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Detection of central fixation using short-time autoregressive spectral estimation during retinal birefringence scanning

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ABSTRACT

The manuscript reports on the implementation of autoregressive spectral estimation aimed at improving the accuracy of detecting short-lasting events in signals acquired by a retinal birefringence scanning device that was reported earlier. A signal consisting of two frequency components is generated, where each frequency is a multiple of the scanning frequency. One frequency is produced during central fixation, while another one prevails during off-central fixation. These components may be of a very short duration, presenting a challenge for the FFT to identify them with sufficient time- and frequency resolution. Autoregressive spectral estimation using the Burg algorithm provided a satisfactory solution, capable of reliably differentiating between the two frequency components (96 and 192 Hz) on signal segments of duration as short as 5 ms. The device and the signal analysis methods were developed originally with the purpose of checking for eye alignment and strabismus – a major risk factor for amblyopia. The method enables the technology to work with less-cooperative patients, such as young children. Other medical and non-medical applications are possible.

1. Introduction

The human fovea is the most sensitive part of the retina, projecting the objects in the direction of gaze. The polarization-changing property (birefringence) of the Henle fibers surrounding the fovea has been used to identify its position and hence the direction of gaze [1–5]. This allows checking for eye alignment and strabismus – a major risk factor for amblyopia. Screening techniques and an instrument have been reported by Hunter et al., based on the birefringence signal derived from circular scanning in the foveal region [6]. Generally, a signal $s(t)$ consisting of several frequency components is produced, where each frequency f_i is a multiple of the scanning frequency f_s. Some frequencies prevail during central fixation, while others appear at para-central fixation. The existence and the mixture of frequencies depend on the opto-mechanical design of the instrument. In the simplest case, discussed here, $f_2 = 2f_s$ is produced during central fixation, while $f_1 = f_s$ prevails during off-central (para-central) fixation. Existing instruments acquire consecutive epochs of $s(t)$, on which the Fast Fourier Transform (FFT) is performed, as reported by Hunter et al. [6] and Gramatikov et al. [7]. A major challenge with such systems is that the FFT power spectrum is a global approach – it tells how much of f_1 and f_2 are represented in the epoch being analyzed, but it does not tell exactly where these frequencies appear and for how long. With less-cooperative patients, such as young children, important short lasting moments of central fixation (f_2) may easily be hidden behind large low-frequency (f_1) components. Analyzing short time intervals is advantageous, yet this is where FFT loses spectral resolution. The goal of this work is to compare the FFT to auto-regressive (AR) spectral estimation in the analysis of short-lasting events in the retinal birefringence scanning (RBS) signal and to determine whether brief moments of central- or para-central fixation are better detectable using AR modeling.

2. Materials and methods

2.1. Apparatus and data

The principle of RBS for the purpose of detecting central fixation has been described before by Guyton et al. [2], Gramatikov et al. [3], and Hunter et al. [6]. In short, a scanning beam of linearly polarized light is used to circularly scan around the predicted center of the fovea, when the eye is looking at a given central target. The fovea changes the polarization state of light depending on the location of the projection of the spot being scanned (Fig. 1). A typical bow-tie pattern (“polarization cross”) exists, created by the radial array of fine Henle fibers which connect the center of the fovea to the optic nerve. The dotted circles on Fig. 1 show two possible paths of the stationary circular scan with respect to the center of the fovea, which moves with the eye. Depending on the region on the polarization cross being scanned, the retro-reflected signal can be of two main

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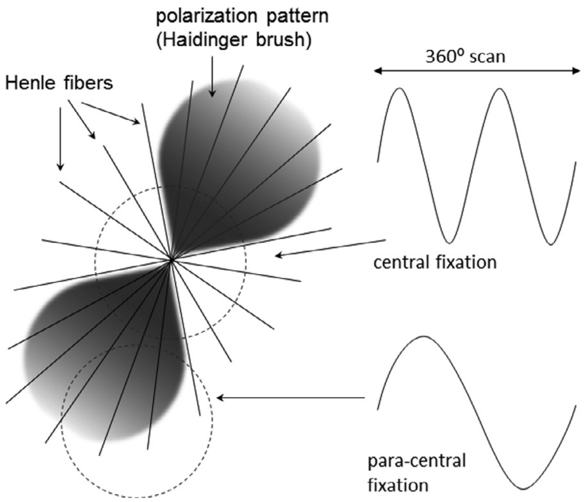

Fig. 1. Polarization pattern created by the fovea when illuminated with NIR linearly polarized light and the signals obtained during circular scanning in the foveal region.

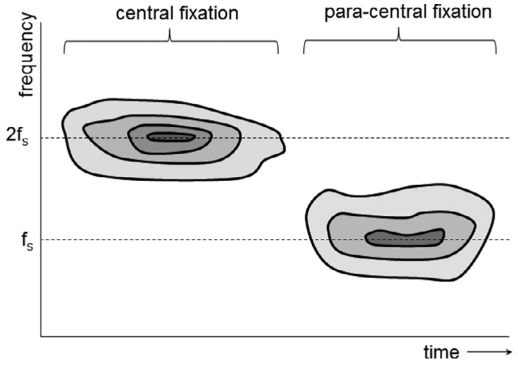

Fig. 2. Time–frequency distribution during central fixation ($f = 2f_s$) and para-central fixation ($f = f_s$), f_s being the circular scanning frequency.

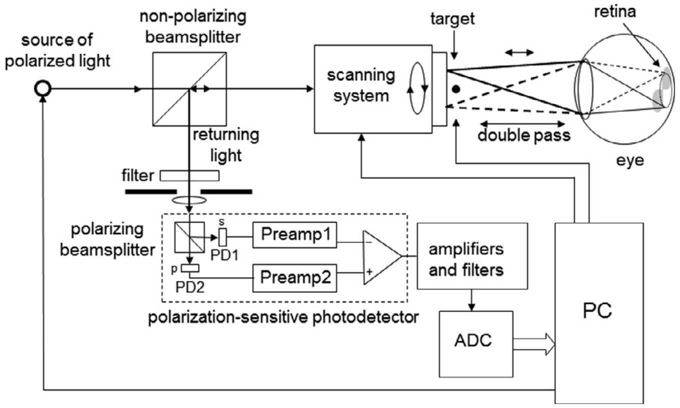

Fig. 3. Hardware implementation of the retinal birefringence scanning system for detection of central fixation.

frequencies. Moments of central fixation, when the centers of the scanning circle and the fovea coincide, are characterized by dominant frequencies $f_2 = 2f_s$ whereas off-central fixation is represented by $f_1 = f_s$, with f_s being the scanning frequency. A typical time–frequency distribution obtained with this type of scanning is shown in Fig. 2, where fixation shifts from central to paracentral, as time progresses. The hardware for obtaining the RBS signal is shown in Fig. 3, and has been explained in more detail by Hunter et al. [6] and Gramatikov et al. [7]. Linearly polarized near-infrared (NIR) light of 785 nm wavelength is sent through a non-polarizing beamsplitter to a scanning system, which converts the stationary beam into a circular scan (of scanning frequency 96 rounds per second) subtending an angle of approximately 3° at the subject's eye. By the eye's own optics, the beam is focused onto the retina, with the eye fixating on a target appearing at the center of the scanning circle. Upon reflection from the ocular fundus, the polarization-altered light follows the same path back and arrives at the non-polarizing beamsplitter, which deflects part of it toward a polarization analyzing unit. The latter consists mainly of a polarizing beamsplitter, which separates the light into two orthogonal components. The vertical polarization component (s) is reflected, while the horizontal polarization component (p) is transmitted. Each component is captured by a photodetector (PD1 and PD2, respectively) and amplified, then the difference of the two is built in hardware, yielding the S_1 component of the Stokes vector. The signal is then filtered, amplified, and digitized by an analog-to-digital converter (ADC) at a sampling rate of 10 kHz. Scanning signals were recorded from six subjects after obtaining written informed consent, following a protocol approved by the Institutional Review Board (IRB) and in compliance with the Helsinki Declaration. Personal identification data was not collected. From each subject, 12 records were acquired, each 400 ms long, for both the right eye and the left eye. The original device used was binocular [6], but since this work focuses on the signal analysis part, only a monocular implementation was considered.

2.2. Autoregressive spectral estimation

In the original version of the above described device, the Fast Fourier Transform (FFT) was employed to detect appearances of $f_s = 96$ Hz and $2f_s = 192$ Hz. Since the frequency resolution is the reciprocal of the time interval T being analyzed, the needed frequency resolution of 96 Hz would require T to be not less than 10.4 ms long. This, however, would hinder the detection of very short lasting episodes (sometimes 5–10 ms long), which have been observed in the signal by Gramatikov [8]. In addition, because the FFT assumes periodicity, spectral leakage can occur due to signal discontinuity. Using a weighting window in an attempt to reduce such leakage also decreases the FFT's frequency resolution.

Autoregressive (AR) spectral estimation was employed to analyze short-lasting segments of the RBS signal, as an alternative to the FFT. The method has an advantage over FFT that, it can use epochs of shorter duration at sufficient spectral resolution. The AR methods [9–13] enable representation of a signal in a time interval by means of a set of parameters, namely the autoregressive coefficients:

$$x(n) = -\sum_{k=1}^{p} a(k)x(n-k) + \sum_{k=0}^{q} b(k)u(n-k) \tag{1}$$

where $x(n)$ is the output sequence of a causal filter that models the observed data, and $u(n)$ is the input driving sequence. If all moving average parameters $b(k)$ are zero, except $b(0) = 1$, then

$$x(n) = -\sum_{k=1}^{p} a(k)x(n-k) + u(n) \tag{2}$$

is strictly an autoregressive process of order p that allows for the calculation of the power spectrum density (PSD) in an unequivocal manner. For each signal segment $x(n)$ being analyzed, once the AR parameters have been estimated, the PSD can be computed as:

$$S_{AR}(f) = \frac{\sigma_p^2 \Delta t}{\left|1 + \sum_{k=0}^{P} a_k \exp\left(-j2\pi f k \Delta t\right)\right|^2} \tag{3}$$

where f is a frequency contained in the signal being modeled, P is the order of the AR process, a_k are the AR coefficients, σ_p^2 is the forward prediction error energy, and Δt is the sampling period of the