ACUITY PERIMETRY AND GLAUCOMA

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INTRODUCTION

VISUAL ACUITY, THE ABILITY OF THE VISUAL SYSTEM TO RECOGNIZE FINE DETAIL, IS greatest in the center of the field of vision and declines toward the periphery. Although the measurement of foveal or central visual acuity is an important part of every clinical eye examination, only a few clinicians[1] have ever measured extrafoveal or peripheral visual acuity, and almost nothing is known about how diseases of the eye and visual pathways alter peripheral acuity. This neglect of peripheral visual acuity by clinicians is curious because peripheral acuity is almost certain to be disturbed by diseases of the eye and brain. Furthermore, the extensive studies that have been made by psychophysicists of peripheral acuity in normal subjects provide a sound basis for clinical studies in patients.

In this thesis, I will describe a new instrument, an acuity perimeter, that can be used in the research laboratory or clinic to test peripheral visual acuity. I will report the results of a series of experiments on normal subjects in which I defined the best testing conditions for clinical measurements of peripheral acuity and determined normal values for visual acuity at various loci in the field of vision. Finally, I will describe how glaucoma alters peripheral visual acuity. I wish to propose and defend the hypothesis that acuity perimetry is a sensitive method, one that is more sensitive than conventional light perception perimetry, for the detection of early glaucomatous optic nerve damage.

DEFINITIONS

Visual acuity is the "capacity to discriminate the fine details of objects in the field of view."[2] Several excellent reviews[2-9] summarize a large body of literature dealing with factors that underlie or influence visual acuity.

The general heading of visual acuity includes several subtypes: resolution acuity (the ability to perceive the parts of an acuity target as separate), detection acuity (the ability to see a target of minimum size), recognition acuity (the ability to name the shape of an object such as a

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Snellen letter or a geometric figure), and Vernier acuity (the ability to discriminate small displacements of one part of the target with respect to the other parts). In this thesis I will be concerned only with resolution acuity. Resolution acuity is measured by determining a resolution threshold, the minimal visual angle (subtended at the eye) by which critical parts of the stimulus must be separated in order to be perceived as distinct. Conventionally, visual acuity is tested with a high contrast stimulus.

Perimetry is the quantitative examination of visual function at selected test locations throughout the field of vision.[10] The visual function tested in conventional perimetry is a very simple one—brightness discrimination or light sensitivity. However, other more complex visual functions, such as color vision,[10] flicker fusion,[10] shape discrimination,[10-12] motion detection,[13] pupillomotor excitation,[10] and contrast sensitivity with stationary or moving grating targets,[14-17] can also be examined perimetrically.

Acuity perimetry is a form of perimetry in which visual acuity is the visual function tested. In acuity perimetry, resolution acuity is measured with high contrast targets at selected areas in the visual field eccentric to the point of fixation.

The term "acuity perimetry" has not to my knowledge been previously used in this exact sense. It has been used by other investigators[10-12] to describe a form of perimetry in which the contrast of a stimulus was increased until the subject could tell if it was square or circular in shape. This, I believe, might more accurately be called "contrast sensitivity perimetry," since target contrast rather than dimension was varied.

PREVIOUS STUDIES OF PERIPHERAL ACUITY

It has been known since antiquity that the fine details of an object are most easily recognized when the object is viewed directly and become blurred when the line of sight moves away from the object. The progressive nature of the decline of acuity with increasingly eccentric viewing was accurately described in 1759 by Porterfield.[18] He attributed it to imperfections of the peripheral optical image and to insensitivity of the peripheral retina, two explanations that remain valid today.

Although several investigators[19,20] in the 19th century attempted to quantify the decline in acuity that occurs with eccentric viewing, Wertheim[21] in 1894 was the first to accurately measure acuity throughout the visual field. He tested acuity along several meridians in his own field of vision using a printed grating as the acuity target. The decline in acuity was more abrupt along the vertical meridian than along the horizontal

meridian, so that Wertheim's acuity isopters (lines joining points in the visual field of equal acuity) were horizontally oval, much like the light sensitivity isopters in conventional perimetry.

Peripheral acuity has subsequently been the subject of many psychophysical studies. These studies can be grouped into two major lines of investigation. The studies in the first category characterize the rate of acuity decline from the center of the visual field to its periphery and explore the testing factors that influence this decline. The studies in the second category attempt to determine how much of the acuity decline from center to periphery is due to optical aberrations associated with peripheral viewing and how much is due to anatomical factors.

I will briefly review some highlights of this work with emphasis on those findings that are important to the methods and rationale of the present study.

RATE OF ACUITY DECLINE

Although all investigators agree that visual acuity declines progressively as the acuity target is moved farther and farther from the point of fixation, the rate at which acuity declines with increasing eccentricity varies widely from study to study. The different results are largely due to the many different testing conditions that have been used. Among the factors that influence the rate of decline are the acuity scale, the meridian tested, the orientation of the target, the stimulus presentation time, the state of retinal adaptation, and variation between test subjects.

Effect of Scale

An important question faced by every investigator of peripheral acuity, one that greatly influences the apparent rate of acuity decline away from fixation, is how acuity should be scaled (Table I). Some investigators[22-28] specify acuity as the resolution threshold or minimal angle of resolution. This is the visual angle subtended at the eye by the smallest resolvable target. Other investigators[29,30] prefer to specify acuity as the log of the minimal angle of resolution. Most investigators[21,27,30-38] prefer to use the reciprocal of the minimal angle of resolution, expressed in decimals or as the Snellen optotype equivalent.

The shape of the curve relating acuity to eccentricity depends on which scale is employed.[39] The acuity decline from center to periphery is often described in textbooks as being abrupt near fixation, more gradual in the midperiphery, and approaching an asymptote in the periphery. This is true only if acuity is scaled as the reciprocal of the resolution threshold—

TABLE I: VISUAL ACUITY SCALES

MINIMAL ANGLE OF RESOLUTION (MAR) (MINUTES OF ARC)	LOG MAR	1/MAR (DECIMAL NOTATION)	1/MAR (SNELLEN EQUIVALENT)	SPATIAL FREQUENCY (CYCLES/DEGREE)
¼	−0.12	1.33	20/15	40
1	0	1.00	20/20	30
2	0.30	0.50	20/40	15
3	0.48	0.33	20/60	10
4	0.60	0.25	20/80	7.5
5	0.70	0.20	20/100	6
7.5	0.88	0.13	20/150	4
10	1.00	0.10	20/200	2
15	1.18	0.07	20/300	2
20	1.30	0.05	20/400	1.5

the Snellen fraction. When acuity is expressed as the minimal angle of resolution, the decline of acuity with increasing eccentricity is moderate and nearly linear near fixation and becomes somewhat steeper in the periphery. The effect of different acuity scales on the rate of acuity decline is illustrated in Fig 1, which displays data obtained from this investigator's eye with the method to be described.

The choice of scale is particularly important when considering how to display results of acuity perimetry in patients. If the results are displayed as the Snellen fraction (as in the conventional recording of central visual acuity), small abnormalities of the minimal angle of resolution near the center of the field will be magnified and large changes in the periphery may not be apparent. In the absence of a compelling reason to select any other scale, for the experimental and clinical studies to be described I have used the simple resolution threshold, expressed as the minimal angle of resolution in minutes of arc.

Effect of Meridian

Few investigators since Wertheim have undertaken a systematic exploration of peripheral acuity throughout the visual field. In the majority of published studies,[25,27,29-33,35-37,40,41] peripheral acuity was measured only along the horizontal meridian. In some studies, measurements were also made along the vertical meridian[34,36] or along the horizontal, vertical, and oblique meridians.[21-24,28,42]

The few investigators that have looked for differences in peripheral acuity from meridian to meridian agree with Wertheim that the decline of acuity is greater along the vertical meridian than along the horizontal meridian. There is also general agreement that acuity is better temporally than nasally. The relative rate of decline above and below fixation is less

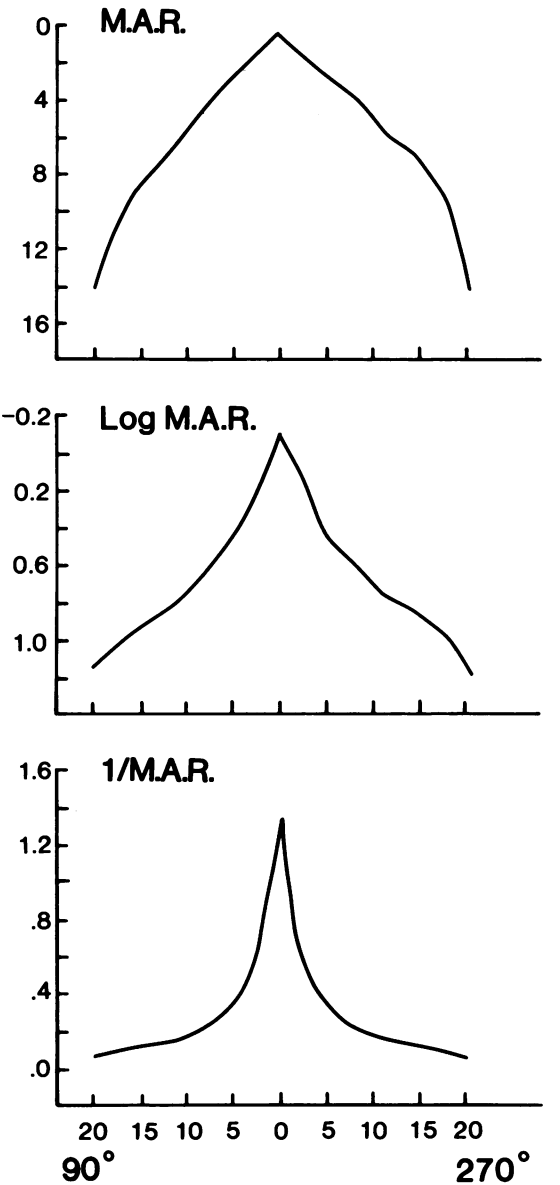


FIGURE 1

Effect of acuity scale on the rate of decline of visual acuity with eccentric viewing along the vertical meridian. The minimal angle of resolution (MAR) is expressed in minutes of arc. (Reprinted with permission from Phelps CD, Remijan PW, Blondeau P: Acuity perimetry. *Doc Ophthalmol Proc Series* 1981; 26:111-117.)

certain. Wertheim,[21] measuring acuity at eccentricities from 2.5 to 40 degrees, found the decline to be steeper above than below. Millodot and Lamont,[34] measuring acuity at eccentricities of 5 to 40 degrees, confirmed Wertheim's finding. However, Weymouth and co-workers,[22] who confined their measurements to within 85 minutes of fixation, found a steeper decline of acuity below than above fixation. Thus the relative rate of decline may depend not only on the meridian, but also upon the eccentricity at which acuity is tested.

Effect of Stimulus Orientation

If a grating target is used as an acuity stimulus, the acuity at any location varies slightly with the orientation of the grating. At fixation, acuity for obliquely oriented targets is poorer than acuity for vertically or horizontally oriented targets.[43-48] Some investigators[36] find that orientation preferences disappear with eccentric viewing, at least along the horizontal meridian. Other investigators[42] find a strong orientation preference at eccentric locations, but find the preferred orientation at any location is unpredictable. Still other investigators[22,28,43] find an orientation preference with eccentric viewing that is predictable: acuity is better when the orientation of the grating is parallel to the meridian of eccentricity, rather than perpendicular to it. In one study,[28] this preference for an orientation parallel to the meridian was strong enough to nullify the oblique effect; oblique targets were preferred over horizontal and vertical targets when the target was presented along the oblique meridians.

I used a grating target in the present study. Furthermore, I varied the orientation of the grating and required the test subject to identify the orientation as confirmation that the grating was perceived. Thus, it was important for me to further explore the effect of target orientation on peripheral acuity.

Effect of Simulus Presentation Time

In general, both central and peripheral visual acuity improve with increasing exposure time.[25] In a clinical test one would like to use a brief presentation time so that the subject will not have time to shift fixation during a long exposure and so that the Troxler effect of local adaptation will not occur. Acuity at fixation improves as exposure time is increased up to 500 milliseconds but does not improve further with exposures longer than 500 milliseconds.[49] Some evidence suggests that in the periphery even longer exposure times may be required for maximal acuity.[25]

However, during long exposures refixational eye movements are likely to occur. It is not clear if eye movement improve or worsen acuity. For central vision there is some evidence that fine physiologic eye movements improve acuity.[40] The effect of large eye movements on acuity has not been studied.

It was necessary for me to further study the effect of exposure time and of eye movements during long exposure times in order to arrive at optimal testing conditions for acuity perimetry.

Effect of Background Illumination

Most investigators of peripheral visual acuity have used photopic levels of background illumination, although the exact level is often unspecified. The background illumination is important because the state of retinal adaptation influences both central and peripheral retinal acuity. For example, Low,[24] in a study of 100 subjects, found that peripheral acuity during scotopic levels was only 5/7 of the peripheral acuity at photopic adaptation.

Under scotopic testing conditions, the visual field contains a central scotoma of about 1 degree. Within this scotoma, the acuity is 0. When the target is moved from the center toward the periphery, scotopic acuity at first increases and then begins to fall again at 4 to 8 degrees eccentricity.[32] As background illumination is increased from scotopic levels to photopic levels, visual acuity at fixation increases, levels off, and after a rod-cone break increases again to finally reach a plateau at about room luminance.[50,51] With even higher luminances there is a broad range over which central acuity is independent of luminance.[37] This appears to also be true for peripheral acuity at all retinal locations out to 30 degrees.[32] However, some investigators[37] find that the effect of retinal adaptation on acuity is much greater at fixation than in the periphery. Kerr[29] found the improvement in acuity at 30 degrees eccentricity with increasing light adaptation was maximal at 0 log millilamberts (10 apostilbs) background illumination and the improvement at fixation was maximal at about 2 log millilamberts (1000 apostilbs).

In order to obtain reproducible results with acuity perimetry, calibration and standardization of background were therefore necessary. As in try with the subject's retina in a photopic state of adaptation so that in a normal eye an acuity isopter would always enclose an area of more central field with better acuity. Thus, an important preliminary task in this study was to determine the optimal background illumination for clinical testing.

Interindividual Variations in Peripheral Acuity

Published values for peripheral acuity vary greatly from study to

study.[21-38,40,42,52] This probably reflects the many different measurement techniques that have been used, the small number of subjects in many of the studies, and, perhaps, large differences between individuals. Interstudy, interindividual, and intraindividual variation increases with increasing distance from fixation.[5,23,26,52]

Low,[23] who has written extensively about the causes of interindividual variation, found no relationship between age and peripheral acuity, but only a small proportion of his subjects were over the age of 40 years. Randall and co-workers[33] also found little difference between young and middle-aged observers but, like Low, had few elderly subjects.

Untrained observers are said to have poorer peripheral acuity than trained observers[53] and may also give less reproducible results. This learning effect is important, because for a test of peripheral acuity to be clinically useful it must give consistent results with untrained and apprehensive observers.

In the present study, if I wished to detect abnormalities of peripheral acuity caused by glaucoma, it was necessary that I first determine normal acuity, including both the average glaucoma and the variance from individual to individual, at various test loci in the field of vision. It was also important to explore further the effects of aging and training on peripheral acuity, since most glaucoma patients are elderly and none are trained subjects.

THE BASIS FOR PERIPHERAL ACUITY

Optical Factors

One of the factors that limits resolution acuity at any retinal location is the focus of the image at that location. Light reaching the eye from each point of an object in space is transformed by the imperfect optics of the eye into a distribution of light on the retina called the "point-spread function."[5,7] The greater the uncorrected refractive error, the wider is the point-spread function. If the point-spread functions of two closely separated object points overlap sufficiently, they will form a single distribution lacking two peaks, and the two objects will not be perceived as separate. The same analysis applies to the resolution of lines in the image of a defocused grating.[54]

Peripheral images are never as well focused as central images because of several optical aberrations that affect eccentric viewing.[55] These include spherical refractive error in the periphery that differs from that of the fovea, astigmatism of oblique incidence, and coma. Thus, one pos-

sible explanation for the decline of acuity with increasing eccentricity is that the stimulus is poorly focused on the peripheral retina.

Studies to test this hypothesis have been inconclusive. Millodot and colleagues,[30] testing acuity at 0, 20, 40, and 60 degrees with Landolt rings and grating targets, found that optical correction improved central acuity but was ineffective in improving peripheral acuity. Rempt and colleagues,[56] using Landolt rings as acuity targets, also found that correction of peripheral refractive error made no difference in visual acuity at 10, 20, 30, 40, 50, and 60 degrees eccentricity. Green[38] found that acuity for perception of interference fringes (which is independent of refractive error) was slightly better than acuity for perception of oscilloscope-generated fringes out to four degrees but not from four to eight degrees eccentricity. However, Frisén and Glansholm,[35] essentially repeating Green's experiment, found that the perception of interference fringes was progressively better than the perception of oscilloscope-generated gratings with increasing eccentricity out to 80 degrees temporally. The latter results suggest that optical factors contribute to the reduction of acuity in eccentric vision. The failure of the three earlier studies to show a refractive contribution may have resulted from the difficulty of correcting peripheral refractive error or, in the study of Green, from technical problems with the method of generating interference fringes.

If optical factors do, in part, account for the reduction of acuity with eccentric viewing, and if focused targets are used to test peripheral acuity, differences in acuity between individuals may to some extent simply reflect differences in the amount of peripheral optical aberrations. For this reason, in the studies to be described I used an interference fringe grating as an acuity target. Its perception does not depend on refraction by the optics of the eye.

Retinal Factors

Another limit of visual resolution is the size of the retinal mosaic. At the fovea, the minimal angle of resolution when tested with a diffraction pattern grating is about 21 seconds of arc.[57] This is close to the estimated diameter of the finest retinal cones (24 to 27 seconds of arc).[58,59] It also correponds approximately to the size of foveal receptive fields, because the ratio of cones to ganglion cells at the fovea approaches 1:1.

However, with increasing eccentricity from the fovea, more and more photoreceptors connect to a single ganglion cell. What, then, is the feature of the retinal mosaic that limits acuity at any retinal locus, the density of photoreceptors or the density of ganglion cells? As long ago as 1846, Weber[60] suggested that acuity must be limited by the density of retinal "functional units." He defined a functional unit as the retinal

elements that connect to one optic nerve fiber. This concept has since been elaborated upon by several writers, including Clemmensen,[58] ten Doesschate,[61] and Frisén and Frisén.[41] They argue that the visual system's ability to distinguish two point images as separate should require, as a minimum, that a message be sent from the eye to the brain along two activated channels (ie, ganglion cells and nerve fibers) which are separted by at least one silent channel. This line of reasoning implies that the density of ganglion cells, not the density of photoreceptors, is the determinant of acuity at any retinal locus.

Three studies provide experimental evidence for this concept. Ten Doesschate[61] compared peripheral acuity taken from the data of Wertheim[21] with cone densities taken from the counts of Osterberg.[62] The two sets of data diverged with increasing eccentricity, so that in the periphery the number of cones per unit of acuity was much greater than in the center. Weymouth[26] compared the minimal angle of resolution at various eccentricities with ganglion cell and cone counts roughly estimated from Polyak.[63] The decline of acuity with increasing eccentricity corresponded better to the ganglion cell counts than to the cone counts. Frisén and Frisén[41] compared visual acuity along the horizontal meridian, measured by interferometry, with the density of neural elements calculated from O'Brien's[59] observations on the size of foveal cones, Osterberg's[62] data on extrafoveal rod and cone densities, and Oppel's[64] counts of retinal ganglion cells. The ratio of visual acuity (expressed as the reciprocal of the minimal angle of resolution) to photoreceptor density varied considerably, but the ratio of visual acuity to ganglion cell density was nearly constant.

These studies have to be interpreted with some caution, because it is difficult to make accurate measurements from fixed tissue and because the correspondence of acuity to cell density depends on the acuity scale that is used. Nevertheless, the hypothesis of a direct relationship between acuity and ganglion cell density has intuitive appeal and provides an impetus for a clinical study of peripheral visual acuity in diseases, such as glaucoma, that damage retinal ganglion cells or their axons.

RATIONALE FOR A STUDY OF PERIPHERAL ACUITY IN GLAUCOMA

The primary pathologic event in glaucoma is destruction of ganglion cell axons with subsequent retrograde degeneration of the cell bodies. This causes a characteristic pattern of visual field loss that can be detected by conventional light sensitivity perimetry.

In some eyes with early glaucoma, the cup of the optic disc begins to enlarge before a visual acuity defect can be detected with sensitive conven-

tional perimetry.[65] The enlargement of the cup might be caused by enlargement of the scleral foramen, by backwards bowing of the lamina cribrosa, by loss of glial cells, or by expulsion of blood from the disc. However, the most likely cause is a diffuse loss of nerve fibers. The histopathologic studies of Quigley and associates[66] suggest that a substantial proportion of optic nervehead axons are lost before a visual field defect develops.

The probable reason that axons can be lost without causing a visual field defect is the relatively large size of the test lights used in the standard perimeters. In the normal retina, the receptive fields of the ganglion cells overlap extensively. It is likely that a large number of axons must be damaged in a localized portion of the optic nerve before a loss of light sensitivity results. If the axon loss is not concentrated sufficiently, but instead is diffusely scattered here and there throughout the optic nerve, the receptive fields of the remaining axons may still overlap sufficiently that the light stimulus will be perceived.

On the other hand, since the acuity of any part of the retina is probably determined by the density of ganglion cells, damage to axons from glaucoma should cause a loss of peripheral visual acuity. If the nerve fiber loss in early glaucoma is scattered rather than concentrated, the reduction of axon density may cause a measureable loss of peripheral acuity before it impairs light sensitivity.

The major purpose of this study was to determine if peripheral acuity is impaired early in glaucoma and if acuity perimetry is more sensitive than conventional light detection perimetry for the diagnosis of early glaucomatous optic nerve damage.

MATERIALS AND METHODS

THE ACUITY PERIMETER

The design of the prototype acuity perimeter used in this study was described in an earlier publication.[67] Only the essential features of the instrument will be reviewed here.

The perimeter is a compact box with external dimensions of 60 × 45 × 18 cm. The research subject or patient looks into the instrument through a viewing eyepiece (Fig 2) and sees in Maxwellian view a uniformly illuminated round background field 40 degrees in diameter. A dim fixation target 0.5 degrees in diameter is in the center of the field. The acuity target, a round red and black grating 1 degree in diameter, is presented briefly at a precisely determined test locus. The subject's task is to state if

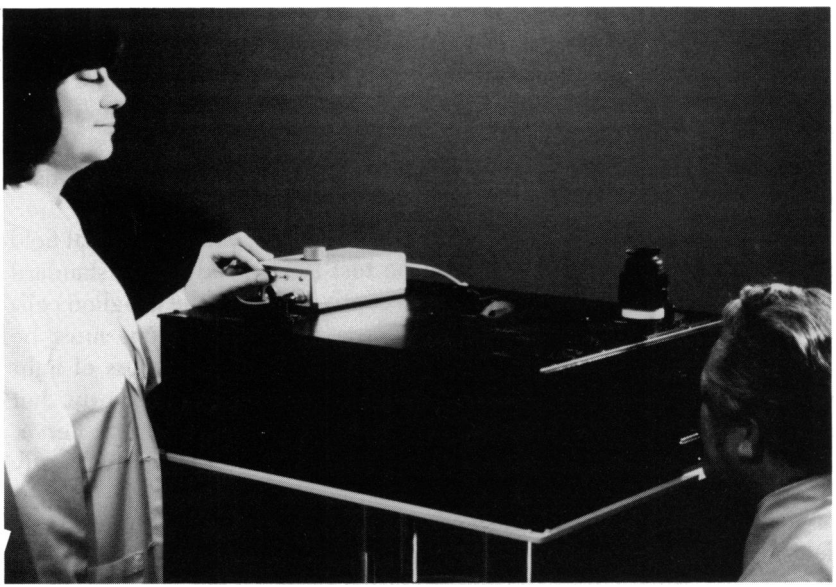


FIGURE 2
The acuity perimeter.

the striped pattern of the stimulus is perceived and to confirm its perception by correctly identifying the orientation of the stripes.

The acuity target is formed by interferometry. The light source for the interference fringes is a 0.9 mW cylindrical helium-neon gas laser. The laser's maximum output in irradiance levels on the retina is about 350 nW, which easily meets Bureau of Radiological Health safety standards for a class 1 laser device.

Light emitted by the laser is separated by a holographic phase grating into two coherent, equal strength, spherical waves. The two waves are each focused near the nodal point of the subject's eye and, as they subsequently diverge and overlap, form inteference fringes on the retina. The greater the separation of the two focal points in the subject's entrance pupil, the smaller the separation of the stripes in the grating. A control dial allows the separation of the stripes to be varied continuously from 1.5 minutes of arc (visual angle of 0.75 minutes or Snellen equivalent of 20/15) to 40 minutes (visual angle of 20 minutes or Snellen equivalent of 20/400). The stripes can be oriented in any direction; stop-positions indicate the vertical, horizontal, and principal oblique positions. The acuity target can

be presented along any meridian at 1-degree intervals out to 20 degrees eccentricity.

Because the interference fringes are not focused by the eye's optics, their perception is not influenced by the eye's refractive error. However, high refractive error may prevent the two diverging beams from overlapping completely on the subject's retina, especially for fine gratings. The subject may then obtain clues to the orientation of the gratings from an apparent elongation of the stimulus. In the acuity perimeter, this possible pseudo-resolution is prevented by a calibrated focusing eyepiece adjustment which corrects for the eye's spherical refractive error.

Background illumination is produced by a white light source. Like the laser light, this is focused in the subject's entrance pupil. The subject sees in Maxwellian view a uniformly illuminated round background field, 40 degrees in diameter. Because of the Maxwellian view, the background illumination is independent of the subject's pupil size. Neutral density filters allow the luminance of the background to be varied from 0.015 to 15.0 apostilbs, permitting acuity testing to be done under either scotopic or photopic conditions.

The fixation target is a round dim white light 0.5 degrees in diameter. Light from the fixation source leaves the eyepiece as a 2-mm collimated beam which is then focused on the subject's fovea by his eye's optics. When the subject has the lateral position of his eye adjusted so that he can see the fixation light and has the longitudinal position of his eye adjusted so that he can see the entire unvignetted background, he will be in proper position to see acuity targets out to an eccentricity of 20 degrees. To further insure proper fixation, we have installed an infrared television monitor which allows the technician to view the subject's pupil during the test.

The interference fringes can be seen with any natural pupil size. For a target with a visual angle of 20 minutes (Snellen equivalent of 20/400) the separation of the two laser point foci in the subject's pupil is only 0.05 mm. For a target with a visual angle of 0.75 (Snellen equivalent of 20/15), the separation of the two laser focal points is still only 1.45 mm. The background light is focused between the two laser foci. Thus, dilation of the pupil is usually not necessary. However, inexperienced subjects or patients using miotics may find it easier to remain correctly aligned if their pupils are slightly dilated.

The acuity target can be presented continuously or, as we prefer, intermittently. The presentations are accurately timed with a electromagnetic shutter that allows the presentation time to be varied from 1/60 to 32 seconds.

INVESTIGATIONS IN NORMAL SUBJECTS

This phase of the study had three purposes. The first was to determine if acuity perimetry was a practical test that would give reproducible results when administered to untrained subjects. The second was to explore the effect of varying the stimulus duration, background illumination, and stimulus orientation. The results of these experiments would enable us to select the optimal test parameters for clinical examinations. The third was to determine normal values and interindividual variation at selected peripheral locations in order to be able to detect abnormality in patients.

We used a forced-choice technique for each experiment. The subject was instructed to respond to each stimulus presentation by describing the orientation of the grating (vertical, horizontal, oblique right, or oblique left). Subjects were requested to guess even if they were unable to see the striped pattern or if they were unsure of the orientation. Preliminary testing indicated that this forced choice technique provided a slightly better acuity and more consistent responses than if the subject responded only when certain of the grating orientation.

The acuity threshold was obtained by presenting the stimulus several times at each spatial frequency (spatial frequency = cycles/degree; Table I). The acuity threshold was arbitrarily taken as the smallest visual angle at which the subject responded correctly to four of five stimulus presentations and (except for the experiment on the effect of stimulus orientation) to at least three of the four possible stimulus orientations.

EFFECT OF STIMULUS DURATION

Method

A background illumination of 4.3 apostilbs was used (for comparison, other commonly used background illuminations include 32.5 apostilbs for the Goldmann perimeter, 10 apostilbs for the Tübingen perimeter, and 4 apostilbs for the Octopus perimeter). Five normal subjects ranging in age from 20 to 44 years were tested at 12 different positions in the visual field: at 5, 10, 15, and 20 degrees eccentricity along the 180-, 270-, and 225-degree meridians of the right eye. Seven stimulus presentation times were tested at each position: 1, ½, ¼, ⅛, 1/15, 1/30, and 1/60 seconds.

Results

The briefer the stimulus presentation, the poorer was the acuity for each subject at all locations tested (Table II, Fig 3a). The decline in acuity with decreasing presentation time was slight until the stimulus duration was less than ⅛ second. When the presentation time was shorter than ⅛

TABLE II: EFFECT OF TARGET PRESENTATION TIME ON PERIPHERAL VISUAL ACUITY (MEAN ± STANDARD DEVIATION OF THE MINIMAL ANGLE OF RESOLUTION, IN MINUTES OF ARC, FOR FIVE NORMAL OBSERVERS)

	MERIDIAN		
	180°	225°	270°
5° eccentricity			
1 second	2.1 ± 0.4	3.1 ± 0.4	3.1 ± 0.6
1/2	2.4 ± 0.6	3.4 ± 0.4	3.4 ± 0.7
1/4	2.5 ± 0.6	3.1 ± 0.4	3.7 ± 0.8
1/8	2.8 ± 0.4	3.3 ± 0.4	3.7 ± 0.3
1/15	2.7 ± 0.3	3.6 ± 0.4	3.8 ± 0.4
1/30	3.4 ± 0.6	3.8 ± 0.3	4.0 ± 0.8
1/60	3.7 ± 1.2	4.0 ± 0.6	4.6 ± 0.8
10° eccentricity			
1 second	2.9 ± 1.0	4.8 ± 0.8	5.3 ± 0.8
1/2	3.4 ± 0.9	4.8 ± 0.3	5.4 ± 0.6
1/4	3.8 ± 0.4	5.3 ± 0.3	5.4 ± 0.6
1/8	4.3 ± 0.5	5.7 ± 0.6	5.8 ± 0.9
1/15	4.7 ± 0.8	6.0 ± 0.8	6.5 ± 1.2
1/30	5.0 ± 0.8	6.3 ± 1.2	7.6 ± 2.6
1/60	5.4 ± 1.2	7.0 ± 1.5	8.0 ± 2.0
15° eccentricity			
1 second	5.6 ± 0.6	8.0 ± 0.6	8.7 ± 1.8
1/2	5.9 ± 0.6	7.8 ± 0.7	9.2 ± 2.4
1/4	6.1 ± 0.6	8.3 ± 0.6	10.2 ± 2.9
1/8	6.3 ± 0.8	8.6 ± 0.6	10.5 ± 2.2
1/15	7.1 ± 1.3	9.3 ± 1.3	12.1 ± 3.6
1/30	7.7 ± 1.0	11.9 ± 3.5	14.6 ± 3.8*
1/60	7.9 ± 1.1	13.9 ± 4.5*	17.6 ± 3.3*
20° eccentricity			
1 second	10.2 ± 1.9	14.2 ± 3.6*	16.0 ± 4.2*
1/2	9.8 ± 2.2	14.4 ± 3.8*	15.5 ± 4.6*
1/4	10.6 ± 2.0	14.8 ± 3.7*	16.2 ± 3.9*
1/8	10.7 ± 2.0	15.2 ± 4.4*	17.2 ± 3.8*
1/15	12.1 ± 3.8	17.0 ± 2.8*	18.0 ± 2.8*
1/30	13.3 ± 4.5*	18.4 ± 2.6*	18.2 ± 2.7*
1/60	14.6 ± 3.4*	> 20†	19.6 ± 0.9*

*The minimal angle of resolution was greater than 20 minutes for some subjects. A value of 21 was then assigned arbitrarily.

†The minimal angle of resolution was greater than 20 minutes for all subjects.

second, the decline became more precipitous, especially at the more peripheral locations. The decline of acuity with brief presentations was also more precipitous in the oblique and vertical meridians than in the horizontal meridian (Fig 3b).

We were concerned that the better acuity with long stimulus durations might be due to involuntary shifts in the subject's fixation. In two subjects we monitored eye movements during the testing sequence using the

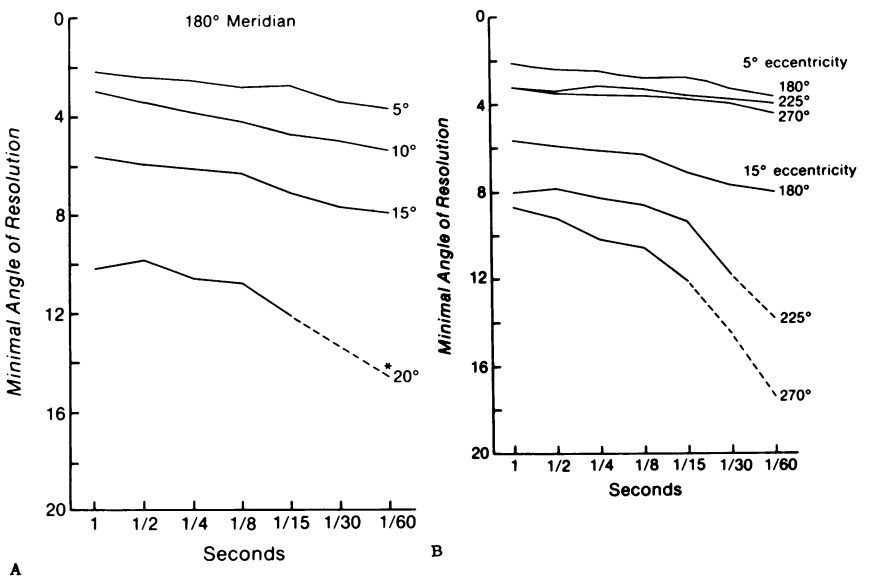


FIGURE 3

Effect of stimulus duration on peripheral visual acuity. (The *data points* connected by a *dashed line* are underestimates of the true mean resolution threshold; some observers were unable to resolve even the 20-minute grating at those loci and were arbitrarily assigned a value of 21 when the mean was calculated.) A: Mean of five normal observers at four eccentricities along the nasal horizontal meridian. B: Mean of five normal observers at 5 and 15 degree eccentricities along three meridians.

recording electrodes usually employed for electro-oculography. No saccades were detected, indicating good fixation.

In a related experiment, we told two subjects where the stimulus would be presented and asked them to purposely cheat: ie, to look for the stimulus when it flashed on for ¼ second. We found that their peripheral acuity was poorer when they looked for the target than when they maintained central fixation. This was true whether the target was presented at 5, 10, 15, or 20 degrees eccentricity.

Comment

In short, for valid test results in patients we had only (1) to be sure by using the infrared television monitor and exhortation that the patient was fixating centrally at the moment when the target was presented and (2) to present the target for such a short time that attempts at refixation could not degrade acuity. We concluded that ¼ second was the optimal stimulus presentation time; it was a long enough time for nearly maximal acuity

at all locations but too short a time to allow a refixation saccade to take place.

EFFECT OF BACKGROUND ILLUMINATION

Method

A stimulus presentation time of ¼ second was used. Testing was done at the same field loci as in the experiments on presentation time, above. Five normal subjects ranging in age from 20 to 44 years were tested. Each subject was dark-adapted for 30 minutes. Peripheral acuity was first measured with no background illumination and with the fixation light at its minimum intensity. It was then measured with background illuminations of 1.5, 4.3, 8.9, and 15.1 apostilbs. The subject adapted to each new background for 5 minutes before testing began.

TABLE III: EFFECT OF BACKGROUND ILLUMINATION ON MINIMAL ANGLE OF RESOLUTION (MEAN ± STANDARD DEVIATION FOR FIVE NORMAL OBSERVERS)

	MERIDIAN		
	180°	225°	270°
5° eccentricity			
0 apostilb	3.4 ± 0.6	3.7 ± 0.6	3.8 ± 6.3
1.5	2.6 ± 0.2	3.3 ± 0.3	3.4 ± 0.2
4.3	2.5 ± 0.6	3.0 ± 0.4	3.3 ± 0.3
8.9	2.5 ± 0.4	3.2 ± 0.3	3.1 ± 0.4
15.0	2.5 ± 0.4	3.0 ± 0.4	3.2 ± 0.6
10° eccentricity			
0 apostilb	4.5 ± 0.9	6.2 ± 0.8	6.3 ± 0.8
1.5	3.9 ± 0.6	5.4 ± 0.6	5.3 ± 1.0
4.3	3.5 ± 0.4	5.2 ± 0.3	5.3 ± 0.8
8.9	3.8 ± 0.4	5.2 ± 0.6	5.5 ± 0.9
15.0	3.9 ± 0.6	5.0 ± 0.4	5.6 ± 1.0
15° eccentricity			
0 apostilb	12.2 ± 7.2*	14.5 ± 5.4*	17.6 ± 4.8*
1.5	6.9 ± 1.2	8.5 ± 1.5	9.9 ± 3.0
4.3	5.9 ± 0.6	7.9 ± 0.9	8.3 ± 1.1
8.9	6.2 ± 1.2	7.8 ± 1.0	9.4 ± 1.9
15.0	6.1 ± 0.6	8.0 ± 1.3	9.2 ± 2.6
20° eccentricity			
0 apostilb	18.8 ± 2.7*	> 20†	> 20†
1.5	11.2 ± 2.1	14.2 ± 4.2*	14.9 ± 3.8
4.3	10.2 ± 2.1	13.4 ± 3.8*	14.0 ± 4.2*
8.9	9.6 ± 1.7	13.0 ± 4.0*	14.7 ± 5.0*
15.0	9.4 ± 1.2	14.0 ± 3.7*	15.4 ± 4.8*

*The minimal angle of resolution was greater than 20 minutes for some subjects. A value of 21 was then assigned arbitrarily.

†The minimal angle of resolution was greater than 20 minutes for all subjects.

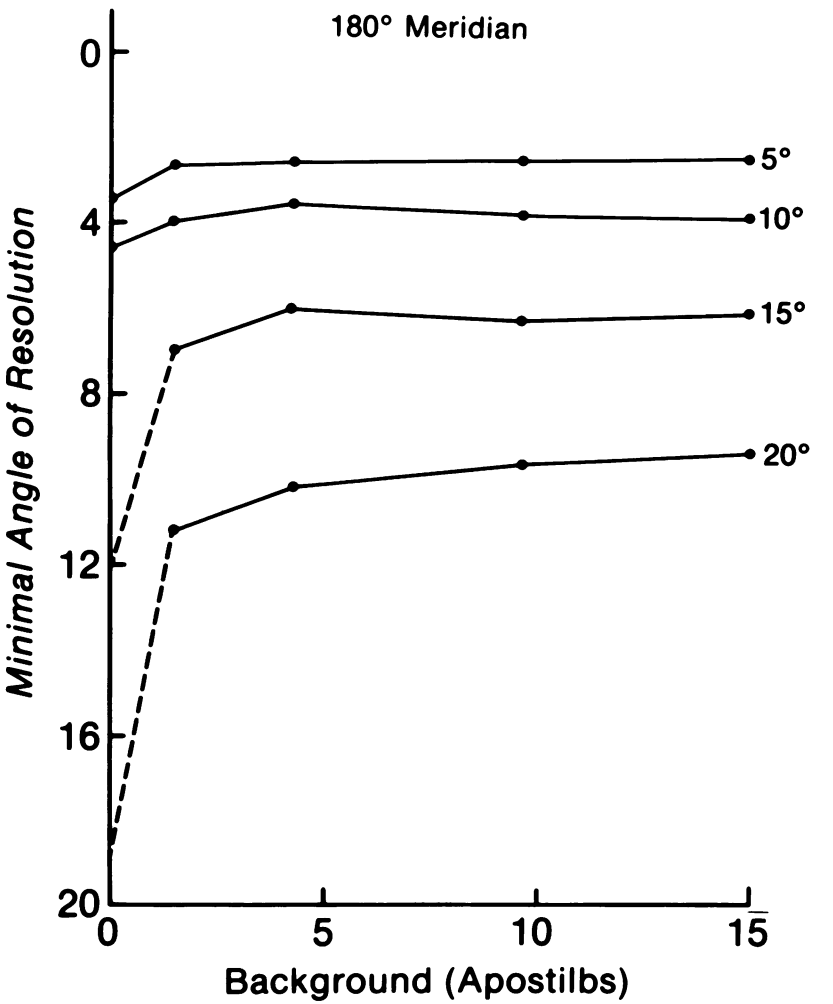


FIGURE 4
Effect of background luminance on peripheral visual acuity. Mean of five observers at four eccentricities along the nasal horizontal meridian. (The resolution thresholds for 0 apostilbs at 15 and 20 degrees eccentricity are underestimates; see legend for Fig 3.)

Results

Peripheral acuity, particularly at the more eccentric loci, was poor at low background illuminations but rose rapidly as the background reached the dim illumination of 1.5 apostilbs (Table III, Fig 4). It reached maximum

between 4.3 and 8.9 apostilbs and remained fairly constant up to the maximum background illumination used in this experiment (15.1 apostilbs). The effect of background illumination was similar along each of the three meridians tested.

Comment

These results demonstrate that the state of retinal adaptation does influence peripheral acuity and must be controlled during acuity perimetry. For clinical testing we wished to have some background illumination so that the patient's retina would be in a photopic state of adaptation. However, any background illumination decreases the contrast of the acuity target, which in the absence of background illumination is 100% for laser interference fringes. To obtain optimal acuity measurements, we needed a background illumination which would be just bright enough to give a photopic acuity profile, but no brighter, so that the target would have the highest possible contrast. For the remainder of our testing, we chose to use a background of 4.3 apostilbs, which is in the low photopic range and which in these preliminary experiments allowed nearly maximum acuity.

THE EFFECT OF GRATING ORIENTATION

Method

We conducted two experiments.

Experiment 1. The purpose of this experiment was to compare the acuity thresholds at different eccentricities of the two oblique orientations, taken in combination, with the combined thresholds of the vertical and horizontal orientations. We studied the right eye of a 28-year-old experienced observer along the nasal horizontal meridian. Acuity was tested at 1-degree intervals from fixation to 20 degrees eccentricity. We presented the target eight times for each of the four possible orientations (32 presentations in all) for each spatial frequency. We began with a slightly suprathreshold grating, for which the subject identified the orientation correctly 100% of the presentations, and gradually increased the spatial frequency until the subject missed more than 50% of the oblique presentations. The spatial frequency was then further increased until the subject missed more than 50% of the combined vertical and horizontal presentations. Threshold for each of the combinations was defined as the finest grating that could be seen during at least 50% of presentations. The standard ¼ second presentation time and 4.3 apostilbs background was used. The experiment involved a total of 2496 target presentations and several test sessions.

Experiment 2. Five nonastigmatic subjects ranging in age from 28 to 43 years were examined at test points located 15 degrees from fixation along the 45, 90, 135, 180, 225, and 315 meridians of the right eye. The 0-degree meridian was not examined because of the blind spot. Forty target presentations (10 of each of the four orientations) were made for each grating size. The procedure for defining threshold was the same as in experiment 1, except that the threshold for each of the four orientations (vertical, horizontal, right oblique, and left oblique) was decided separately. This experiment entailed about 2000 target presentations per subject.

Results

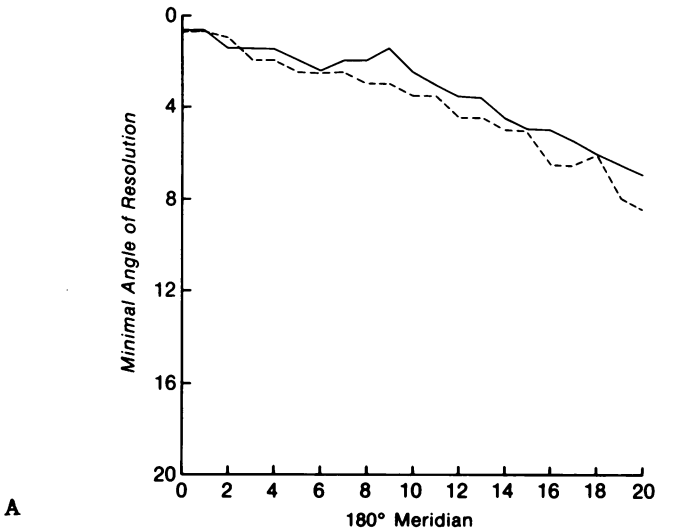
Experiment 1: At all loci eccentric to 2 degrees, the acuity for vertical and horizontal presentations was slightly better than the acuity for oblique presentations (Fig 5a). The identical results at fixation and at 1 degree of eccentricity are probably spurious, since our instrument is not designed to measure acuities with a minimal angle of resolution less than 0.75 (Snellen equivalent of 20/15). The difference between the two acuities tended to increase slightly with increasing eccentricity.

Experiment 2: The pooled results for the five subjects are displayed in Fig 5b. During the testing sessions, the subjects had the impression that a grating oriented parallel to the meridian was seen more easily than one perpendicular to the meridian. The results showed this impression to be true for the horizontal, vertical, and 225-degree meridians. It was not true for the other oblique meridians, although for these meridians the acuity was better for the oblique target orientation parallel to the meridian than for the oblique target orientation perpendicular to the meridian.

Discussion

These results confirm that the oblique effect, described for central visual acuity by many investigators, is present for eccentric viewing as well. They partially confirm the finding of Rovamo and co-workers[28] that in eccentric viewing along oblique meridians a strong preference for a target orientation parallel to the test location meridian may outweigh the usual effect of poorer acuities with oblique targets.

The orientation effect is important to recognize because it affects the measurement of acuity threshold when gratings are used as the target. However, the difference between the maximal and minimal acuities for different stimulus orientations at a given test locus is usually small, and, if it is not necessary for the subject to correctly identify all four orientation, the variance induced by using several grating orientations during a testing



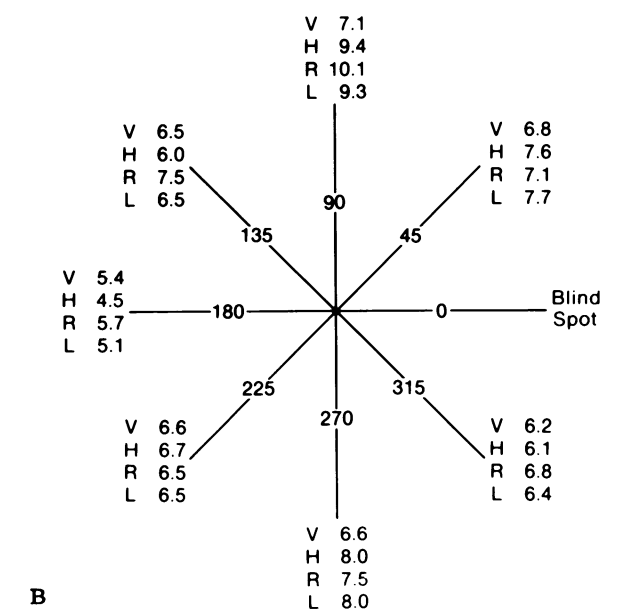


FIGURE 5

Effect of stimulus orientation on peripheral visual acuity. A: Acuity for oblique orientations (*dashed line*) and combined vertical and horizontal orientations (*solid line*) of a single normal observer tested along his nasal horizontal meridian. B: Acuity for vertical (V), horizontal (H), oblique up-to-right (R), and oblique up-to-left (L) orientations. Mean of five normal observers at 15 degrees eccentricity.

sequence will also be small. In contrast, if only one stimulus orientation is used, differences in acuity from one meridian to another will, in part, result from the particular orientation selected.

INTRAINDIVIDUAL VARIATION

Method

Two subjects were tested along one meridian at every 2 degrees of eccentricity. The test was repeated on 10 different days. Mean and standard deviation of the acuity thresholds were computed.

Results

The first subject was tested along the 90- to 270-degree meridian (Fig 6a), and the second subject was tested along the 0- to 180-degree meridian (Fig 6b). The absence of standard deviation at fixation is due to the fact that both subjects had a better central acuity than could be tested with this instrument (0.75 minutes). There was a slight tendency for the variance to increase with increasing eccentricity. The standard deviation was small at all loci for both subjects.

Comment

This experiment indicates that the measurement of peripheral acuity thresholds in normal subjects is quite repeatable from day to day. It suggests that acuity perimetry can be used to follow patients for stability, progression, or regression. In the absence of disease-associated changes, the measurements should be similar from examination to examination. However, further studies are needed of long-term variability of acuity thresholds in areas of abnormal acuity before stability can be assumed with certainty.

INTERINDIVIDUAL VARIATION AND NORMAL VALUES

Method

We tested acuity thresholds of 28 normal subjects who ranged in age from 20 to 73 years. Acuity was measured at 5, 10, 15, and 20 degrees of eccentricity along the vertical, horizontal, and two oblique meridians. We calculated means and standard deviations of the thresholds at the different test loci. We also averaged the thresholds for the eight points at each eccentricity and looked for a relationship between peripheral acuity at each eccentricity and subject age.

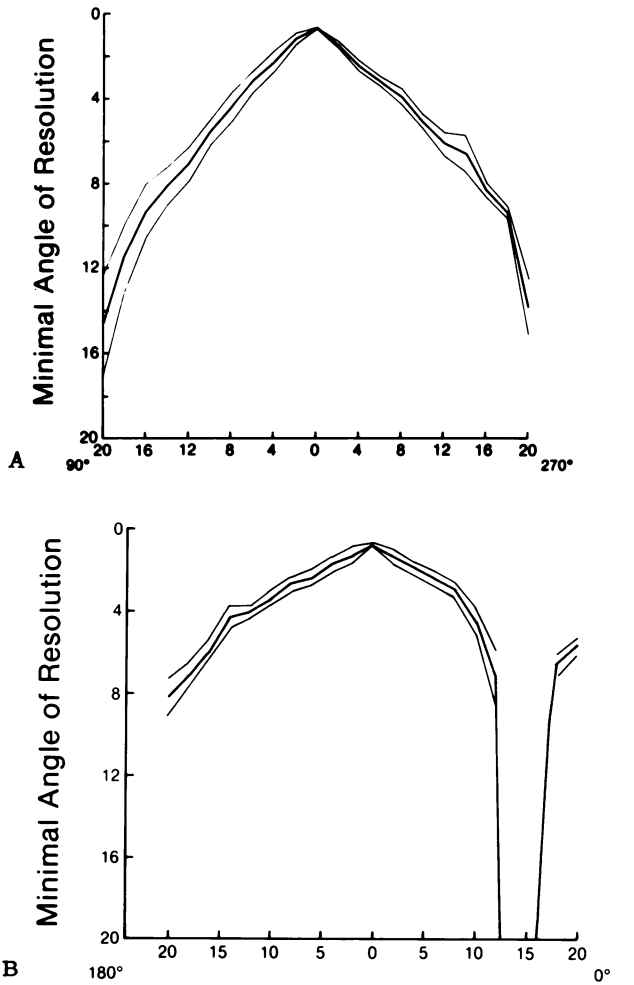


FIGURE 6
Reproducibility of acuity perimetry. Mean (*dark line*) and one standard deviation (*light line*) of 10 determinations on separate days. A: Measurements along the vertical meridian of one observer's right eye. B: Measurements along the horizontal meridian of a second observer's right eye.

Results

The average acuity thresholds for each locus are displayed in Fig 7, and the intraobserver variation is listed in Table IV. Acuity was better along the horizontal than along the oblique or vertical meridians. Except at 5 degrees eccentricity, it was better below than above fixation, confirming

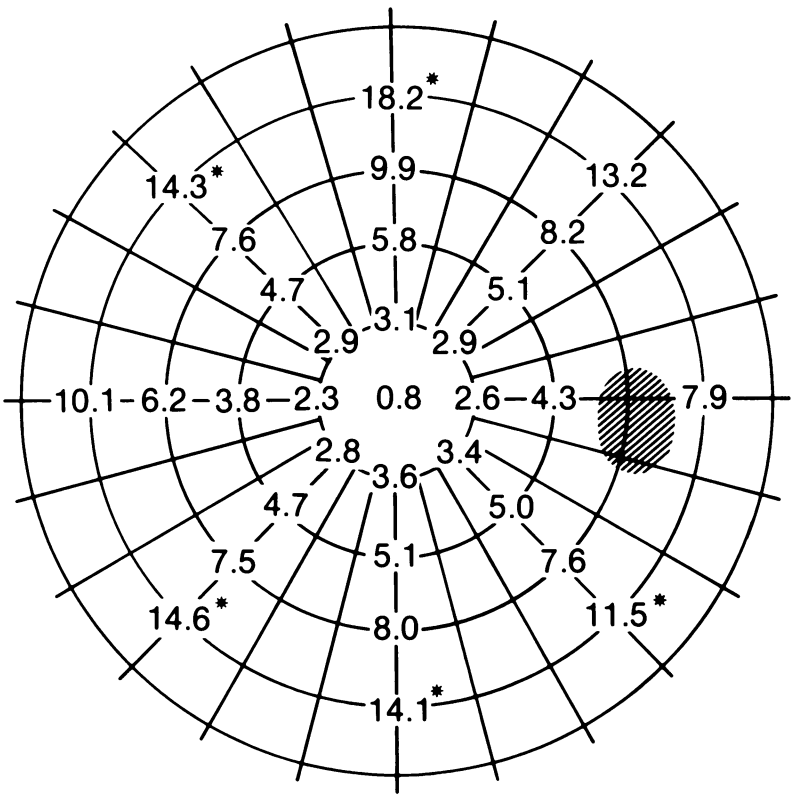


FIGURE 7
Average peripheral visual acuity in minutes of arc resolution for 28 normal observers at 32 locations in the visual field. (Acuities marked with an *asterisk* are underestimates; see legend for Fig 3.)

the results of previous investigators.[21,22,34] At 20 meridians eccentricity along several of the meridians, some subjects were unable to see the largest target. Thus, the true average values and variances for these locations could not be calculated, and the displayed results (marked with asterisks) are underestimates. Little variation occurred between observers at eccentricities of 5, 10, and 15 degrees, but considerable variation occurred at 20 degrees.

The best acuities were found in the temporal field. The acuity at 20 degrees eccentricity temporal to the blind spot was especially high (the average minimal angle of resolution was only 7.9), and consistently re-

TABLE IV: PERIPHERAL VISUAL ACUITY (MEAN ± STANDARD DEVIATION) FOR 28 NORMAL OBSERVERS AT 32 LOCATIONS IN THE RIGHT VISUAL FIELD

MERIDIAN	ECCENTRICITY			
	5°	10°	15°	20°
0°	2.6 ± 0.4	4.3 ± 0.5	Blind spot	7.9 ± 1.7
45°	2.9 ± 0.5	5.1 ± 0.9	8.2 ± 1.6	13.2 ± 3.7*
90°	3.1 ± 0.8	5.8 ± 1.3	9.9 ± 2.9	18.2 ± 3.2*
135°	2.9 ± 0.6	4.7 ± 0.8	7.6 ± 1.5	14.3 ± 3.6*
180°	2.3 ± 0.5	3.8 ± 0.6	6.2 ± 0.9	10.1 ± 2.3
225°	2.8 ± 0.5	4.7 ± 0.7	7.5 ± 1.2	14.6 ± 3.7*
270°	3.6 ± 1.2	5.1 ± 0.8	8.0 ± 1.5	14.1 ± 3.9*
315°	3.4 ± 1.0	5.0 ± 1.0	7.6 ± 1.4	11.5 ± 3.9*

*The minimal angle of resolution was greater than 20 minutes for some subjects. A value of 21 was then assigned arbitrarily.

sembled the acuities at 15 degrees eccentricity along the other meridians tested.

No relationship was found between age and peripheral acuity at 5, 10, and 15 degrees eccentricity (Fig 8). At 20 degrees eccentricity, acuity decreased significantly with age ($P = 0.01$). The linear regression equation for the relationship between acuity at 20 degrees eccentricity and age (in years) was

$$\text{MAR} = 10.0 + 0.07\ \text{Age}.$$

However, the failure of some individuals to see even the 20-minute target along one or more meridians at this eccentricity makes this regression calculation of dubious validity.

The results of acuity perimetry can be displayed, like the results of conventional perimetry, as profiles (Fig 1), isopters (Fig 9a), or grids (Fig 7). The average isopters for the 2.5, 5, 7.5, and 10 minute targets in normal subjects are displayed in Fig 9b.

The determination of acuity isopters with our instrument is time-consuming and cumbersome. We prefer to measure acuity thresholds along a meridian or in a grid, similar to the static light sensitivity profiles and grids measured on the Tübingen and Octopus perimeters.

INTEROCULAR DIFFERENCE

Method

Acuity was tested along the vertical meridian at 5, 10, and 15 degrees eccentricity in both eyes of 11 normal observers.

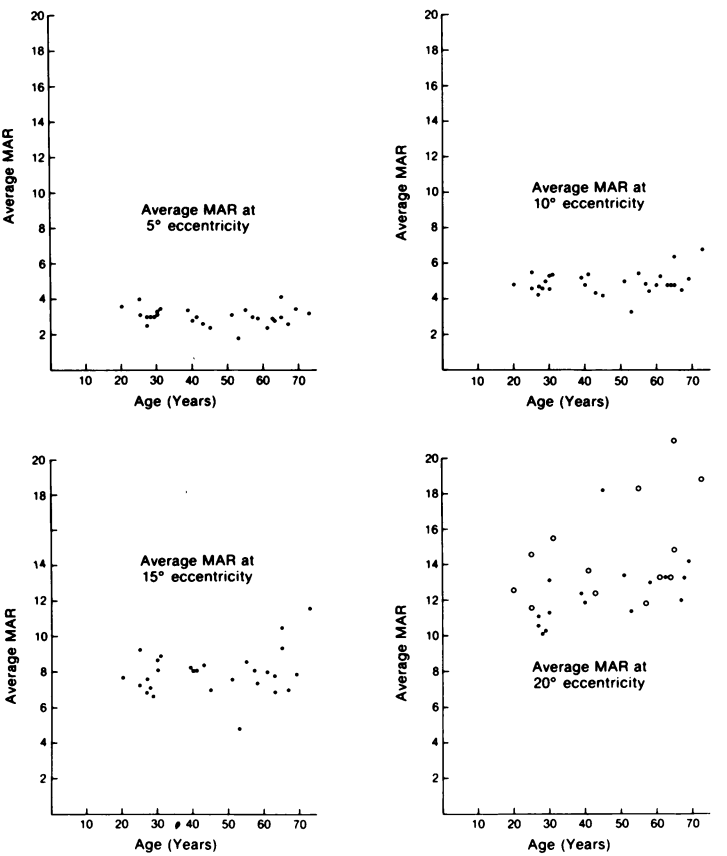


FIGURE 8

Relationship between the minimal angle of resolution (MAR) and age. Each *point* represents the average for one subject of acuity measurements along eight different meridians at that eccentricity. *Open circles* are probably underestimates because they include some locations for which an MAR greater than 20 minutes was arbitrarily assigned a value of 21 when the mean was calculated.

Results

The mean difference between right and left eyes was greater at 15 degrees eccentricity than at 5 and 10 degrees eccentricity (Table V). The variation from observer to observer also increased with increasing eccentricity.

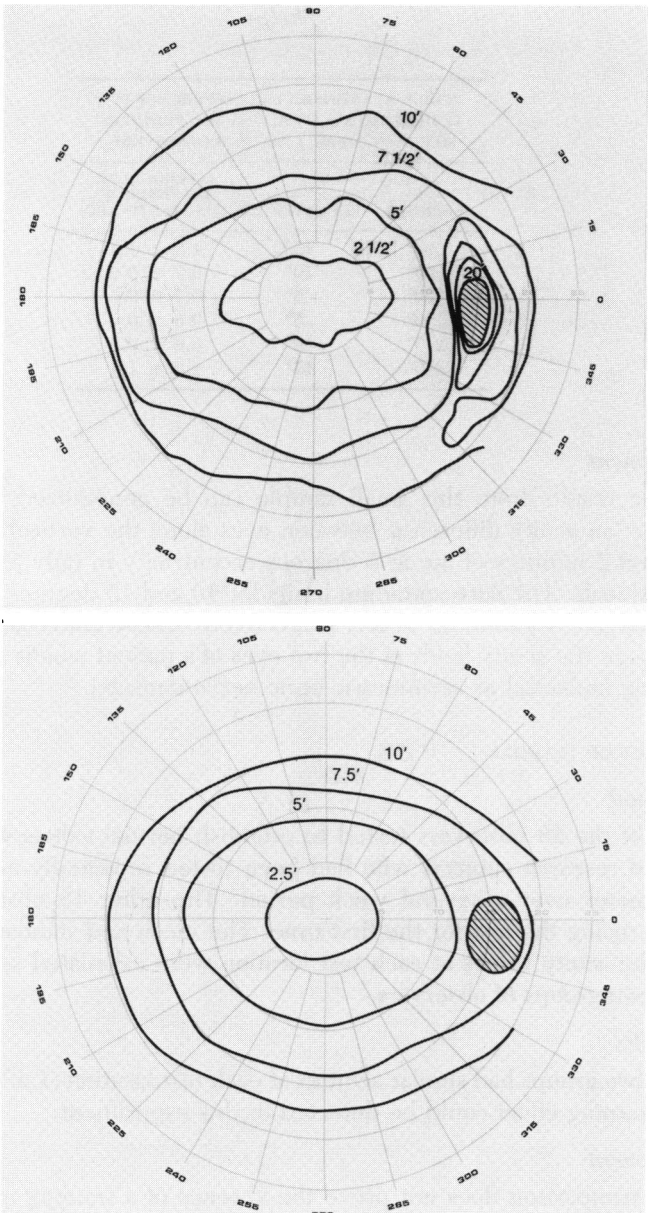


FIGURE 9

Acuity isopters. A. The acuity isopters of an experienced normal research subject tested at meridians 15 degrees apart. (Reprinted with permission from Phelps CD, Remijan PW, Blondeau P: Acuity perimetry. *Doc Ophthalmol Proc Series* 1981; 26:111-117.) B. Average normal acuity isopters, calculated by interpolation from the average acuities for 28 normal observers displayed in Fig 7 and listed in Table IV.

TABLE V: INTEROCULAR DIFFERENCE IN PERIPHERAL ACUITY ALONG THE VERTICAL MERIDIAN (MEAN ± SD OF 11 OBSERVERS)

MERIDIAN	ECCENTRICITY	INTEROCULAR DIFFERENCE (MINUTES OF ARC)
90°	15°	1.3 ± 1.4
90°	10°	0.7 ± 0.9
90°	5°	0.7 ± 0.6
270°	5°	0.6 ± 0.7
270°	10°	0.8 ± 0.9
270°	15°	1.3 ± 1.4

Comment

If the results from this small sample can be generalized, one should expect an acuity difference between eyes along the vertical meridian to exceed 2 minutes of arc at 5 degrees eccentricity in only 5% of normal individuals. The corresponding limits for 10 and 15 degrees eccentricity are 2.5 and 4.1 minutes of arc, respectively. These limits can be used to compare the acuity fields of the two eyes of a patient who is suspected of having unilateral or asymmetric optic nerve damage.

EFFECT OF TRAINING

Method

Ten of the 28 observers tested to establish normal values were experienced research subjects who had been tested repeatedly on the acuity perimeter over a several week period. The other 18 observers were undergoing the test for the first time. The mean and standard deviation for the acuity values at each test location were calculated separately for the two groups of observers.

Results

The two groups had similar acuities at each test location (Table VI). Thus, no learning effect could be detected in this experiment.

Comment

This comparison does not prove the absence of a training effect for peripheral acuity. Perhaps one would be present if an individual was tested repeatedly during a brief time span. However, it suggests that no training occurs when an individual is tested at intervals ranging from days to weeks. Thus, acuity perimetry can be used for sequential testing of patients with little risk of spurious improvement from training.

TABLE VI: EFFECT OF TRAINING ON PERIPHERAL VISUAL ACUITY (MEAN ± STANDARD DEVIATION OF MINIMAL ANGLE OF RESOLUTION OF 10 EXPERIENCED AND 18 NOVICE OBSERVERS)

	MERIDIAN							
	0°	45°	90°	135°	180°	225°	270°	315°
5° eccentricity								
Experienced	2.5 ± 0.5	2.8 ± 0.3	3.4 ± 0.4	2.9 ± 0.3	2.3 ± 0.3	2.9 ± 0.4	4.5 ± 1.3	4.4 ± 1.1
Novice	2.7 ± 0.3	2.9 ± 0.5	3.1 ± 0.8	3.0 ± 0.7	2.3 ± 0.7	2.8 ± 0.5	3.1 ± 0.6	3.3 ± 0.9
10° eccentricity								
Experienced	4.2 ± 0.5	5.3 ± 0.9	6.2 ± 1.0	4.7 ± 0.5	3.8 ± 0.5	4.9 ± 0.6	5.1 ± 0.8	4.7 ± 0.6
Novice	4.4 ± 0.6	4.5 ± 0.9	5.8 ± 1.0	4.7 ± 0.9	3.8 ± 0.7	4.7 ± 0.8	5.1 ± 0.8	5.2 ± 1.1
15° eccentricity								
Experienced	Blind spot	8.8 ± 1.1	10.4 ± 1.4	7.5 ± 1.1	6.4 ± 0.7	7.6 ± 0.8	8.3 ± 1.6	7.7 ± 1.4
Novice	Blind spot	7.9 ± 1.7	9.6 ± 1.4	7.6 ± 1.6	6.0 ± 1.1	7.5 ± 1.4	7.8 ± 1.5	7.6 ± 1.5
20° eccentricity								
Experienced	7.3 ± 0.9	12.5 ± 1.4	18.5 ± 2.9*	13.8 ± 4.0*	9.9 ± 2.7	14.3 ± 3.5*	13.4 ± 4.2*	9.2 ± 1.3
Novice	8.7 ± 2.1	13.5 ± 4.5*	17.9 ± 3.4*	14.5 ± 3.4*	10.4 ± 1.9	14.1 ± 3.9*	14.6 ± 3.0*	12.8 ± 4.3

*The minimal angle of resolution was greater than 20 minutes for some subjects. A value of 21 was then assigned arbitrarily.

PERIPHERAL ACUITY AND GLAUCOMA

PATIENT SELECTION

Fifty-two patients with primary open-angle glaucoma and 35 patients with ocular hypertension were tested with acuity perimetry. Conventional visual field testing was done with either the Goldmann perimeter (using the Armaly suprathreshold static technique for screening) or the Octopus perimeter (using Program 32). Bilateral visual field loss was present in 24 of the glaucoma patients. The other 28 patients had visual field defects in only one eye and a normal visual field in the other eye. One of the ocular hypertensive patients was blind in one eye from nonglaucomatous reasons. Thus, the study material consisted of 76 eyes with glaucomatous visual field defects by conventional perimetry, 28 fellow eyes without visual field defects, and 69 eyes of patients with high intraocular pressures but no visual field defect in either eye. Most of the glaucomatous visual field defects were minimal, either small nasal steps or isolated paracentral scotomas.

Optic disc stereophotographs were examined to determine the amount and type of glaucomatous disc cupping. Glaucomatous eyes were classified according to whether the disc cup was enlarged in only one quadrant or was generally enlarged. Fellow eyes and ocular hypertensive eyes were classified as "probably normal" or "suspicious" on the basis of the appearance of the neuroretinal rim. Thinning, notching, absence, hemorrhage, or abnormal translucency of the rim was considered suspicious. Ocular hypertensive patients were classified as having asymmetric cupping if the horizontal cup:disc diameter ratio in the two eyes differed by 0.2 or more.

Acuity perimetry was done using the same testing conditions that had been used in the normal subjects, including a background illumination of 4.3 apostilbs, a target presentation time of ¼ second, and a forced choice response. Threshold was defined as the minimal angle at which the patient responded correctly to three of five presentations, including three of four of the target orientations. Acuity was measured at 5, 10, 15, and 20 degrees eccentricity along the 45-, 90-, 135-, 225-, 270-, and 315-degree meridians. Other locations were tested in some patients, especially 15 degrees above and below the nasal meridian or adjacent to locations with poor acuity.

An acuity determination was considered abnormal if the minimal angle of resolution was at least two standard deviations above the mean value for the normal observers at that location. The values for the six loci 20 degrees from fixation were disregarded in the analysis, because of the

difficulty some normal observers had at this eccentricity. Thus, only 18 test locations were used when evaluating the patients' acuity fields. An acuity field was considered abnormal if two adjacent test loci were abnormal or if three loci somewhere in the field were abnormal. Acuity fields in patients with ocular hypertension were considered asymmetric if the two eyes had acuities at corresponding loci at 5, 10, or 15 degrees eccentricity that differed by 2, 2.5, or 4.1 minutes of arc, respectively.

RESULTS

All eyes with glaucomatous visual field defects by conventional perimetry had corresponding defects of peripheral acuity. In areas of absolute scotomas on conventional field testing, the patients, of course, were also unable to see the acuity stimulus. In areas of relative scotomas, the patients were usually able to see the acuity stimulus but were unable to resolve the striped pattern even when tested with the coarsest grating.

The loss of peripheral acuity often involved a much more extensive area of the visual field than did the defect as plotted by conventional perimetry. Areas of relative loss of acuity surrounded the areas that had no measurable acuity. Eyes in which the field loss by conventional perimetry was confined to the upper or lower half of the visual field often had acuity defects in the opposite hemifield as well.

However, in other eyes the acuity defect was sharply localized to the area defective to conventional perimetry. When the acuity fields were compared to the optic disc photographs, a consistent pattern was found: the eyes with widespread acuity loss had generalized cup enlargement, while the ones with focal acuity loss had focal disc damage.

Acuity perimetry disclosed abnormalities of peripheral acuity in both eyes of 12 of the 24 glaucoma patients who by conventional perimetry had unilateral field defects. In each of these patients the optic disc in the fellow eye was thought to be "suspicious."

Of the 69 eyes (35 patients) with ocular hypertension, 17 eyes (15 patients) were abnormal by acuity perimetry. Twelve of these 17 eyes had "suspicious" appearing optic discs. In the other five eyes, the disc did not look glaucomatous but had some cupping.

Nineteen of the ocular hypertensive eyes had optic discs that appeared "suspicious." Twelve (63.2%) of these eyes had abnormal acuity fields. The optic discs appeared "probably normal" in 50 eyes. Only 5 (10.0%) of these 50 eyes had abnormal acuity fields ($\chi^2 = 18.2$, $P = 0.0002$).

Fourteen of the ocular hypertensive patients had asymmetric disc cupping and 20 had symmetric disc cupping (1 patient had only one eye).

Asymmetry of acuity fields in the predicted direction was present in 10 (71.4%) of the patients with disc asymmetry and in 5 (25.0%) of the patients without disc asymmetry ($\chi^2 = 5.44$, $P = 0.02$). One patient with asymmetric cupping had asymmetry of acuity fields in the opposite direction! This one discrepancy remains unexplained.

Three ocular hypertensive eyes with abnormal acuity fields (including both eyes of one patient) developed visual field defects by conventional perimetry 2 years later. In each instance, conventional fields were normal on several occasions preceding the acuity field and at least once after the acuity field before the conventional field became abnormal. The visual field defects eventually found by conventional perimetry developed in the same areas that were initially defective with acuity perimetry.

DISCUSSION

ACUITY PERIMETER

Acuity perimetry tests a slightly more complex visual function than simple light detection perimetry and, as a result, seems to provide a more sensitive means of detecting nerve fiber damage. In general, the test is easy to perform and produces reproducible results. Subjectively, patients and research subjects comment that the transition from a slightly subthreshold stimulus to one that is easily discerned is quite abrupt.

Our current prototype acuity perimeter, which uses laser interferometry to generate the acuity fringes, has several advantages over a projection system or one that uses an oscilloscope to generate the fringes. The perception of the grating does not depend on the stimulus being correctly focused on the patient's peripheral retina. It is not influenced by off-axis refractive aberrations such as coma, astigmatism of oblique incidence, or spherical refraction different from that of the fovea. Early cataracts degrade the perception of interference fringes only by scattering some of the light and thus reducing the contrast of the fringes. Thus, the use of laser interference fringes to form the acuity target eliminates the possibility that an unusual abnormality of peripheral refraction in a patient might cause an abnormally low peripheral acuity that could be falsely attributed to disease of the retina or optic nerve.

The grating pattern is a simpler target than printed or projected targets such as Snellen letters and Landolt rings. Perception of Snellen letters depends on recognition as well as resolution. Perception of Landolt rings depends to some extent on the orientation of the break in the ring—recognition is less likely if the ring, which is imaged over a portion

of the retina containing areas of differing acuities, is oriented with its break away from fixation rather than toward fixation.

The present prototype instrument has some limitations. It tests only out to 20 degrees eccentricity. Thus, it does not test the acuity of the far periphery of the retina, that portion outside of the central 40 degrees, which according to Drasdo's[68] calculations contains about 30% of the retinal ganglion cells.

We were limited to one size of acuity target because of the way the instrument's field stops were made. Two conflicting considerations influenced our choice of target size. We wanted the target to be as small as possible because we wished to restrict the area of the retina being tested. However, a small target also limits the number of stripes per field, a consideration that is especially important with low acuity targets. Our compromise choice was a test field 1 degree in diameter. With a grating that has an angular separation of the stripes of 20 minutes of arc (20/400 Snellen equivalent), the 1-degree field contains only one and one-half light-dark cycles. Although such a small number of stripes is not optimal, we found that most subjects could correctly identify the orientation of this coarse grating at eccentricities out to 20 degrees from fixation.

Although the test, in general, is not difficult for patients, a few patients were unable to remain correctly aligned for acuity perimetry even though they could be tested adequately with conventional perimetry. In addition, the test is time-consuming. It took 30 to 45 minutes per eye to measure acuity at 24 locations with the thresholding method that we employed.

PERIPHERAL ACUITY IN NORMAL EYES

The usual reaction of a clinician, when told that the average interference fringe acuities 5, 10, and 15 degrees from fixation are the equivalents of Snellen acuities of 20/60, 20/100, and 20/160, respectively, is one of disbelief. These values seem incompatible with the common clinical observation that eyes with small foveal cysts or holes, which appear to occupy only the central two or three degrees of the macula, often have visual acuities of 20/80 to 20/200. However, grating and Snellen acuities may not be equivalent for eccentric viewing. Snellen acuity tests recognition as well as resolution. It is also possible that some macular lesions with poor central acuity have microscopic retinal abnormalities that extend beyond the clinically recognized boundaries of the lesion.

The shape of the acuity isopters corresponds roughly to the shape of the "ganglion cell layer thickness" isopters plotted by van Buren.[69] The acuity isopters are horizontally oval with a temporal expansion. The latter corre-

sponds to a nasal extension beyond the optic disc of a double layer of ganglion cells in the retina.

The absence of an aging effect on peripheral acuity is surprising, especially since in one semiquantitative histologic study[70] there appeared to be a decrease in the number of optic nerve fibers with aging. It may be that an effect of aging on peripheral acuity will become apparent if we test more elderly normal subjects. Only one of our normal subjects was over the age of 70 years.

ACUITY PERIMETRY: A SENSITIVE TEST FOR GLAUCOMA

This study provides strong evidence for the concept that acuity perimetry is more sensitive than conventional perimetry for the detection of early glaucomatous optic nerve damage: (1) The area of the visual field involved in a glaucomatous defect is usually larger with acuity perimetry than with conventional perimetry. (2) In a glaucomatous eye that by conventional perimetry has a field defect in only the upper or lower half of the visual field, the "uninvolved" hemifield may be abnormal by acuity perimetry. When this occurs, there is usually generalized enlargement of the optic disc cup, indicating the probability of nerve fiber loss throughout the retina. It does not seem to occur when the cup is localized to one pole of the disc. (3) Open-angle glaucoma patients who by conventional perimetry have field defects in only one eye may have abnormal acuity fields in their other eye. This seems to occur only when the fellow eye has a suspiciously enlarged cup of its optic disc. (4) Abnormal acuity fields may be found in patients with ocular hypertension. Usually this occurs in eyes with suspicious discs. Nearly a fourth of the ocular hypertensive eyes in this study had abnormal acuity fields. This proportion, of course, is not representative of all ocular hypertensive patients. Some of the patients in this study were selected for acuity perimetry because they had suspicious discs but normal conventional fields. (5) Ocular hypertensive patients with asymmetric disc cupping had asymmetric peripheral acuity much more frequently than did those whose discs were symmetrical. The defective acuity fields were, with only one exception, in the eye with the larger cup. (6) Three ocular hypertensive eyes with defective peripheral acuity subsequently developed visual field defects by conventional perimetry. The light sensitivity defects developed in the same part of the visual field as the acuity defects.

These observations are consistent with the two concepts that formed the rationale for this study: (1) peripheral acuity at any place in the field of vision is determined by the concentration of ganglion cell-nerve fiber units arising in the corresponding area of the retina, and (2) the early

generalized enlargement of the optic cup that often occurs in glaucoma before the development of conventional field defects is caused by a diffuse loss of nerve fibers.

That acuity perimetry should be more sensitive than conventional brightness discrimination perimetry is not surprising. The size I test stimulus on the Goldmann perimeter is 7.7 × 5.4 minutes (or 41.6 solid minutes), and the size III Goldmann stimulus commonly used on the Octopus perimeter is 15.4 × 10.8 minutes (or 166.3 solid minutes). In the fundus one linear minute of visual angle covers about 0.065 mm of retina. A target 1 solid minute in area would cover 0.004 mm^2 of retina. Thus, the area of retina covered by conventional perimetry targets is 0.17 mm^2 for the size I target and 0.67 mm^2 for the size III target. Estimates of ganglion cell density vary, but range from 80,000/mm^2 in the macula to 2,000/mm^2 in the far periphery.[69] Therefore, the size I perimetric target can be roughly estimated to cover, at a minimum, 340 ganglion cells. The corresponding number of cells for the size III target is 1340. It is likely that a large percentage of the ganglion cells in any area of the retina must be destroyed by glaucoma before sensitivity for light detection decreases. Acuity, on the other hand, probably becomes defective when there is only a modest reduction in the density of ganglion cells.

THOUGHTS ABOUT FUTURE RESEARCH DIRECTIONS

The testing procedure for acuity perimetry needs to be streamlined so that the examination can be done in less time. Work needs to be done on ways to speed up the threshold determination.

Further research is needed to definitely establish the place of acuity perimetry in the diagnosis of glaucoma. More ocular hypertensive patients need to be followed with sequential acuity and conventional fields. Patients who have abnormal acuity fields but normal conventional fields must be tested with intensive static threshold perimetry (static profiles or a dense static grid such as the Octopus Program 11 through the suspicious area) to be sure that the conventional field is, indeed, normal. Patients should be tested before and after pressure lowering by glaucoma medications to determine if any of the acuity loss in glaucoma is reversible.

Acuity perimetry should be evaluated in other ocular disorders. Lesions such as dysthroid ophthalmopathy or pituitary tumors that compress the optic nerve or chiasm may reduce peripheral acuity before producing field defects by conventional perimetry.

CONCLUSIONS

Acuity perimetry using laser interference fringes for acuity targets is a practical way to test eccentric visual acuity at selected test locations in the paracentral visual field.

Peripheral acuity is greatest with exposure times of at least ½ second duration and with low photopic levels of retinal illumination. It is slightly affected by the orientation of the grating target. The average acuity (minutes of arc resolution) is 3.0 at 5 degrees eccentricity, 5.0 at 10 degrees eccentricity, and 8.0 at 15 degrees eccentricity. These values are only approximate, since the acuity along the horizontal meridian is somewhat better than the acuity along the vertical meridian.

Peripheral acuity is often impaired by glaucoma before a visual field defect can be detected with conventional perimetry. The reduction of visual acuity is probably the result of a diffuse loss of optic nerve fibers, which is not localized sufficiently in any one bundle to reduce light sensitivity. Acuity perimetry, therefore, is more sensitive than conventional perimetry for the early diagnosis of glaucoma.

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