Mueller Optical Coherence Tomophraphy Technique for Non-Invasive Glucose Monitoring

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Abstract: A new and novel technique for non-invasive (NI) glucose sensing based on Mueller optical coherence tomography (OCT) technique is proposed. The feasibility of the proposed technique is demonstrated by detecting the optical rotation angle and depolarization index of phantom solution containing de-ionized water (DI), glucose solutions with concentrations ranging from 0~4000 mg/dL and 0.02% lipofundin. The practical applicability of the proposed technique is demonstrated by measuring the optical rotation angle and depolarization index properties of the human fingertip of normal healthy volunteers.

1 INTRODUCTION

With rising obesity levels around the world, diabetes has emerged as a major concern with serious health and economic implications. Consequently, reliable methods for its testing and diagnosis are urgently required. Of the various methods available, NI techniques based on measuring the glucose concentration in human blood are particularly attractive due to their accuracy and painless aspects. However, NI devices are presently not widely used in clinical diabetes applications due to their poor precision, robustness, stability and analytical performance compared to that of conventional blood glucose meters. Consequently, much work remains to be done in improving the performance of NI glucose monitoring systems such that they provide a more viable approach for clinical diagnosis.

OCT is a powerful technique for performing the in-depth cross-sectional imaging of scattering-type media. Moreover, recent enhancements to the traditional OCT structure now make possible the incorporation of polarization control into the system such that the anisotropic properties of certain optical materials can be observed. In this study, an analytical model based on a hybrid Mueller matrix formalism for extracting the optical rotation angle and depolarization index of anisotropic optical samples. The validity of the proposed technique is demonstrated by detecting optical rotation angle of phantom solution samples and on human fingertip of volunteers.

2 MUELLER OCT SYSTEM

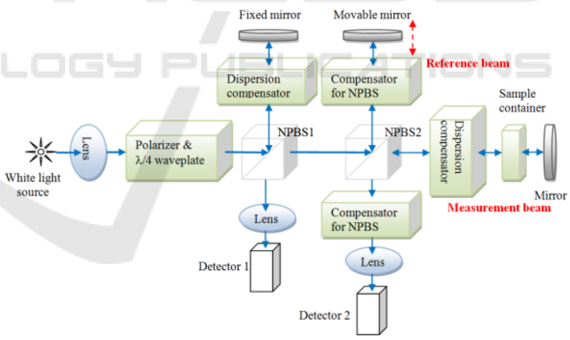

Figure 1: The schematic illustration of Mueller OCT system.

The schematic of the proposed Mueller OCT system is illustrated as Fig. 1. As shown in Fig 1, the OCT system additionally includes two compensators for non-polarized beam splitter (NPBS), each comprising two quarter-waveplates and one half-waveplate, designed to compensate the polarization distortion induced by the non-perfect beam splitters.

In performing experiments, signals obtained by detector 2 are employed to measure anisotropic properties of the sample by calculating the amplitude of the interferometric signal. To calculate the Mueller matrix of the sample, the quarter-wave plate

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and polarizer shown in Fig. 1 are rotated to obtain four different polarization states of the light incident on the sample, namely H (horizontal linear polarization), V (vertical linear polarization), P (45° linear polarization), and R (right-circular polarization). In addition, the variable wave plate in the reference arm is adjusted to change the polarization state of the reference beam sequentially to H, V, P, and R, respectively, for each of the four incident lights. Thus, a total of 16 interferometric signals are produced with which to investigate the sample and detected by detector 2. The 16 elements in the 4×4 Mueller matrix are then computed as (Liao, 2015)

$$\mathbf{M}=\begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{bmatrix} = \begin{bmatrix} HH+HV+VH+VV & HH+HV-VH-VV & 2PH+2PV-M_{11} & 2RH+2RV-M_{11} \\ HH-HV+VH-VV & HH-HV-VH+VV & 2PH-2PV-M_{21} & 2RH-2RV-M_{21} \\ 2HP+2VP-M_{11} & 2HP-2VP-M_{12} & 4PP-2PH-2PV-M_{31} & 4RP-2RH-2RV-M_{31} \\ 2HR+2VR-M_{11} & 2HR-2VR-M_{12} & 4PR-2PH-2PV-M_{41} & 4RR-2RH-2RV-M_{41} \end{bmatrix} \quad (1)$$

3 DIFFERENTIAL MUELLER MATRIX FORMALISM

An optical sample can be described by the matrix formulation $S=MS'$ where S is the Stokes vector of the output light, M is the 4×4 Mueller matrix of the sample, and S' is the Stokes vector of the input light. Given the use of five different input lights, is providing the sufficient equation to determine the complete Mueller matrix M of the sample. The differential Mueller matrix can be obtained from an Eigen value analysis of M as follow (Phan, 2017)

$$m=V_M\left(\ln(V_D)/z\right)V_M^{-1}=\begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{34} & m_{44} \end{bmatrix} \quad (2)$$

where V_M and V_D are the Eigenvectors and Eigenvalues of Mueller matrix M, respectively. The differential Mueller matrix of samples with circular birefringence properties under consideration of depolarization effect can be obtained as

$$m_{CB}=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 2\gamma+\eta'_v & 0 \\ 0 & -2\gamma+\eta'_v & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

where γ and η'_v are the optical rotation angle and differential parameters described the the anomalous depolarization. Thus, the optical rotation angle can be determined as

$$\gamma=\frac{m_{23}-m_{32}}{4},0\le\gamma\le180° \quad (4)$$

And the depolarization index can be determined as

$$\Delta=1-\sqrt{\frac{e_1^{\,2}+e_2^{\,2}+e_3^{\,2}}{3}},0\le\Delta\le1 \quad (5)$$

where e_1, e_2, e_3 are the diagonal elements of the Mueller matrix describing the depolarization effects.

4 RESULTS AND DISCUSSION

4.1 Glucose Concentration Detection for Aqueous Phantom Samples

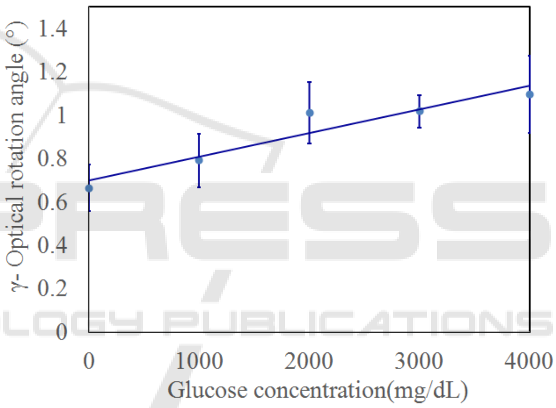

Figure 2: Experimental results for extracted values of γ for the aqueous phantom samples with glucose concentration ranging from 0-4000 mg/dL.

Glucose samples in phantom solution were prepared using 100 ml glucose solution samples (100 mg/ml-Merck Ltd) with concentration over the range of 0-4000 mg/dL in 1000 mg/ml increments mixed with 0.02% lipofundin (lipofundin MCT/LC1 20% B| Braun). Figure 2 shows the experimental results obtained for the optical rotation angle. As shown, the optical rotation angle γ values increase linearly with an increasing glucose concentration. The standard deviation of the experimental γ values obtained over four repeated tests for each glucose sample was found to be ± 0.26°. Furthermore, the sensitivity of the measured γ values was determined as 7.5×10^{-5} (degree)/(mg/dl).

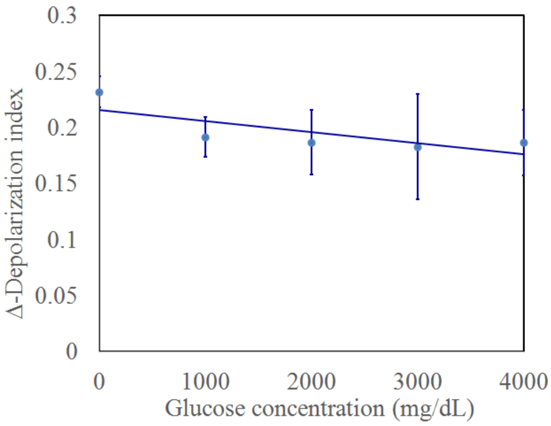

Figure 3: Experimental results for extracted values of γ for the aqueous phantom samples with glucose concentration ranging from 0-4000 mg/Dl.

Figure 3 shows the experimental results obtained for the depolarization index of the samples. As shown, the depolarization index Δ values decrease linearly with an increasing glucose concentration. The standard deviation of the experimental Δ values obtained over four repeated tests for each glucose sample was found to be ± 0.04. Furthermore, the sensitivity of the measured γ values was determined as 1.5×10^{-5} /(mg/dl).

4.1.1 NI Measurement of Glucose Concentration on Human Fingertip

The practical feasibility of the proposed technique was evaluated by measuring the optical rotation angle and depolarization index of human fingertip of four selected normal healthy volunteers. The volunteers were asked to swallow sugar rich water contained 75 gram sugar. The test was performed before and 1 hours after volunteers consumed sugar water. Figure 4 and 5 show the experimental results for extracted γ and Δ values of volunteer's fingertip over four repeated tests, respectively. As shown the average extracted γ values increases after the ingestion of sugared water for all volunteers other than volunteer 3. Furthermore, the average extracted Δ values decreases after the ingestion of sugared water for all volunteers. Therefore, the results are in good qualitative agreement with the extracted values for the aqueous phantom samples from section 4.1. The high deviation might be contributed by the imperfection of the optical elements, the calibration procedure, the moisture of the skin and the change in glucose concentration within the volunteer's body over the time. In overall, the feasibility of the proposed technique for NI glucose monitoring is confirmed.

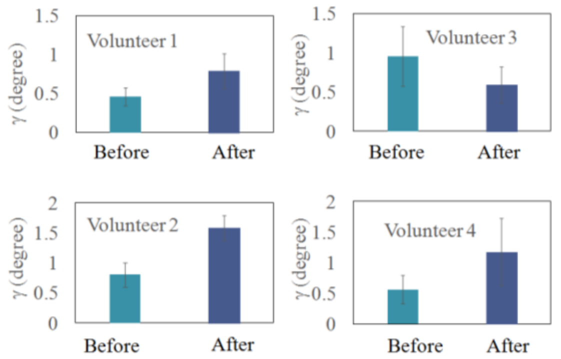

Figure 4: experimental results for extracted values of γ of fingertip of selected normal healthy volunteers

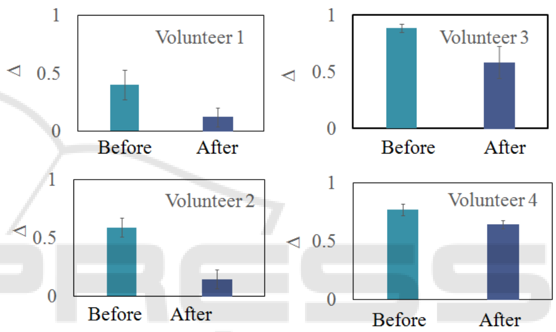

Figure 5: Experimental results for extracted values of Δ of fingertip of selected normal healthy volunteers.

5 CONCLUSIONS

The novel technique for NI glucose monitoring based on Mueller OCT system has been proposed. The proposed technique has measured the optical rotation angle and depolarization index of samples for detecting glucose concentration. The feasibility of the proposed technique has been demonstrated by detecting glucose concentration of aqueous phantom solution over the range of 0-4000 mg/dl with 0.02% lipofundin. The results have shown that the proposed techniques enable to detect γ and Δ with a sensitivity of 7.5×10^{-5} (degree)/(mg/dl) and 1.5×10^{-5} /(mg/dl), respectively. Furthermore, the practical application of the proposed technique has been demonstrated by measuring the optical rotation angle and depolarization index of human fingertip of four normal healthy selected volunteers. In general, the proposed technique provides a potential tool for NI glucose monitoring and diabetes diagnosis applications.

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