SHORT WAVELENGTH AUTOMATED PERIMETRY (SWAP)

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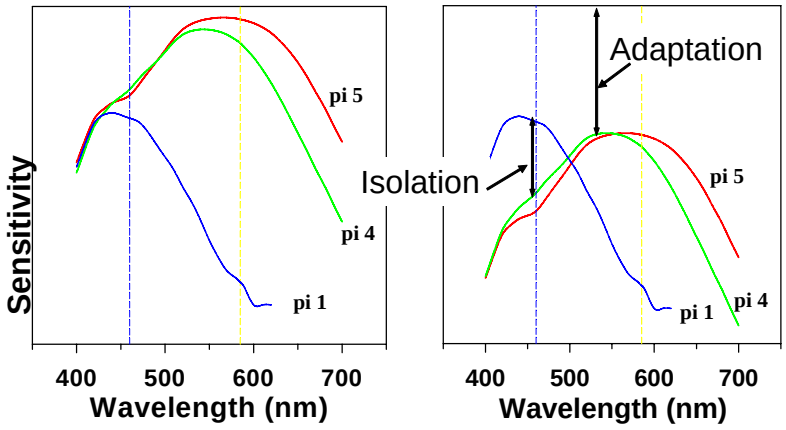
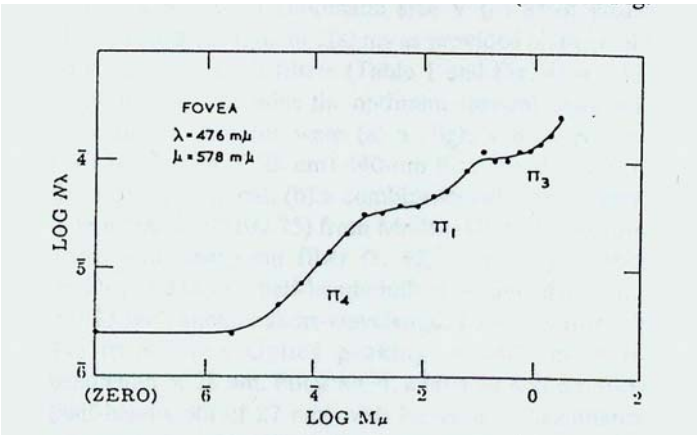
INTRODUCTION

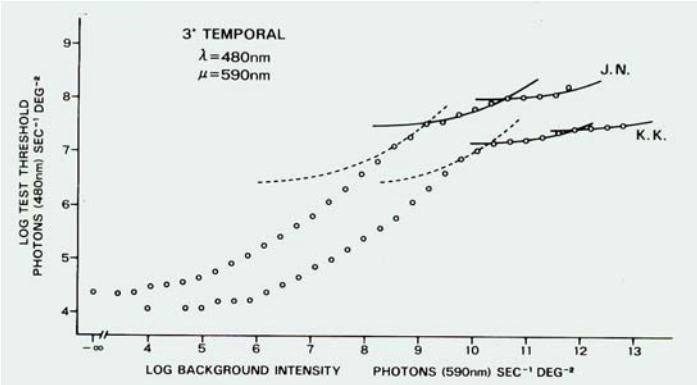
The pioneering work of Stiles provided a means of psychophysically isolating and measuring the sensitivity of individual color vision mechanisms through the two-color increment threshold procedure.[1,2] Basically, this approach involved decreasing the sensitivity of some color vision mechanisms (termed π mechanisms by Stiles) by using a chromatic adapting background light, and then measuring the sensitivity of another color vision mechanism by means of a narrow band chromatic stimulus. According to Stiles' terminology, π0 refers to the sensitivity of the rod system, π1, 2 and 3 are short wavelength ("blue") sensitive mechanisms, π4 is a middle wavelength ("green") sensitive mechanism, and π5 is a long wavelength ("red") sensitive mechanism. Isolation of π1, the principal short wavelength ("blue") sensitive mechanism, was best achieved with a high luminance (greater than 50 cd/m^2) white or broad spectrum yellow background (530 nm short wavelength "cutoff" filter), and a large (greater than 2 degrees in diameter) narrow band (440 nm peak wavelength with a 10-20 nm bandwidth) short wavelength stimulus. The figure below and to the right shows the spectral sensitivity of three color vision mechanisms (π1, π4, and π5) under normal viewing conditions on the left graph. The vertical blue line indicates the peak of the short wavelength mechanism and the vertical yellow line indicates the peak wavelength of the background. The graph is plotted in a threshold versus wavelength format, in which the background chromaticity and luminance are constant, the stimulus wavelength is varied and the stimulus increment threshold is determined. Note that under these conditions, sensitivity to a short wavelength stimulus is higher for the middle and long wavelength systems than for the short wavelength system. The graph to the right shows the same spectral sensitivity profile in the presence of a bright broadband yellow background. Here one can observe that there is substantially decreased sensitivity for the middle and long wavelength mechanisms, thereby permitting the short wavelength mechanism's sensitivity to be isolated and measured.

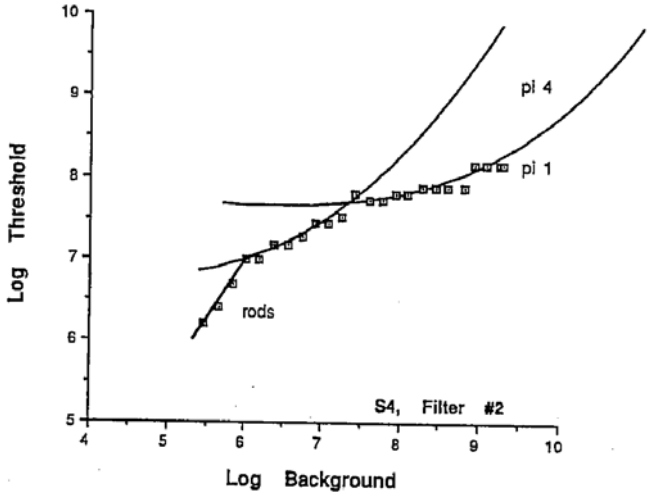


Several investigators were able to adapt this technique for use in testing patients with various ocular and neurologic disorders.[3,4] Most of this initial work concentrated on the evaluation of the fovea and possibly a limited number of extra foveal locations. An

example of the results obtained from these early studies is shown on the top graph presented to the right. This data representation format is a threshold versus intensity (or threshold versus radiance) type of representation in which the chromaticity of the stimulus and background are held constant, the luminance of the background is varied on successive trials, and the stimulus increment threshold is determined. As shown by the left portion of the graph (labelled π4), the increment threshold sensitivity is unaffected by the luminance of the background, thereby demonstrating a horizontal line. At some point, the background begins to exert an effect, and more light must be added to the stimulus to make it detectable, and this relationship between stimulus and background luminance is linear. When the background luminance becomes higher, it may significantly adapt one mechanism (in this instance, π4) and another, more sensitive, mechanism may then detect the stimulus, as indicated in the figure where π1 becomes prominent. Thus, the departures from linearity in the graph are indications that stimulus detection is being transferred from one mechanism to another, more sensitive mechanism. A similar threshold versus intensity curve is presented in the middle graph for an extrafoveal location.[4]







More recently, several laboratories have attempted to adapt this procedure for automated perimetric testing.[5-12] In particular, a procedure that isolates and measures the short wavelength sensitive mechanisms has been of interest, and it has come to be referred to as Short Wavelength Automated Perimetry (SWAP). The lower graph on this page presents threshold versus sensitivity curves for an eccentric location that was obtained using the two-color increment threshold technique on a modified automated perimeter.

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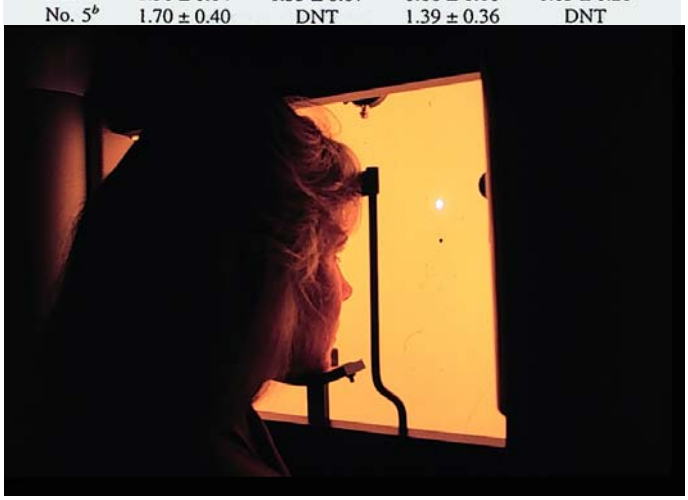
Initially, it was also determined that there were normal aging effects that were greater than for standard automated perimetry,[5,10] and that these aging effects were partly due to optical factors[12] and some were due to neural losses.[6] Subsequent investigations found that normal aging effects were essentially equivalent for all visual field procedures if the dynamic ranges are taken into account.[13] It has also been reported that there are learning effects that occur for SWAP.[14,15] Specific details about the SWAP procedure are beyond the scope of this presentation, and the interested reader is encouraged to review the literature citations included with this presentation.[1-63] The initial methods for performing SWAP were slightly different among the various laboratories, but after its clinical effectiveness had been established, many of the laboratories were able to collaborate and define optimal clinical test conditions for SWAP, which was extremely beneficial for its application in the eye clinic.[16] It was determined that a broadband yellow filter (OG530 Schott filter – a 530 nm short wavelength cutoff filter) for the background, a background luminance of 100 cd/m^2, a large stimulus (Goldmann Size V, about 1.7 degrees diameter) with a narrow band short wavelength interference filter (440 nm peak transmission, with a 15 nm bandwidth) and a 200 millisecond stimulus duration was the most appropriate set of conditions for performing SWAP testing. The table to the right indicates that under these conditions, the bottom filter condition (5b) shows that one was able to obtain 1.4 to 1.7 long units of isolation of the short wavelength sensitive mechanisms (14 to 17 dB), which subsequent studies have shown makes it possible to maintain isolation of these mechanisms throughout the entire operating range of the visual field instrument and for all levels of visual field damage.[17-19] In this Table, DNT refers to "did not test". The figure to the right presents a view of the SWAP procedure as performed by an automated perimeter that was modified to conduct this test procedure. Our best current understanding of the mechanisms underlying SWAP detection is that it is mediated by input from the cone photoreceptors through inner retinal interactions and subsequent processing by a group of retinal ganglion cells that are responsible for coding blue-yellow opponent color processing.[64,65] These ganglion cells comprise approximately 5% of the total number of ganglion cells and are believed to project to the intralaminar cells (Koniocellular cells) in the lateral geniculate nucleus.[64,65] In this view the neural mechanisms underlying SWAP are sparse and are uniquely designed to be specifically responsive to this type of stimulus display.

TABLE 2. *Mean isolation (±SD) in log units for each stimulus at fixation and 20° eccentricity (n = 6) and at 100 and 200 cd/m² backgrounds*

	Isolation			
	Fixation		20°	
Filter	100 cd/m²	200 cd/m²	100 cd/m²	200 cd/m²
No. 1	1.34 ± 0.13	1.31 ± 0.14	0.83 ± 0.29	0.82 ± 0.35
No. 2	1.17 ± 0.25	1.26 ± 0.30	0.78 ± 0.35	0.85 ± 0.34
No. 3	1.13 ± 0.37	1.29 ± 0.36	0.71 ± 0.35	0.75 ± 0.34
No. 4[a]	1.30 ± 0.14	1.35 ± 0.07	0.88 ± 0.18	0.85 ± 0.21
No. 5[b]	1.70 ± 0.40	DNT	1.39 ± 0.36	DNT



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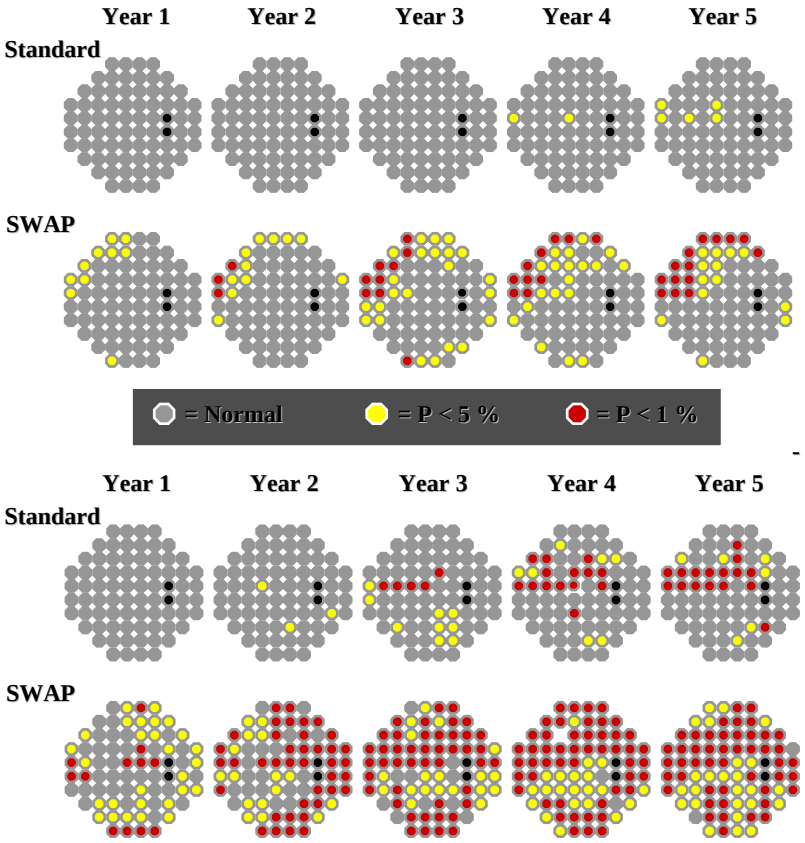
As with all diagnostic test procedures, SWAP has some advantages and disadvantages. Longitudinal investigations performed at several different laboratories have demonstrated that SWAP is able to identify glaucomatous visual field deficits earlier than standard (white-on-white) automated perimetry,[8,20-34] revealing deficits in approximately 20-25% of patients at risk of developing glaucoma who have repeatedly normal visual field results for standard automated perimetry. The pattern of visual field loss corresponds to those that would be expected to occur as a consequence of retinal nerve fiber bundle deficits in glaucoma.[7,35] Additionally, the size of SWAP defects are usually larger than those observed for standard automated perimetry,[7,9,36-38] and progression of SWAP deficits is typically greater than for standard automated perimetry.[7,9,36-38] Additional studies have demonstrated that SWAP deficits can be confirmed by subsequent testing more frequently than standard automated perimetry losses,[24] and that isolation of short wavelength sensitive mechanisms can be maintained throughout the entire dynamic range for SWAP testing, even in damaged visual field areas.[17-19] Perhaps the greatest advantage of SWAP is that it is able to predict the onset and location of future glaucomatous visual field deficits for standard automated perimetry by 3-5 and possibly 10 years.[20-34] Two examples of this predictive value of SWAP are presented below, where SWAP results for five consecutive years are presented in the bottom panels and standard automated perimetry results are presented in the top panels. Locations that are within the 95% normal confidence limits (adjusted for age) are indicated by gray circles, whereas locations that are worse than the lower normal 5% limit are indicated by yellow circles, and locations that are worse than the lower 1% level are denoted by red circles.



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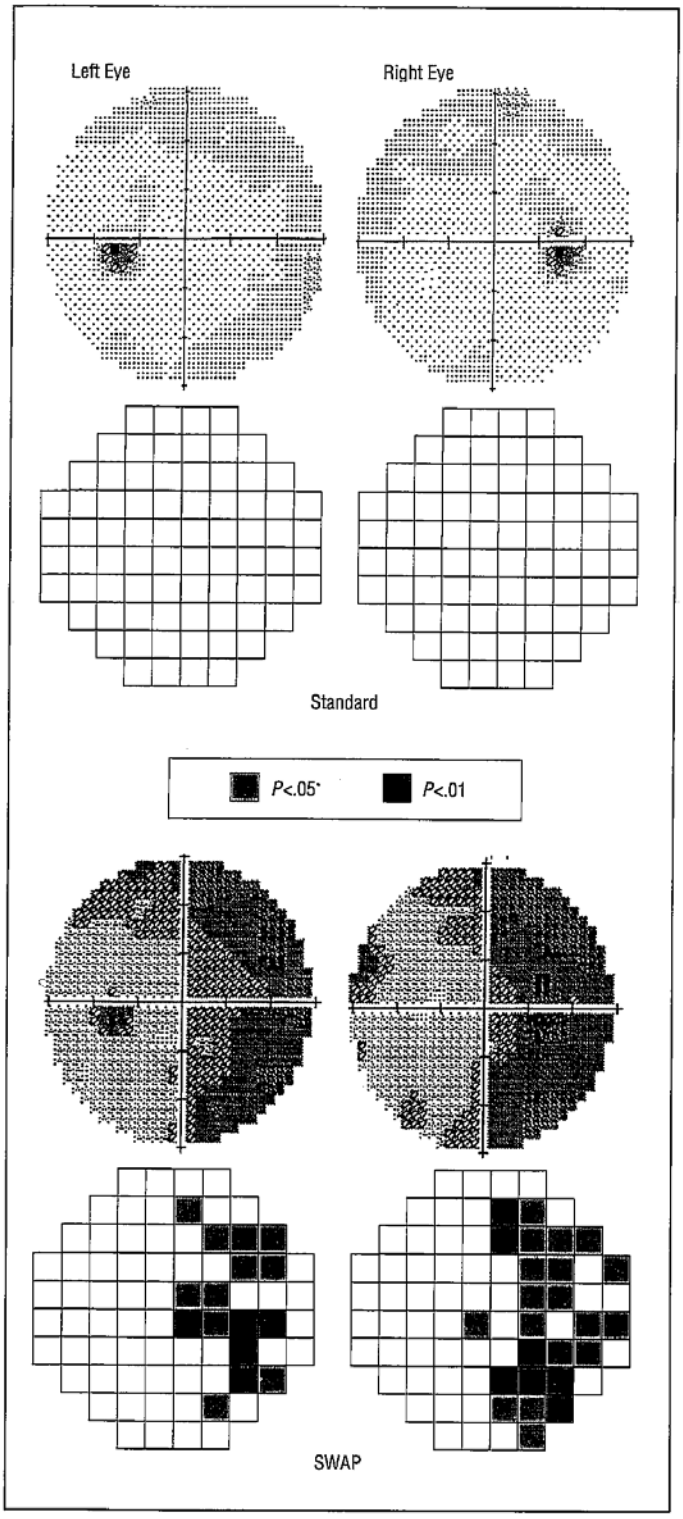
SWAP has several disadvantages as well. First, it is more variable than standard automated perimetry,[39] is affected by the absorption properties of the crystalline lens,[12] and is more difficult for some patients to perform. However, these disadvantages do not deter from the clinical value of SWAP, and methods have been developed to account for these disadvantages. This has enhanced the robustness and viability of SWAP as a routine clinical diagnostic test procedure. Recently, several laboratories have examined the relationship between SWAP deficits and structural deficits produced by glaucoma, thereby enhancing our knowledge of the basis for glaucoma pathophysiology. [40-43]

SWAP has also been useful for diagnostic evaluation of ocular and neurologic diseases other than glaucoma. SWAP has been found to be useful in the visual field evaluation of patients with diabetic retinopathy and other retinal diseases,[44-53] optic neuropathies, pre-chiasmal, chiasmal and post chiasmal deficits,[54-56] migraine,[57,58] and other disorders. In most instances, the deficit noted for SWAP is more extensive than those observed for standard automated perimetry, or the deficit is present for SWAP but is not evident on standard automated perimetry. The figure to the right[56] demonstrates an example of standard automated perimetry (top graphs) and SWAP (bottom graphs) for both eyes of a patient with normal test results (repeatedly) for standard automated perimetry and a right homonymous hemianopic visual field deficit for SWAP (repeatedly). Several neuro-ophthalmology exams revealed no remarkable findings that could account for the



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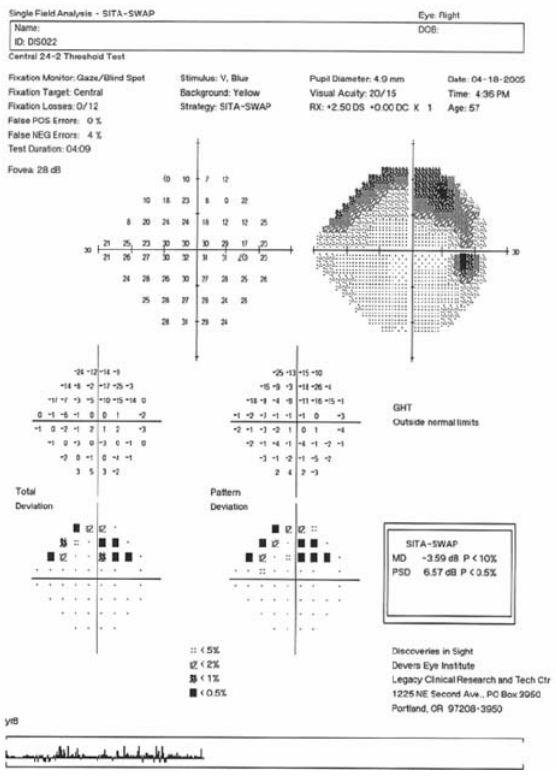
hemianopic visual field deficit for SWAP. However, an MRI scan revealed multiple disseminated plaques that were present in both hemispheres, but were particularly prominent in the left hemisphere that would correspond to the right SWAP homonymous hemianopsia.

One of the shortcomings associated with the commercial version of SWAP is the length of time required to perform testing. Typically, SWAP testing required 2-3 minutes longer that the Full Threshold procedure for standard automated perimetry, creating test times of 15-20 minutes per eye. Recently, several laboratories have applied Bayesian test strategies to the SWAP procedure in order to provide a more efficient method of testing for clinical diagnostic purposes.[59-62] SITA SWAP has been reported to provide sensitivity for detection of glaucomatous visual field loss that is highly similar to the Full Threshold SWAP approach. Also, the variability of SITA SWAP, both within and between subjects, was found to be equal to or less than that observed for the standard SWAP procedure.[59-62] Additionally, the SITA SWAP procedure has been reported by two independent laboratories to have 4-5 dB of increased sensitivity for each test location, when compared to the standard SWAP procedure.[59-62] This has the advantage of increasing the dynamic range of SWAP, which makes it possible to monitor damaged visual field areas in a better manner, which is a distinct benefit in view of SWAP's more limited response operating range when compared to standard automated perimetry. Some of the factors responsible for this increased dynamic range for SITA SWAP have been identified, while other remain to be determined.[63] The figure to the right shows an example of SITA SWAP for the right eye of a patient with glaucomatous visual field loss. A superior partial arcuate deficit is detected within a test duration interval of approximately 4 minutes and 9 seconds.



SWAP is currently implemented on several commercially available automated perimeters (along with a normative database and statistical analysis package), include the Humphrey Field Analyzer II (Model 700 and higher) and Octopus perimeters. In view of the available literature devoted to SWAP, it would also be a rather straightforward procedure for many other manufacturers to provide SWAP as a test procedure as well.

In summary, SWAP has been a technique that has taken many years to develop and refine, has had several laboratories conducting longitudinal evaluations of its clinical capabilities, and continues to be refined. It therefore serves as a good example of the type of work necessary to validate a clinical diagnostic test procedure.

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