{\partial I(r,t,\hat{s})}{\partial t}+\hat{s}\nabla I(r,t.\hat{s}) \qquad (2.2)$$

is the difference between the number of photons entering the volume and the number of photons leaving it per unit time (Fig. 4),

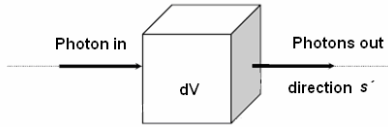


Fig. 4 Difference between the number of photons entering the volume and the number of photons leaving it per unit time.

$$(\mu_a + \mu_s^{'}).I(r,t,\hat{s}) \qquad (2.3)$$

is attenuation given to light due to absorption and scattering (Fig.5),

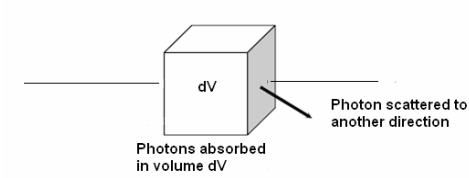


Fig. 5 Attenuation of light due to absorption and scattering.

$$\mu_s^{'} \int_{4\pi} p(\hat{s},\hat{s}^{'}).I(r,t,\hat{s}^{'}).d^2\hat{s}^{'} \qquad (2.4)$$

is increase in the light due to scatter from all directions to the final direction given by unity vector $\hat{s}'$ (Fig. 6)

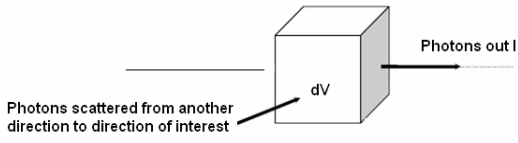


Fig. 6 Increase in the light due to scatter from all directions to the final direction.

and $q(r,t,\hat{s}')$ is a local source of light in material (*i.e.* fluorescence) (Fig.7).

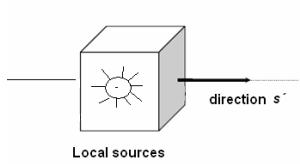


Fig. 7 Local sources of light in material.

Here, two important parameters are $\Phi(r,t)$ which represents photon density or diffuse photon fluence (inside the element), and $J(r,t)$ which is the photon flux or current (at its boundary). The latter is a measurable parameter and allows equation (2.1) to be solved for μ_s' and μ_a, respectively

$$\Phi(r,t) = \int_{4\pi} I(r,t,\hat{s}').d\hat{s}' \qquad (2.5)$$

$$. J(r,t) = \int_{4\pi} \hat{s}.I(r,t,\hat{s}').d\hat{s}' \qquad (2.6)$$

Exact solutions for the RTE exist for simple cases such as isotropic scattering in simple geometries.

All polarization states could be described using the Jones vector and the Stokes parameter. As shown in Fig.8, once the incident light and the output light's polarization states are identified, the polarization elements of an optical device, which is a black box, can be determined subsequently.

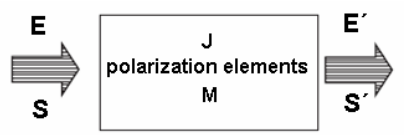


Fig 8 Jones matrices and Mueller calculus.

At present, popular theories of polarized radiation interaction with optical elements or scattering media may be divided into two groups:

- Jones calculus, which assumes a coherent addition of waves [17]; and
- Stokes-Mueller calculus, which assumes an incoherent addition of waves [18].

The state of polarization and intensity of a light beam incident on the medium is specified by the 4×1 Stokes vector **S** in the following form:

$$\mathbf{S} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} . \qquad (2.7)$$

Here $I \equiv S_0$ is total intensity, $Q \equiv S_1$ – polarization at 0° or 90° to the scattering plane, $U \equiv S_2$ – polarization at ±45° to the scattering plane, and $V \equiv S_3$ – left or right circular polarization, and S_0, S_1, S_2, S_3 represent four elements of Stokes vector **S.**

The degree of polarization (DOP), which is important characteristics in ageing measurement, can be calculated through output intensities and the values of measured intensities lie between -1 and 1, and they represent the tendency of the measured light to be polarized linearly, ±45°, and right or left-handedness.

DOP is a measure of the polarization purity of light. $DOP = 1$ means that light is completely polarized; $DOP = 0$ means the light is completely depolarized; $DOP < 1$ means the light is partially polarized.

$$DOP = \frac{\sqrt{Q^2 + U^2 + V^2}}{I} = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}, \tag{2.8}$$

and indicates the fraction of the light intensity that is polarized regardless of whether it is linear and/or circular. Similarly, the degree of ***linear*** polarization DOP_{L} is defined by

$$DOP_{\mathrm{L}} = \frac{\sqrt{Q^2 + U^2}}{I} = \frac{\sqrt{S_1^2 + S_2^2}}{S_0}. \tag{2.9}$$

The quantity $\sqrt{Q^2 + U^2}$ represents the magnitude of linear polarization in the light field. However, it does not specify the orientation of the electric vector. Further, the degree of ***circular*** polarization (DOP_{c},) is defined by

$$DOP_{\mathrm{C}} = \frac{V}{I} = \frac{S_3}{S_0}. \tag{2.10}$$

Also note that $DOP = \sqrt{(DOP_{\mathrm{L}})^2 + (DOP_{\mathrm{C}})^2}$.

The 4×4 scattering matrix $\mathbf{S}(\Theta)$ transforms the Stokes vector of an incident light beam to the Stokes vector of a scattered light beam. The scattering matrix can be obtained experimentally, or derived in a rigorous manner.. The form of this matrix is given by

$$\mathbf{S}(\Theta) = \begin{bmatrix} p_{11}(\Theta) & p_{21}(\Theta) & 0 & 0 \\ p_{21}(\Theta) & p_{11}(\Theta) & 0 & 0 \\ 0 & 0 & s_{21}(\Theta) & -d_{21}\Theta) \\ 0 & 0 & d_{21}(\Theta) & s_{21}(\Theta) \end{bmatrix}. \tag{2.11}$$

where $\mathbf{S}(\Theta)$ is a function of the included angle Θ between the incident and scattered light beams. $p_{11}(\Theta)$, $p_{21}(\Theta)$, $s_{21}(\Theta)$ and $d_{21}(\Theta)$ are independent parts of Mie phase function representing four elements of the matrix.

3 EXPERIMENTAL RESULTS

In this chapter, we present only most important results of the thesis.The tissue polarimetry of scattered light ends in two major directions, tissue imaging and tissue characterization. For our purpose only the second item is useful. In the checking of ageing state of meat tissue control, accurate measurement of the polarization retaining signal is extremely important.

For the purpose of our investigation, different kinds of biological tissue and media have been used, as follows:

- pork chop meat [19, 20, 21],
- chicken breast meat [22],
- milk [23], and
- polystyrene bills as phantom for the computation of scattering [23].

The samples from porcine or chicken meat were cut in slices with thickness of 1.0-5.0 mm in a parallel or perpendicular way to the muscle fibers (Fig. 9). Their surface area has been 1×1 cm^2 for transmitted light, and greater then one square centimeter for backscattering experiments.

Measurements were provided in three different temperatures. The meat samples were hold in ambient room temperature (20°C), in the cooler (4°C) and ice-box (-8°C) for three days.

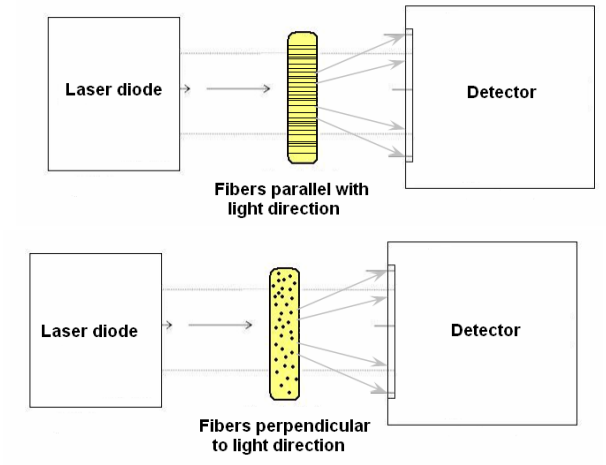


Fig.9 Orientation of muscle fibers during investigation.

3.1. STOKES VECTOR POLARIMETER

Multiple scattering measurement in thick tissues leads to depolarization of light, creating a large depolarized source of noise that hinders the detection of the small remaining information-carrying polarization signal.

Hence a schematic of the experimental polarimetry system employing polarization modulation and synchronous lock-in-amplifier detection is shown in Fig.10.

Light from a He-Ne laser (λ = 632.8 nm) first passes through a mechanical chopper operating at a frequency f_c ~ 500 Hz; this is used in conjunction with lock-in amplifier detection to accurately establish the overall signal intensity levels. The input optics enables generation of any of the four input Stokes polarization parameters of light which can be determined by performing six intensity measurements involving linear and circular polarization states [19].

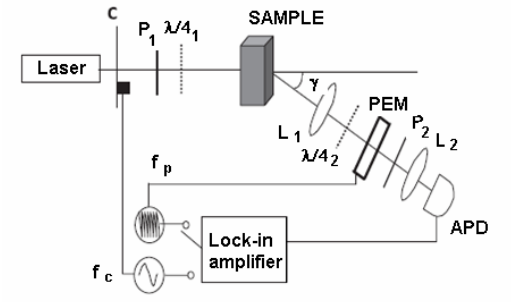


Fig. 10 Scheme of the experimental polarimetry system employing polarization modulation and synchronous lock-in-amplifier detection [19].

The detected signal is sent to a lock-in amplifier with its reference input switching between the frequencies of the chopper (500 Hz) and the PEM controller (50 kHz and harmonics) for synchronous detection of their respective signals.

3.2 MONTE CARLO ANALYSIS OF MULTISCATTERED LIGHT

The proposed Monte Carlo analysis of multiple scattering events of light in turbid biotissue media is based on the radiative theory [2, 24]. It is assumed that the scattering event of light is independent and has no coherence effects.

Simulation of the photon trajectories in Monte Carlo method consists of the following key stages (Fig.10):

- injection of the photon in the medium, generation of the photon path-length,

- generation of a scattering event,
- definition of reflection/refraction at the medium boundaries,
- definition of detection and
- accounting for the absorption.

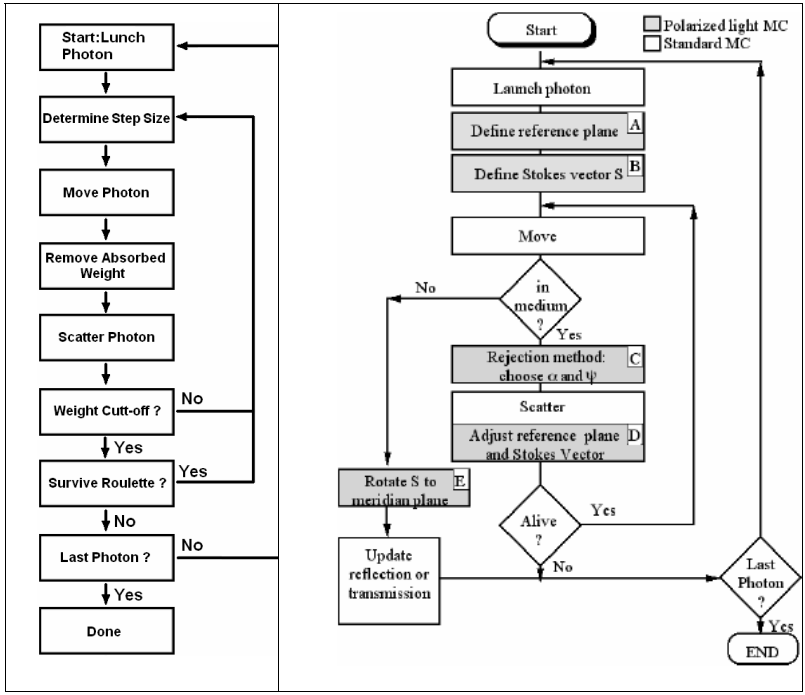


Fig. 10 Standard Monte Carlo program and proposed Polarized Light Monte Carlo program (PLMC) flow charts.

3.2.1 Intensity and degree of polarization

The radial (Fig.11) variation of the backscattered polarized intensity appears to have the same form as that observed for the scalar problem [25, 26].

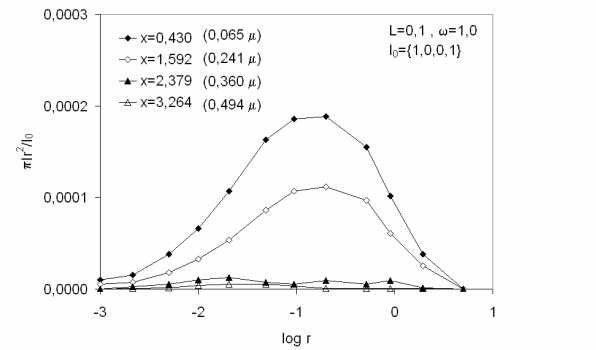


Fig. 11 Normalized intensities vs. distance of detector r for a number of size parameters x and optical thickness $L = 0.1$ mm.

In Fig. 12 the vector and scalar estimates of the intensity for one optical thickness L are compared. Clearly, for smaller size parameters, the difference between the vector and scalar theories is significant whereas it is smaller for larger size parameters. Also, it appears that for very large optical radii the difference between vector and scalar solutions decreases.

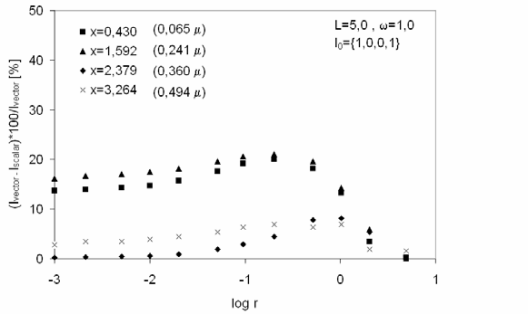


Fig. 12 Difference between the vector and scalar radiative transfer solutions for diffuse light field in distance r for a number of size parameters x and optical thickness $L = 5.0$ mm.

The behavior in Fig. 13 is very interesting. The DOP_L at small optical radii is the same irrespective of optical depth. This is because at small optical depths, the multiple scattering is primarily second-order.

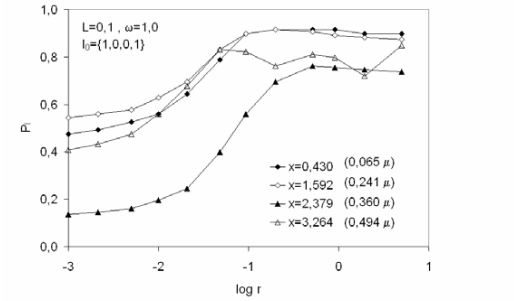


Fig. 13 Computed DOP_L in distance of detector r for a number of size parameters x and optical thickness $L = 0.1$ mm.

In Fig. 14, the DOP_C (2.10) is shown. In this case DOP_C is identical for all optical depths at small optical radii. At large optical radii, the trend is an increase in the degree of circular polarization for larger size parameters. This can be explained as follows: for small size parameters, the d_{21} term in the scattering matrix (4.11) is negligible, and often = 0. This implies that the circular component of the vector radiative transfer equation (2.1) is essentially decoupled.

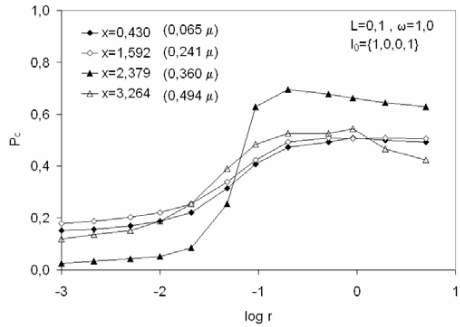


Fig. 14 Degree of circular polarization (DOP_C) in distance of detector r for a number of size parameters and optical thickness L = 0.1 mm.

3.3 AGEING PROCESS

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 ageing process within muscle fibers.

Two types of measurements were provided [26]:

1. Measurement of polarized light transmitted through the biological tissue sample.
2. Measurement of polarized light reflected and twice transmitted forward and backward through the biological tissue sample – meat slice attached on sample holder mirror.

First for a purpose of our investigation, we have used a pork chop 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 (Fig. 9).

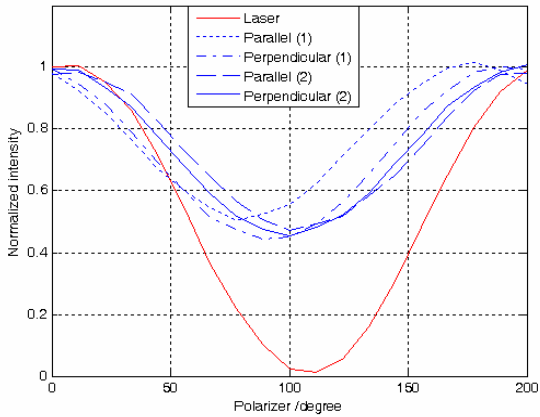


Fig.15 Angular dependence of polarization directions of diffused light for two meat samples sliced along the muscle fibers and orthogonally to them.

Figure 15 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. 16 represents calculated DOP in on a thickness of the meat layers. Next we have examined how polarization degree was related to the thickness of the sample.

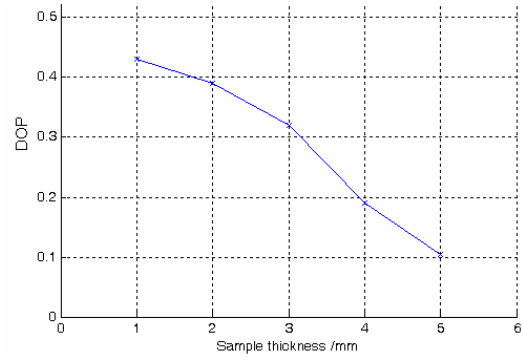
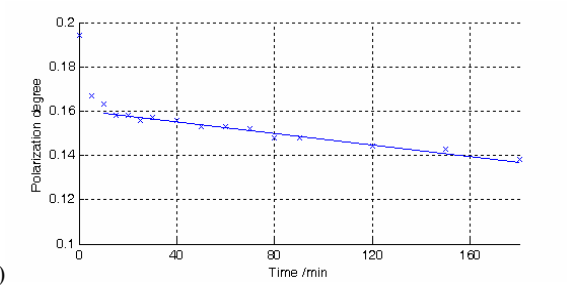
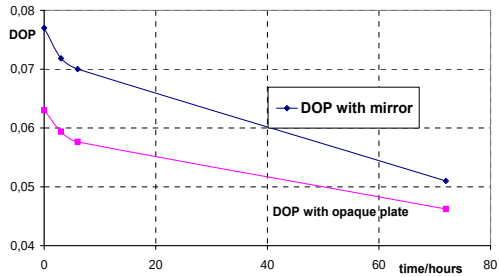


Fig. 16 Dependence of degree of polarization (DOP) (Eq2.8) on optical thicknessess of meat slices (L = 1.0 mm, 2.0 mm, 3,0 mm, 4,0 mm and 5.0 mm).

We have investigated the relationship between the polarization changes and meat ageing.



a)



b)

Fig. 17 Dynamics of DOP vs. meat aging time after slice processing. a) in transmitted light, b) in backscattered light with mirror and opaque plate.

Figure 17a shows the result obtained in transmitted light during first 180 minutes with a sample thickness of 4.0 mm. Here, the chiral characteristics of the light polarization were measured every 5 minutes during first 180 minutes for a

commercial meat sample with the muscle fiber orientation perpendicular to the background nontransparent plate. We can see that after approx. 20 minutes the degree of polarization decreases linearly with time after meat slicing. Figure 17b gives the result obtained in backscattered light with mirror and opaque plates as sample holders. This measurement was provided after storing the meat 3, 6 and 72 hours in temperature 20°C [27].

Figure 18 represents results of temporal dependence of linear polarization, due to the water evaporation at room temperature +20°C. In this case the sample was fixed on the mirror. Similar results, but with lower reflected intensity, was then obtained using opaque background plate instead mirror. In both cases a slight drift of polarization maxima to the left is evident.

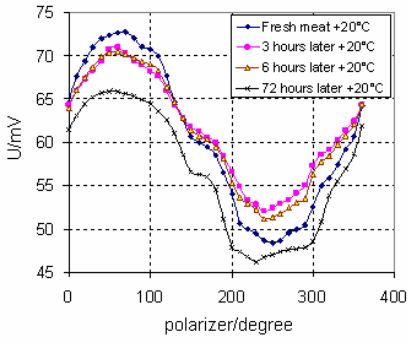


Fig. 18 Dynamic shift of polarization maxima due to the ageing.

Finally, we have considered the meat sample as a linearly birefringent turbid medium consisting of a stack of horizontal fibers with diameter of 2 μm. Using the PLMC method it was possible to compare results of simulated back-scattering Mueller matrix for suspension of linear detectors with diameter of 2 μm (Fig. 19a) with experimental back-scattering Mueller matrix measurement for fresh pork chop fibers of similar diameter (Fig. 19b) [25].

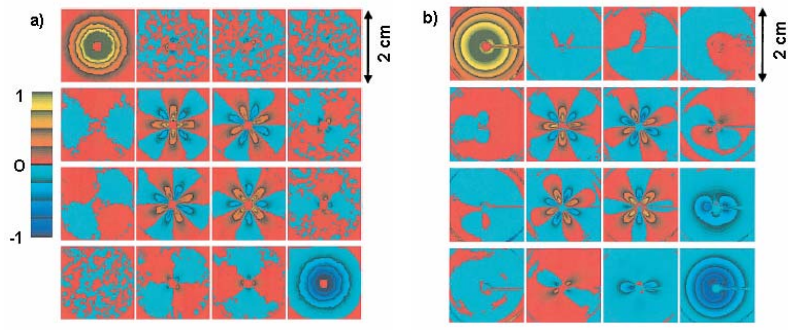


Fig. 19 a) Simulated back-scattering Mueller matrix for suspension of linear detectors with diameter of 2 μm. b) Experimental back-scattering Mueller matrix for fresh pork chop fibers. Each image displays a 2×2 cm area of the surface.

4 CONCLUSIONS

Optical inspection of biological tissues is essential tool for the medical and food quality control investigations. So the study of the light propagation in biological tissue, where cell dimensions are larger than the wavelength of the used light, is growing in importance. As a result of interaction of light and the matter, the Mie scattering of transmitted or reflected light arises and thus produces various polarization states. Thus, it is possible to take advantage of changes in polarization state of light to measure the freshness or ageing of processed food.

Having this in mind, the principal **objectives** of this dissertation thesis were to **provide**

- **better understanding** of nature of **various physical phenomena** (polarization, scattering, birefringence) in turbid media, *i.e.* biological tissue, and
- **measurement of temporal variations of polarization states due to multiple scattering** of light in biological tissue (processed meat) **going to the ageing**.

These objectives also include a **study** of:

1. **complex nature of polarization effects** in tissue,
2. **depolarization** of signal as a result of tissue **multiple scattering**,
3. **difficulty** in measuring typically s**mall tissue polarization signals**,
4. **analysis and quantification** of measured signals or images, and mainly
5. **complexity** in understanding and **interpreting tissue polarimetry results**.

To achieve these objectives, we have chosen, from enormous variety of properties and measuring techniques, a study of optical properties, and more precisely polarization, scattering in the tissues, and their behaviors during the tissue ageing.

However, it is still not clear what specific muscle properties are responsible for optical scattering. As an effort to answer these questions, we conducted several controlled experiments in which we studied the changes of scattering coefficient with muscle length (or sample thickness), temperature and ageing time. The optical scattering coefficient of pork and chicken muscles were measured based on a diffusive fitting of spatially resolved reflectance measurements. Samples with different thickness were prepared from freshly slaughtered animals. Our results indicated that muscle scattering coefficient increased with ageing time and sample thickness. This study suggests that muscle structural properties have significant impact on muscle optical scattering coefficients. These experimental observations can be confirmed and explained based on simulation using Stokes vector and Mueller matrix calculus on the basis of Radiate Transfer Equation and modified Monte Carlo method for polarized light.

Our novel approach to this field was based on the hypothesis that a state of polarization changes in meat with time. The results of thesis with personal contribution to the field are as follows:

1) Scattering – polarization properties of tissue ageing

Most of this work has involved a characterization of biological tissue optical properties as a function of ageing time [19, 20, 21, 22, 23, 26].

If the thick layer of meat sample is illuminated, the multiple scattering occurs, and this phenomenon varies accordingly. In the case of the postmortem tissue (meat) the changes caused by ageing are not caused not only by a chemical process, but also by drying of the sample leading to the variation of polarization state of the light.

Two kinds of experimental measurement were performed: scattering of polarized light passing forwards and backwards in the sample and only transmitted light.

Our measurements show a significant curl of polarized light. This depends on the orientation of the muscle fibers and ageing process of meat. The correlation of polarization changes of light in meat vs. meat ageing shows that the dynamic angular behavior of the polarization could be used as a predictor for meat ageing.

2) **Simulation of polarized light photon transport in multiscattered media** whose characteristics dependent on several factors [19, 21, 23, 24, 27]:

Experimental observations shown that the problem, due to its complexity, is not easy to explain, therefore it was necessary to simulate photon transport, in the case when light changes its polarization state in turbid biological tissue.

So the modified polarized light Monte Carlo method (PLMC) allows compute the photon forward and backward transfer in the tissue. The comparison of simulated back-scattering Mueller matrix for suspension of linear detectors with diameter of 2 μm and experimental back-scattering Mueller matrix for fresh pork chop fibers shows a high correlation.

Finally, to conclude we can assert that our hypothesis was partially confirmed and approved, mainly in red meats which need some time to their maturity and tenderness. We are basically able to evaluate, under normal condition of cooling, the state of meat freshness.

A non-negligible result of this thesis is also its pedagogical aspect. Therefore, the present text can be considered as a useful textbook for our students in Libya.

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8 ABSTRACT

Tissue optics becomes a rapidly expanding field of great interest and a precise knowledge of biological tissues optical properties is essential for medical and food quality control investigation.

If the sample of tissue is illuminated, the multiple scattering occurs. In the case of the postmortem tissue (meat) the cell dimensions are larger than the wavelength. Mie scattering of transmitted or reflected light arises and produces various polarization states.

Polarization properties of light scattered from a scattering medium have been studied with experiments and modeling. Two modified experiments were performed: scattering of polarized light passing twice the sample (forward and backward) and only transmitted light. The measurements of scattered light display depolarization and rotation of polarized light, which depend both on orientation of the muscle fibers and ageing process of meat. Theoretical description of turbid biological tissue and computing of radiative transfer equation by modified Polarized Light Monte Carlo (PLMC) method has also been executed.

It is shown that the degree of polarization is sensitive to the optical properties of the turbid medium. The results demonstrate that polarized light scattered from a scattering medium is sensitive to the state of input polarization and the optical properties and thickness of the tissue during the ageing. The correlations of polarization changes and freshness of meat, as well as dynamic behavior of the polarization in ageing meat are shown.