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Saccadic Vector Optokinetic Perimetry (SVOP): A Novel Technique for Automated Static Perimetry in Children Using Eye Tracking*

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Abstract— **Perimetry is essential for identifying visual field defects due to disorders of the eye and brain. However, young children are often unable to reliably perform the preferred method of visual field assessment known as automated static perimetry (ASP). This paper introduces a novel method of ASP specifically developed for children called Saccadic Vector Optokinetic Perimetry (SVOP). SVOP uses eye tracking to detect the natural saccadic eye response of gaze orientation towards visual field stimuli if they are seen. In this paper, the direction and magnitude of a sample of subject gaze responses to visual field stimuli is used to construct a software decision algorithm for use in SVOP. SVOP was clinically evaluated in a group of 24 subjects, comprising children and adults, with and without visual field defects, by comparison with an equivalent test on the Humphrey Field Analyser (HFA). SVOP provides promising visual field test results when compared with the reference HFA test, and has proven extremely useful in detecting visual field defects in children unable to perform traditional ASP.**

I. Introduction

Perimetry is a method of measuring the visual field (VF) and is essential for identifying VF defects to aid the diagnosis and monitoring of ocular and neurological diseases. Automated static perimetry (ASP), for example as employed by the Humphrey Field Analyser (HFA) [1], is currently the preferred assessment method used in clinical practice with compliant patients. This form of ASP requires the patient to maintain fixation on a central target throughout the test while light stimuli are presented at predetermined locations in their VF. The patient indicates if they see the stimuli by pressing a button. Children <8 years can have difficulty with this visuo-motor task [2]. In particular, children <5 years find it very challenging to inhibit the natural response of looking towards the light stimuli [3]. Additionally, children may not tolerate the restrictions of head movement imposed on them by the use of a chin-rest. Manual kinetic perimetry, where a trained examiner controls the location of the light stimuli, is often used for young children as the test procedure can be adapted to a child's age and ability [4]. However, it still suffers from many of the problems inherent to ASP. In infants and younger children, perimetry is limited to "confrontation" where an examiner observes if the child sees an object moved into their VF. This technique gives coarse results and does not generate quantitative data.

The lack of a reliable, quantitative form of perimetry in children and infants is a longstanding clinical problem as VF assessment is crucial in the diagnosis and management of children with visual pathway tumours and cerebral visual impairment (CVI) due to, for example, developmental brain defects, hypoxic ischemic encephalopathy, traumatic brain injury and infections of the central nervous system [5].

Recognising the difficulties associated with performing perimetry in children, previous research has largely concentrated on investigating the lower age limit of using current adult perimetry techniques [6-8], rather than developing a child specific method. In this paper we detail a novel method of VF assessment specifically developed for children. The technique, termed "Saccadic Vector Optokinetic Perimetry" (SVOP) [9] uses an eye tracker to monitor a patient's eye gaze responses to visual stimuli presented on a display screen at predetermined VF locations. A decision algorithm makes an automated decision on whether the stimuli have been seen or not based on the vector of any detected eye movements.

The aim of this paper is to introduce SVOP, describe the detail of the decision algorithm it uses, and to demonstrate its potential clinical value. The clinical testing in this paper uses 24 subjects from a larger cohort recruited for a continuing validation study and are different from those presented previously [9]. However, the algorithm detailed in this paper is the same as that used in [9].

II. Theory and Methods

A. SVOP theory of operation

The SVOP system (Fig. 1) comprises a personal computer (PC), a 20" LCD monitor, and an x50 eye tracker (*Tobii Technology, Sweden*). The eye tracker is non-contact and provides "real-time" (sample rate of 50Hz and typical latency of 25-35ms) data on: (i) 3D eye position relative to the eye tracker; and (ii) the point of gaze on the display screen. This allows: (i) the screen coordinates of VF stimuli

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to be calculated; and (ii) eye gaze responses to VF stimuli to be assessed. A software algorithm determines if VF stimuli have been perceived based on the direction and amplitude of a subject's eye gaze response. A secondary display screen is used by the operator to input patient details, set up tests and monitor test progress.

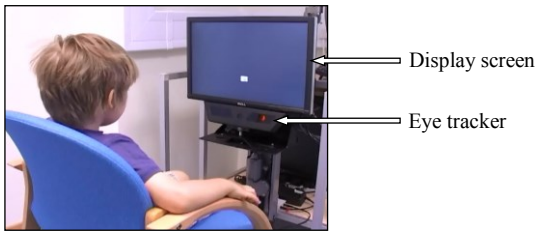

Figure 1. The Saccadic Vector Optokinetic Perimetry (SVOP) setup

In standard ASP testing the patient's head is maintained in a static position and gaze is sustained on a central fixation target throughout the test. In such a situation, the location for any individual VF stimulus is always the same. SVOP does not require a static head position or continual central fixation, so the screen location for any particular VF stimulus is dependent upon the 3D position of the eye being tested relative to the point of fixation. The 3D eye position data, provided by the eye tracker, enables the calculation of the correct size and screen location of any particular VF stimulus. A VF location can be described in a polar coordinate system with the origin at the point of fixation (Fig. 2). The polar angle (θ) is zero when the VF point is located horizontally to the right of fixation. The distance from the origin is expressed as the angle subtended at the eye (∅) and is termed the eccentricity.

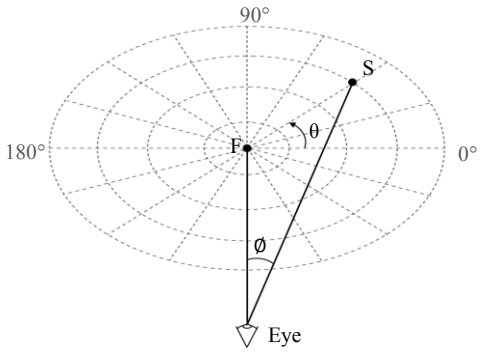

Figure 2. Polar coordinate system for visual field locations showing fixation point (F), visual field stimulus point (S), polar angle (θ) and eccentricity (∅)

Equations (1) and (2) are used to calculate the screen location (S_x and S_y) of any given VF point based on the 3D eye location (e_x, e_y, e_z) relative to the fixation point, and the polar coordinates describing the VF point (∅ and θ). Figs. 2 and 3 illustrate the parameters used in these equations.

$$S_x = e_x - e_z\left(\frac{S'_x - e_x}{S'_z - e_z}\right) \tag{1}$$

$$S_y = e_y - e_z\left(\frac{S'_y - e_y}{S'_z - e_z}\right) \tag{2}$$

Where:

$$S'_x = \frac{\tan \emptyset}{\sqrt{e_x^2 + e_z^2}}\left(ee_z \cos\theta - e_x e_y \sin\theta\right) \tag{3}$$

$$S'_y = \tan \emptyset \sin\theta \sqrt{e_x^2 + e_z^2} \tag{4}$$

$$S'_x = \frac{\tan \emptyset}{\sqrt{e_x^2 + e_z^2}}\left(ee_x \cos\theta - e_y e_z \sin\theta\right) \tag{5}$$

and:

$$e = \sqrt{e_x^2 + e_y^2 + e_z^2} \tag{6}$$

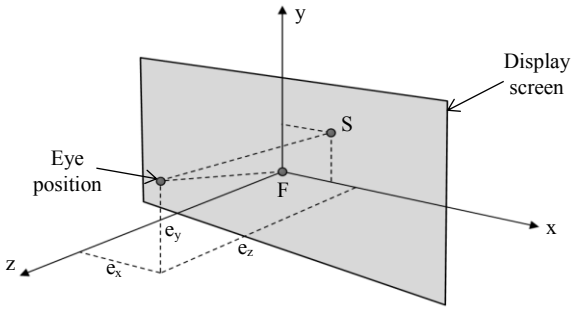

Figure 3. Schematic of variables used in the calculation of a visual field stimulus (S), based on the fixation point (F) and 3D eye location (e_x,e_y,e_z).

B. Assessment of Eye Gaze Responses to VF Stimuli

The algorithm which determines whether a VF stimulus has been seen or not, uses the vector of any initial change in fixation following the presentation of a VF stimulus. This vector can be compared to the vector between the original fixation target and the presented VF stimulus (hereafter termed "stimulus vector"). In order to determine appropriate parameter limits for this decision algorithm, the characteristics of a sample of normal eye gaze responses to VF stimuli were recorded and analysed.

Custom software was developed to display a VF stimulus when a subject was gazing at a fixation target. At the same time, the fixation target would be erased from the screen. The direction and magnitude of any subsequent fixation change was recorded. This process was repeated using a predetermined set of VF locations (a VF test pattern). The direction bias and magnitude bias between the fixation change vector and the stimulus vector was calculated using (7) and (8), where θ_G and θ_S are the polar angles of the gaze response and stimulus vectors respectively, and $\emptyset_G$ and $\emptyset_S$ are the eccentricities of the gaze response and stimulus vectors respectively.

$$Direction\ Bias = \theta_G - \theta_S \tag{7}$$

$$Amplitude\ Bias\ (\%) = \left(\frac{\emptyset_G}{\emptyset_S} - 1\right) \times 100 \tag{8}$$

Three VF test patterns, containing points within the first central 25° of the VF, were used for this data collection process. The left and right eye test patterns (Fig. 4a and 4b respectively) are a replication of the C-40 screening test

patterns used by the HFA. A third, custom test pattern was also used for binocular testing (Fig. 4c).

VF stimuli were presented for a duration of 200ms, at a luminance of 137cd/m^2 (equivalent to 14dB on the HFA luminance scale) on a background luminance of 10cd/m^2. Each VF stimulus was presented at a diameter of 0.43° (equivalent to Goldmann size III, the standard stimulus size used by the HFA).

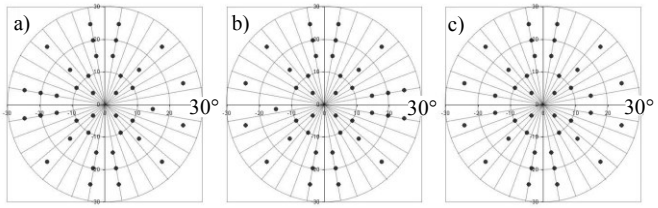

Figure 4. Test patterns for (a) right eye, (b) left eye, and (c) binocular tests.

38 volunteers were recruited for this data collection. The subjects and test patterns used are shown in Table I. Using the data collected with these subjects, appropriate parameter limits were applied to the SVOP decision algorithm and SVOP was evaluated clinically.

TABLE I. SUBJECTS FOR FIXATION CHANGE CHARACTERISTICS TESTS

Subject group	n	Age (years)		Test patterns used		
		Mean	*Range*	*Binocular*	*Left*	*Right*
Children	18	8.8	2-17	18	14	14
Adults	20	44.9	21-74	20	19	19
Total	38	-	-	38	33	33

C. Clinical SVOP testing

SVOP was used to test the visual fields of 24 subjects including children and adults both with and without visual field defects (Table II).

Subjects performed monocular (right and left eye) SVOP tests. If able, they also performed monocular HFA C-40 screening tests using a 14dB stimulus to provide a direct comparison with SVOP test results. Five of the younger children performed a binocular (rather than monocular testing) test and did not perform HFA tests.

TABLE II. SUBJECTS FOR SVOP TESTS

Subject group	n	Age (years)		SVOP tests performed		
		Mean	*Range*	*Binocular*	*Left*	*Right*
Children with VF defects	6	6.0	4-9	4	2	2
Adults with VF defects	7	63.4	18-74	0	6	7
Normal children	4	7.5	5-9	1	3	3
Normal adults	7	25.7	18-50	0	7	7
Total	24	-	-	5	18	19

III. RESULTS

A. Assessment of Eye Gaze Responses to VF Stimuli

All of the test patterns used (Fig. 5) contain multiple points located at 5°, 10°, 15°, 20° and 25° eccentricity. Eccentricity was found to have the largest effect on the eye gaze vector bias data. As such, the results are presented in relation to these five eccentricity values. Moreover, there was no significant difference between the means of the vector bias data collected for the adults and children (two sample t-test, $p>0.05$, for all eccentricity values). Consequently, the child and adult vector data was analysed collectively, with the aim of deriving a set of limits for the SVOP decision algorithm.

Fig. 5a shows a normalised histogram of the direction bias data at 15° eccentricity and a corresponding Pearson distribution fit with mean, standard deviation (SD), skew and kurtosis obtained from the collected data. This process was repeated for all eccentricities and Fig. 5b shows the corresponding fitted distributions. Each of these was approximately symmetric around a mean bias close to zero degrees, and showed a decrease in SD and an increase in kurtosis with increased eccentricity. A kurtosis value greater than 3 indicates a leptokurtic distribution which has a higher peak and heavier tails as compared to the normal distribution. This signifies more values close to the mean, but also a higher probability of more extreme values as compared to a normal distribution.

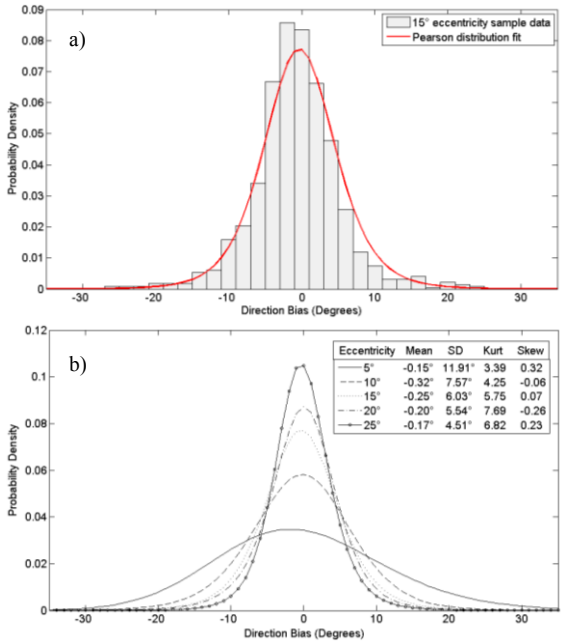

Figure 5. (a) Histogram of direction bias data at 15° eccentricity and Pearson distribution fit. (b) Distributions at all eccentricities.

This analysis process was repeated for the magnitude bias data. Fig. 6a shows a normalised histogram of the magnitude bias data at 15° eccentricity and corresponding Pearson distribution fit, while Fig. 6b shows the fitted distributions for all eccentricities. Similar to direction bias, increased eccentricity produced a decrease in SD and an increase in kurtosis. In addition, the magnitude bias distributions showed mean values which were consistently negative, and the distributions became more negatively skewed with increased eccentricity.

As previously described, the aim of collecting this vector bias data was to produce a set of limits for the SVOP decision algorithm. Due to the increased kurtosis found in all the distributions, it was decided to use a wide range of limits corresponding to the mean values ±3 SD's at each level of

eccentricity. Responses that fall within the limits will indicate that a VF stimulus is considered seen by the SVOP decision algorithm in the clinical testing.

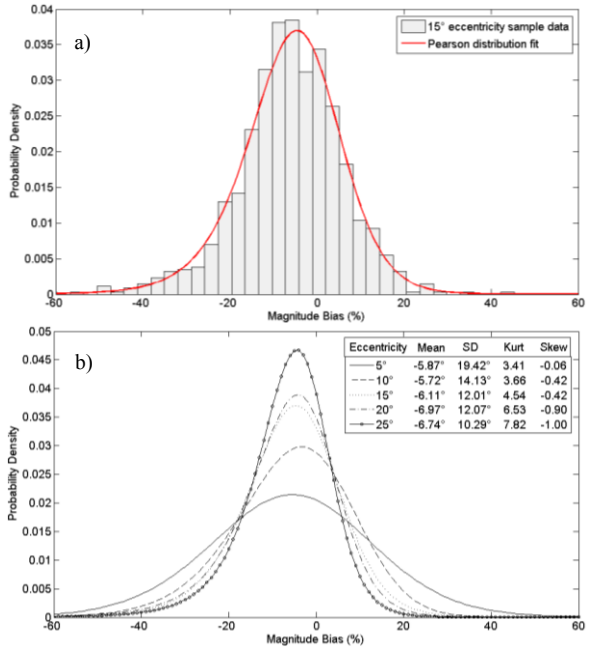

Figure 6. (a) Histogram of magnitude bias data at 15° eccentricity and Pearson distribution fit. (b) Distributions at all eccentricities.

B. Clinical SVOP testing

In subjects able to perform SVOP and a HFA equivalent test, the HFA was used as a reference "gold standard" to directly compare each test point. Overall, the sensitivity and specificity of SVOP was calculated as 73% and 90% respectively.

As an example, Fig. 7a shows a monocular (left eye) HFA test result of a 61 year old male with pigmentary glaucoma, and Fig. 7b shows the equivalent SVOP test result. Filled points in each VF plot represent unseen points.

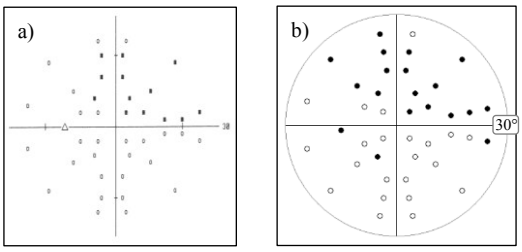

Figure 7. (a) HFA and (b) SVOP test results of left eye from 61 year old male with pigmentary glaucoma.

Fig. 8 shows examples of SVOP test results from two children with visual field defects who were unable to perform the HFA reference tests. Fig. 8a shows the SVOP test result from a 5 year old girl diagnosed with a hypothalamic pilocytic astrocytoma. She has no vision in her right eye, and was thought to have a complete temporal defect following confrontational visual field testing. Fig 8b. shows the binocular SVOP test result from a 4 year old girl diagnosed with a left temporal pilocytic astrocytoma. On confrontation VF testing she was found to have right homonymous hemianopia.

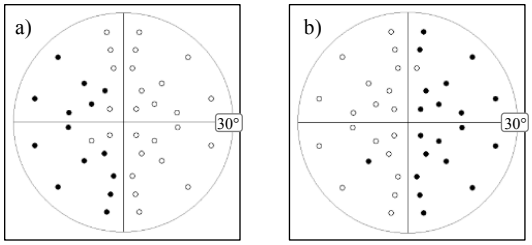

Figure 8 (a) SVOP test result from a 5 year old girl diagnosed with a hypothalamic pilocytic astrocytoma. (b) SVOP test result from a 4 year old girl diagnosed with a left temporal pilocytic astrocytoma

IV. Discussion and Conclusion

This paper introduces the technique of SVOP with emphasis on the software algorithm which makes the decision on whether a VF stimulus has been seen or not, and its basis on eye gaze responses to VF stimuli. The vector eye response data collected showed that normal subjects are generally more accurate with the direction than the magnitude of their initial gaze response, with a tendency to underestimate the magnitude. Furthermore, no significant difference in these characteristics was found between the child and adult groups. A larger set of normative data would be useful to investigate these aspects in greater detail and determine any effects of childhood development on these gaze responses. A more extensive normative database may have wider application for assisting the diagnosis of other ocular disorders (e.g. eye movement abnormalities) and neurological conditions such as autism spectrum disorder where gaze behavior disruption is known to occur [10].

SVOP has provided promising visual field test results and has proven extremely useful in detecting VF defects in young children. SVOP is currently undergoing a larger clinical trial to fully validate the technique.

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