Clinical Ophthalmology

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METHODOLOGY

Volume of visual field assessed with kinetic perimetry and its application to static perimetry

This article was published in the following Dove Press journal:
Clinical Ophthalmology
22 April 2011

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Background: The purpose of this study was to quantify the volume of the kinetic visual field with a single unit that accounts for visual field area and differential luminance sensitivity.
Methods: Kinetic visual field perimetry was performed with a Goldmann perimeter using I4e, I3e, I2e, and I1e targets. The visual fields of 25 normal volunteers (17 women, eight men) of mean age 33.9 ± 10.1 (range 17–64) years were obtained and digitized. Isopter areas were measured with a method devised to correct cartographic distortion due to polar projection inherent in perimetry and are expressed in steradians. The third dimension of each isopter represents sensitivity to target luminance and was calculated as log (target luminance^{-1}). If luminance is expressed in cd/m^2, the values for the third dimension are 0.5 for I4e, 1.0 for I3e, 1.5 for I2e, and 2.0 for I1e. The resulting unit is a steradian (log 10^3 (cd/m^2)$^{-1}$ which is referred to as a Goldmann. In addition, the visual fields of four patients with representative visual defect patterns were examined and compared with normal subjects.
Results: Mean isopter areas for normal subjects were 3.092 ± 0.242 steradians for I4e, 2.349 ± 0.280 steradians for I3e, 1.242 ± 0.263 steradians for I2e, and 0.251 ± 0.114 steradians for the I1e target. Isopter volumes were 1.546 ± 0.121 Goldmanns for the I4e target, 1.174 ± 0.140 Goldmanns for I3e, 0.621 ± 0.131 Goldmanns for I2e, and 0.126 ± 0.057 Goldmanns for I1e. The total mean visual field volume in our study for the I target was 3.467 ± 0.371 Goldmanns.
Conclusion: The volume of the island of vision may be used to quantify a visual field with a single value which contains information about both visual field extension and differential luminance sensitivity. This technique may be used to assess the progression or stability of visual field defects over time. A similar method may be applied to static perimetry.
Keywords: visual field, kinetic perimetry, static perimetry, steradian, cartographic distortion

Introduction

The kinetic visual field has been classically interpreted by measuring one or more isopter field areas. Areas are expressed in degrees squared, centimeters squared, average diameter, or steradians. However, these units are usually limited to one isopter field area, and no information about the sensitivity to target luminance is included. This study presents a method that quantifies the kinetic visual field as a three-dimensional form by expressing both isopter area and sensitivity to target luminances of a particular target size. This quantification of a visual field can be used clinically to follow changes in the visual fields of patients over time.[1]

Methods

Kinetic perimetry was performed with a Goldmann perimeter (Haag-Streit Inc, Bern, Switzerland) using target sizes of I4e, I3e, I2e, and I1e. Twenty-five normal

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DOI: 10.2147/OPTH.S18815

subjects, comprising eight males and 17 females of mean age 33.9 ± 10.1 (range 17–64) years were selected. One subject was under 20 years of age, 10 were aged 20–29 years, nine were 30–39 years, and five were 40 years or older (Table 1). The study was approved by the National Eye Institute Institutional Review Board, and was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. All subjects gave their informed consent prior to their inclusion in the study. None were on medications that affected pupil size or ocular function. Best corrected visual acuity using the Early Treatment of Diabetic Retinopathy Study Lighthouse Chart was measured and a complete dilated ophthalmologic examination was performed on each volunteer. All patients had best corrected visual acuity of 20/20 or better in the tested eye, and there were no media opacities or other abnormal findings on dilated slit lamp and fundus examination that would affect perimetric testing. In addition, visual fields of four patients with representative visual defects obtained during the course of their normal clinical visits were chosen to illustrate this method. These were concentric contraction (gyrate atrophy), temporal hemianopia (craniopharyngioma), arcuate scotoma (glaucoma), and central scotoma (macular dystrophy).

The area of a visual field isopter can be measured in steradians. One steradian is the area on the surface of a sphere that is subtended by a solid angle emanating from the center of a sphere.[2] The two-dimensional kinetic visual field is an equidistant polar projection of the interior of the perimetry bowl onto a flat surface (azimuthal). Such projections contain equally spaced circles that are equidistant only along

Table 1 Isopter areas and volumes with total volume from Goldmann perimetry in normal subjects

#	Age (years)	I-4 (sr)	I-3 (sr)	I-2 (sr)	I-1 (sr)	I-4 (Gn)	I-3 (Gn)	I-2 (Gn)	I-1 (Gn)	SUM (Gn)
1	17.76	3.073	2.273	1.315	0.382	1.537	1.137	0.658	0.191	3.522
2	24.34	3.080	2.366	1.207	0.288	1.540	1.183	0.604	0.144	3.471
3	24.68	3.067	2.357	1.105	0.172	1.534	1.179	0.553	0.086	3.351
4	24.82	2.820	2.231	1.267	0.300	1.410	1.116	0.634	0.150	3.309
5	25.17	3.211	2.565	1.224	0.244	1.606	1.283	0.612	0.122	3.622
6	25.85	3.180	2.503	1.081	0.129	1.590	1.252	0.541	0.065	3.447
7	27.78	3.337	2.918	1.902	0.390	1.669	1.459	0.951	0.195	4.274
8	27.79	3.618	2.562	1.209	0.431	1.809	1.281	0.605	0.216	3.910
9	28.45	3.099	2.387	1.509	0.312	1.550	1.194	0.755	0.156	3.654
10	29.87	3.544	2.729	1.515	0.242	1.772	1.365	0.758	0.121	4.015
11	29.91	2.943	1.876	1.003	0.367	1.472	0.938	0.502	0.184	3.095
12	30.64	3.002	2.171	1.229	0.346	1.501	1.086	0.615	0.173	3.374
13	32.18	2.893	2.469	1.563	0.314	1.447	1.235	0.782	0.157	3.620
14	32.28	3.041	2.478	1.358	0.348	1.521	1.239	0.679	0.174	3.613
15	32.61	3.177	2.190	0.863	0.115	1.589	1.095	0.432	0.058	3.173
16	32.81	2.648	1.631	0.803	0.172	1.324	0.816	0.402	0.086	2.627
17	33.38	3.410	2.515	1.167	0.125	1.705	1.258	0.584	0.063	3.609
18	34.31	3.359	2.693	1.754	0.473	1.680	1.347	0.877	0.237	4.140
19	38.35	3.133	2.300	1.207	0.219	1.567	1.150	0.604	0.110	3.430
20	39.23	3.145	2.461	1.371	0.127	1.573	1.231	0.686	0.064	3.552
21	42.73	2.949	2.167	1.066	0.110	1.475	1.084	0.533	0.055	3.146
22	42.94	2.578	1.885	1.067	0.222	1.289	0.943	0.534	0.111	2.876
23	44.96	3.004	2.445	1.300	0.098	1.502	1.223	0.650	0.049	3.424
24	52.92	2.958	2.364	1.114	0.088	1.479	1.182	0.557	0.044	3.262
25	64.64	3.034	2.188	0.861	0.266	1.517	1.094	0.431	0.133	3.175
Mean	33.62	3.092	2.349	1.242	0.251	1.546	1.174	0.621	0.126	3.467
SD	10.11	0.242	0.28	0.263	0.114	0.121	0.14	0.131	0.0569	0.371
Mean	20–29	3.190	2.449	1.302	0.288	1.595	1.225	0.651	0.144	3.615
SD		0.250	0.283	0.269	0.095	0.125	0.142	0.134	0.047	0.360
Mean	30–39	3.090	2.323	1.257	0.249	1.545	1.162	0.629	0.124	3.459
SD		0.232	0.308	0.303	0.127	0.116	0.154	0.152	0.063	0.407
Mean	>40	2.905	2.210	1.082	0.157	1.452	1.105	0.541	0.078	3.176
SD		0.186	0.216	0.156	0.081	0.093	0.108	0.078	0.041	0.200

Notes: Volumes for each isopter are shown while the total volume is that of all isopter of I target size. Averages and standard deviations for patients aged 20–29, 30–39, >40 years are shown at the bottom of the table.

Abbreviations: sr, steradians; Gn, Goldmanns; SD, standard deviation.

meridians.[3] Units such as degrees squared, centimeters squared, or average diameter, that are measured on a planar surface, distort the true size of peripheral field regions by making them appear larger than equivalent central field regions. Tangential azimuthal deformation increases greatly with eccentricities beyond 50° from the center (20% at 60° and 57% at 90°).[4] Small distortions using the solid angle to measure visual fields still exist with regard to retinal eccentricity, and require certain assumptions and approximations in order to be corrected mathematically.[2,6–8] Despite these, the steradian is a more appropriate unit to quantify visual field area than other units. Steradians can be converted to degrees squared. One steradian is one radian squared and since one radian subtends 57.3°, one steradian equals $(57.3°)^2$ or 3283.3° squared.

The visual fields obtained were scanned and each of the four isopters was then digitized. The area of each isopter was calculated in steradians using a method described by Weleber and Tobler that corrects for cartographic distortion due to polar projection.[2] The series of formulae is listed in Table 2. The digitized x and y coordinates for each isopter are listed in columns A and B. The formulae in each of the columns can be copied and pasted into a spreadsheet application, such as Microsoft Excel®. The total area of an isopter in steradians is the sum of all of the values in column P. It should be noted that an x coordinate of 0.000 will be read as infinity by the formula in column C (= ATAN B1/A1), therefore an x coordinate of 0.000 is converted to 0.001.

Table 2 Formula for calculation of isopter area in steradians

Column	Title	Formula
A	x-axis	x coordinates (from digitization)
B	y-axis	y coordinates (from digitization)
C	U theta (rad)	= ATAN (B1/A1)
D	U theta (deg)	= (C1*360)/(2*3.14159265)
E	theta (deg)	= If (AND(A1 > 0, B1 > 0), D1, If (A1 < 0, D1 + 180, D1 + 360)
F	Distance	= ABS(A1/COS[C1])
G	R	= (F1*3.14159265)/180
H	T	= (E1*3.14159265)/180
I	D1	= ABS(H1 − H2)*0.5
J	X	= (G2 − G1)*0.5
K	Y	= (G2 + G1)*0.5
L	T1	= 1/Tan(I1)
M	D3a	= Cos(J1)/Cos(K1)*L1
N	D3b	= 2*ATAN(M1)
O	E uncorrected	= N1 + 2*I1 − 3.14159265
P	E corrected	= fF(H2 ≥ H1, O1, O1*(−1))

Notes: Series of formulae to calculate the area of an isopter in steradians correcting for cartographic distortion due to polar projection adapted from Weleber and Tobler.[2] The formula can be applied for spreadsheet application such as Microsoft Excel.

The vertical dimension of the visual field volume is inversely proportional to target luminance. Thus, a dim target luminance, such as 1e, will require greater sensitivity to be perceived and will have a greater vertical height. We utilized cd/m^2, ie, SI units, rather than apostilbs, to describe luminance per area. Apostilbs can be converted to SI units (cd/m^2) by dividing apostilbs by π. The inverse of the target luminance values is used to describe target luminance sensitivity. The log of the sensitivity compresses the axis scale and the units are multiplied by 1000 to keep the log units positive. The resulting units are expressed in log 10^3 $(cd/m^2)^{-1}$. The volume of each visual field isopter is the product of area and sensitivity to target luminance. The resulting units are steradians log $10^3(cd/m^2)^{-1}$, referred to as Goldmanns. The derivation of the log of sensitivity is illustrated in Table 3.

The volume of the visual field of the four luminances for the size I target is calculated by summing the products of area and height for each isopter. In this study, the same target size (I) for each isopter measurement is used, so the only variable change is target luminance. In order to avoid duplication of visual field volume between isopters, the height of each I isopter is 0.5 log $10^3(cd/m^2)^{-1}$. Larger target sizes can be used by multiplying the area by the appropriate target luminance factor. This would increase the height of the I target because of its decreased luminance relative to larger target sizes (Table 3). If there is a visual field deficit present, the volume of the scotoma is similarly calculated for each isopter and the total is subtracted from the total visual field volume. The area of the blind spot is 0.012 steradians or 0.048 Goldmanns and may or may not be subtracted from the total volume measurement as long as the measurements between studies are consistent.

This method of calculating the volume of the visual field can also be applied to automated static perimetry. In threshold static perimetry, differential luminance sensitivity units

Table 3 Conversion of apostilbs to sensitivity to target luminance log ($[cd/m^2]^{-1}$)[3]

Target	Asb	cd/m^2	$(cd/m^2)^{-1}$	10^3 $(cd/m^2)^{-1}$	log 10^3* $(cd/m^2)^{-1}$
V4e	1000	318.31	0.003142	3.14	0.50
IV4e	315	100.268	0.009973	9.97	1.00
III4e	100	31.831	0.031416	31.42	1.50
II4e	31.5	10.0268	0.099733	99.73	2.00
I4e	10	3.1831	0.314159	314.16	2.50
I3e	3.15	1.00268	0.997331	997.33	3.00
I2e	1	0.31831	3.141593	3141.59	3.50
I1e	0.315	0.10027	9.97331	9973.31	4.00

are expressed in decibels of target luminance attenuation. Each threshold value already represents the "height" of a specific area of the visual field. The Humphrey field analyzer (Carl Zeiss, Meditec, Dublin, CA) 30-2 program contains 76 threshold measurements, each one representing 36 squared degrees (or 0.011 steradians). Thus, there are 76 columns of visual space in the Humphrey field analyzer 30-2 program. The volume of each column is the product of the area of the base and its height, and the total volume (dB) is the sum of all the column volumes. The foveal threshold is not included in this calculation because it overlaps with the four surrounding threshold columns. The total volume can be converted to Goldmann units by multiplying the decibels of luminance attenuation with a conversion factor. The Humphrey field analyzer 30-2 represents a total area of $(36°)^2 \times 76/(3283.3°)^2$/steradians or 0.8333 steradians. The height of the visual field is determined by converting the mean target luminance attenuation in decibels (dB_{mean} or $\log (cd/m^2))^{-1}$ to apostilbs using a conversion chart. In static perimetry, 0 decibels equals 10,000 apostilbs. Thus, to keep the log units positive, $(cd/m^2)^{-1}$ is multiplied by a factor of 10,000 instead of the 1000 used in kinetic perimetry. The relationship between decibels of target luminance attenuation and $\log 10^4(cd/m^2)^{-1}$ is linear, and is described by the following equation: $\log 10^4(cd/m^2)^{-1} = 0.1 \times (dB_{mean}) + 0.5$.

For the Humphrey field analyzer 30-2, the sensitivity to luminance can be converted to Goldmanns by multiplying by 0.8333 steradians. Thus: $Gn = 0.8333 [(0.1 \times (dB_{mean})] + 0.5)$. Because of inherent differences, units obtained by static perimetry cannot be interchanged with the volumetric measurements obtained from kinetic perimetry.

Results

The assignment of a vertical dimension for luminance sensitivity reinterprets the island of vision for a particular target size from the classical planar figure that is used in kinetic perimetry to a three-dimensional form (Figures 1A and 1B). Isopter areas and volumes, as well as total volume obtained with Goldmann perimetry for each subject and their age, are listed in Table 1. The mean total volume of the 25 normal subjects for the I isopter was 3.467 ± 0.37 Goldmanns, but these decreased in the older age groups. The mean for the 10 subjects aged 20–29 years was 3.615 ± 0.36 Goldmanns, that of the nine subjects aged 30–39 years was 3.459 ± 0.407 Goldmanns, and for the five subjects older than 40 years, was 3.176 ± 0.200 Goldmanns.

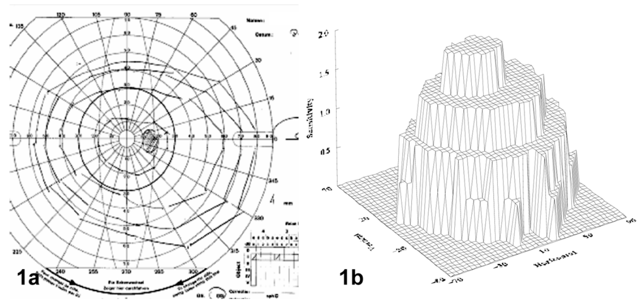

Figure 1 The assignment of a vertical dimension for luminance sensitivity reinterprets the island of vision for a particular target size (I) from the classical planar figure that is used in kinetic perimetry (**1a**) to a three-dimensional form (**1b**).

Table 4 depicts the isopter volumes and total volume of the four representative visual field defects illustrated in Figures 2A–D. The field with concentric contraction (Figure 2A) demonstrates a large decrease in the total isopter I volume (0.212 Goldmanns). In addition, the differential sensitivity to target luminances dimmer than I4e decreases abruptly in this particular patient, resulting in a volume that is mostly comprised of the I4e isopter (62.3% of total I isopter volume versus 44.7% for age-matched controls). The patient with temporal hemianopia (Figure 2B) demonstrates a proportional decrease in volume between isopters. Figures 2C and

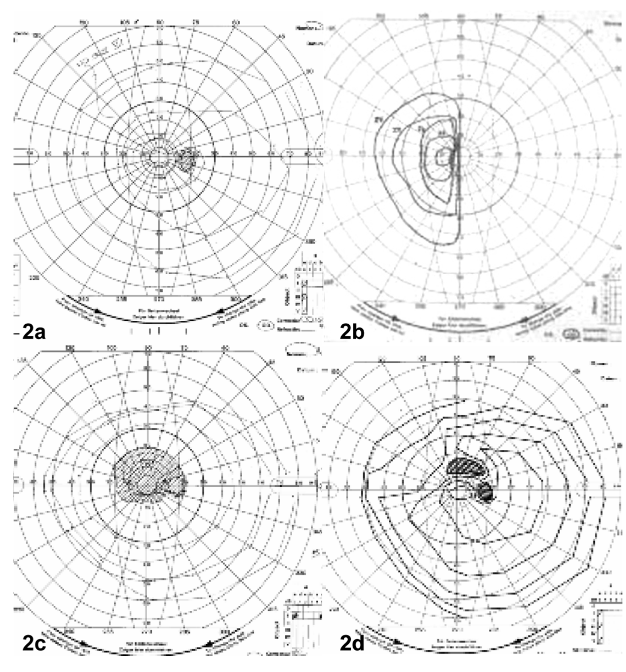

Figure 2 Four representative visual field defects obtained with Goldmann perimetry. **2a**) demonstrates concentric contraction in a patient with gyrate atrophy and **2b**) represents temporal hemianopia in a patient with craniopharyngioma. **2c**) reveals a field with a central scotoma in a patient with macular dystrophy and **2d**) an arcuate scotoma in a patient with glaucoma.

Table 4 Isopter and scotoma volumes of four representative visual field defects

Visual field defect	Disorder/age (years)	I4e	I3e	I2e	I1e	Scotoma	Total volume
Concentric contraction	Gyrate atrophy (32.7)	0.132	0.057	0.016	0.007	0	0.212
Temporal hemianopia	Craniopharyngioma (34.4)	0.426	0.291	0.150	0.040	0	0.907
Central scotoma	Juvenile macular dystrophy (25.3)	1.436	1.125	0.621	0.000	−0.254	2.928
Arcuate scotoma	Glaucoma (72.6)	1.080	0.653	0.252	0.010	−0.022	1.970

2D are fields with scotomas. Although the I-2e isopter area of the central scotoma is 0.2605 steradians, or 5.9 times larger than that of the arcuate scotoma (0.044 steradians), the central scotoma contains greater "depth" because it extends across three isopters and is 11.5 times the volume of the arcuate scotoma (0.254 Goldmanns versus 0.022 Goldmanns). Figure 3 illustrates three-dimensional examples of 30-2 Humphrey visual field measurements in a normal subject. The average differential luminance sensitivity over 76 points represented in the 30° field was 30.54 dB or 2.96 Goldmanns.

Discussion

This report presents a quantitative method to interpret kinetic visual fields by using a single volumetric measurement that incorporates all isopter areas of one target size as well as differential luminance sensitivity. This can be used as a global index comparable with mean sensitivity in static perimetry to describe quantitatively the hill of vision as assessed by kinetic perimetry. This measurement can be used to follow the visual field of a patient over time or to compare between patients.

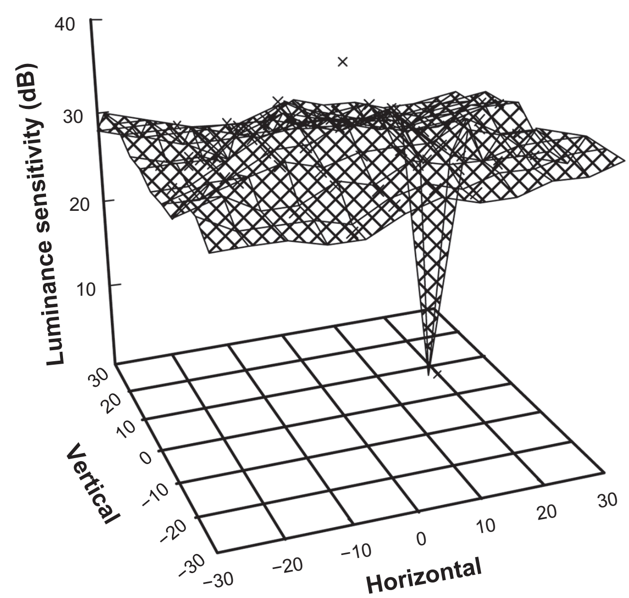

Figure 3 Three-dimensional illustration of 30-2 Humphrey perimetry in a normal subject. The small area of depression seen in the normal visual field corresponds to the blind spot.

Goldmann perimetry is a widely used form of kinetic perimetry today. Although it can be cumbersome to scan and digitize each isopter using a manual kinetic perimeter, the process can be greatly ameliorated with the use of more recent semiautomated perimeters, such as the Octopus 101 (Haag-Streit, Köniz, Switzerland), that can digitally store the coordinates at each measured isopter point and calculate the isopter areas.[9–13] The area of each isopter and total field volume can then be calculated with appropriate software. In static perimetry, conversion to a volume unit simply involves multiplying the sum of the decibels of target luminance attenuation with a conversion factor. Because current static perimeters are automated, they could be programmed to perform such a function. Three-dimensional modeling of the hill of vision using both semiautomated kinetic and automated static perimetry has been previously described.[11,14–16] These offer the possibility of modeling visual field volumes using normal age-dependent local reference values, thereby generating age-normalized mean defect values.[17]

In Goldmann perimetry, the volume of the island of vision that is measured is an underestimate of the true volume. First, target differential luminance sensitivity for an isopter target size is often well below threshold levels. Second, a finite number of points for each isopter is collected by the perimetrist. Third, a small number of target luminances (usually four) are used in clinical kinetic perimetry. Thus, the illustration in Figure 1B representing a normal visual field depicts a four-stepped pyramid, when a cone-like structure would be a closer approximation of the "true" island of vision for a particular isopter target. Based on the "stepped" structure from the measured isopter volumes, a smoother hill of vision could be modeled with interpolation software. Nevertheless, standard Goldmann perimetry provides a method of kinetic visual field testing that is consistent, practical, and requires few assumptions for measuring the size of a visual field.

The use of a volumetric parameter in kinetic perimetry can be used to evaluate more accurately the amount of field contraction or scotoma enlargement over time than the area of one isopter alone. In patients with dense scotomas or, in conditions such as retinitis pigmentosa or gyrate atrophy with reduced light sensitivity, kinetic visual fields contain smaller I4e isopter areas when compared with normal fields, but field volumes that are often proportionally much smaller than the isopter area. In the patient with gyrate atrophy, the I4e isopter volume was 8.5% compared with the mean of our age-matched controls, while the volume was 6.1% because of decreased differential luminance sensitivity to dimmer targets. By contrast, in a patient with a proportionate decrease in visual field across all isopter luminances for a particular target size, such as in hemianopia, the visual field demonstrates a more consistent decrease between area and volume (27.6% and 26.2%, respectively, in the patient with craniopharyngioma). The use of semiautomated kinetic perimetry can be used to measure scotoma size and to relate scotoma depth with age-related normal values as mean defect, a function not available with standard Goldmann perimetry.[17]

We chose one target size (I) to represent the island of the visual field because this limits the number of assumptions in constructing the volume. It avoids the added variable of spatial summation that occurs when using different target sizes with similar luminances, In Goldmann perimetry, dimmer luminances (3e, 2e, and 1e) are most frequently used with I target rather than III or V target size. However, use of the I target alone truncates the true island of vision considerably, in essence measuring the top portion of the island of vision. Nevertheless, the use of one target size requires few assumptions about the luminance levels of other target sizes and avoids variance seen with far peripheral field measurements using larger target sizes. Larger target sizes, such as V4e and III4e, can be added by multiplying the isopter by the appropriate luminance attenuation factor. Although standard luminance levels for larger target sizes can be found in Table 1,[18] it would be useful to calibrate the luminance of each target to obtain a more accurate conversion factor for luminance sensitivity.

Most isopter readings ignore the size of the physiologic blind spot. However, considerable differences in its size between individuals has been recently demonstrated with semiautomated kinetic perimetry.[16] Whether the physiologic blind spot is included in isopter size calculations or whether one or more target sizes are used, it is consistency in visual field volume formulation that allows for more accurate evaluation of visual field changes over time.

In our study, 20 of 25 subjects were under the age of 40 years, so our results do not represent normative data from a widely ranged age group. The decrease in differential luminance sensitivity in the peripheral portions of the visual field and decreased sensitivity to smaller and dimmer targets has been eloquently demonstrated to correlate with increasing age, particularly after the age of 40 years.[12,13–16,19] In addition, semiautomated kinetic perimeters, such as the Octopus 101, allow for measurement of reaction time or the interval between stimulus onset and patient response. Isopter and scotoma sizes derived by semiautomated kinetic perimetry can be corrected for variable response times reducing variance of isopter area.[12,17,20] Although not available with standard Goldmann perimetry in this study, reaction time corrected isopters could be used with newer automated perimeters to derive visual field volume.

The 30-2 Humphrey visual field analyzer measures the central 30° "core" of the island of vision. There is a small amount of cartographic distortion inherent with two-dimensional projection from a curved surface. For the central 30° surface, the volumetric increase is small, approximately 2% of the entire central 30° surface, and was not accounted for in this study.[4] It should be noted that volumetric measurements between static and kinetic perimetry cannot be compared because of inherent differences between the two methods. Physiologic dissociation between kinetic and static stimuli in perimetry is well known, particularly with achromatic target perception.[21] Moreover, the sensitivity for kinetic stimuli has been shown to be greater than for static stimuli independent of age, stimulus size, and eccentricity.[22] Static perimetry may leave areas within a measured visual field untested, especially with the use of small target sizes and scattered grids with limited coverage. Thus, direct comparison of static and kinetic visual field volumes is inaccurate, and extrapolation between the two methods by a simple conversion factor is inaccurate. Finally, unlike manual perimetry, differences in individual local differential luminance sensitivity values in static perimetry are related to age-corrected normal differential luminance sensitivity values, and the resulting deviations are used to determine global indices, such as mean defect. Nevertheless, description of a visual field as a volume represents a useful index of quantifying the visual field for each of these perimetric techniques.

Conclusion

This study presents a method to quantify the volume of the island of vision using a method to correct for cartographic distortion due to polar projection, with a single value containing information about both visual field area and sensitivity to luminance. This technique can be applied to assess the progression or stability of visual field defects quantitatively over time in both kinetic and static perimetry. Newer semiautomated kinetic perimeters may be able to incorporate this type of volumetric measurement in the assessment of the visual field.

Acknowledgments

The support lent to this study by the late Dr Muriel Kaiser-Kupfer at the National Eye Institute is gratefully acknowledged, as is the guidance provided by Dr Rafael Caruso during this project.

Disclosure

The author reports no conflict of interest in this work.

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