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ORIGINAL ARTICLE

Vision Evaluation of Eccentric Refractive Correction

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ABSTRACT

Purpose. This study investigates the benefits of eccentric refractive correction to resolution and detection thresholds in different contrasts for seven subjects with central visual field loss (CFL) and for four healthy control subjects with normal vision.

Methods. Refractive correction in eccentric viewing angles, i.e., the preferred retinal location for the CFL subjects and 20° off-axis for the control subjects, was assessed by photorefraction with the PowerRefractor instrument and by wavefront analysis using the Hartmann-Shack principle. The visual function with both eccentric and central corrections was evaluated using number identification and grating detection.

Results. For the CFL subjects, the resolution and detection thresholds varied between individuals because of different preferred retinal locations and cause of visual field loss. However, all seven CFL subjects showed improved visual function for resolution and detection tasks with eccentric correction compared with central correction. No improvements in high-contrast resolution were found for the control subjects.

Conclusions. These results imply that optical eccentric correction can improve the resolution acuity for subjects with CFL in situations where healthy eyes do not show any improvements.

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Key Words: low vision, macular degeneration, periphery, detection threshold, resolution acuity, eccentric refractive correction

Individuals with absolute central visual field loss (CFL) have to rely on their remaining peripheral vision for all visual tasks. In large eccentric viewing angles, the reduced capacity of the peripheral retina is known to be a limiting factor. However, the optical imperfections of the human eye may also limit peripheral vision; an optical correction designed for the eccentric viewing angle of the preferred retinal location (PRL) can therefore improve the remaining vision for subjects with CFL.[1] The current study represents the first evaluation of eccentric refractive correction in CFL with regard to resolution and detection acuity.

The dominating optical errors in the peripheral eye induced by large field angles are defocus and astigmatism. These eccentric refractive errors show large individual variations even in a foveally emmetropic population.[2] Apart from the refractive errors, the peripheral optics also have large higher order aberrations, which make normal clinical subjective and objective refraction methods difficult to use. Jackson et al.[3] found that retinoscopy was more difficult to perform off-axis. Therefore, a recent study evaluated four different refraction methods in eccentric angles of subjects with normal central vision.[4] Wavefront sensing and the PowerRefractor instrument[5,6] proved to be useful tools to assess the eccentric refraction and are therefore both used in the current study, although the PowerRefractor cannot measure at large angles if the pupil is small.

A number of researchers have measured the off-axis optical errors of the eye (reviewed by Atchison[7]), and there have been some attempts to correct them in visually normal eyes.[8–17] In peripheral vision, different visual tasks, e.g., detection (i.e., to see whether an object is present or not) and resolution (i.e., to distinguish the type of presented object), show different sensitivity to changes in retinal image quality. Detection tasks seem to be limited by the contrast of the image on the retina and can therefore often be improved with eccentric refractive correction. On the other hand, experiments have indicated that resolution acuity for high-contrast targets in the periphery shows little change with defocus due to the limited sampling density of the retinal ganglion cells.[12,14–17] The visual improvement with eccentric refractive correction in subjects with CFL has previously been evaluated using optotypes from high-pass resolution perimetry,[18] so-called vanishing optotypes.[1,19] However, it was not clear whether these optotypes assessed the threshold of detection or resolution.[17,20] If the eccentric correction only improves detection acuity, as previously found, it might be less useful. However, if there is an improvement also in resolution acuity, it would facilitate tasks such as reading and watching television for individuals with CFL. Although the acuity measurement with the special high-pass filtered optotypes is a simple detection task, it was originally asserted that the optotypes had very similar detection and resolution thresholds.[18] The argument is that when the target no longer can be resolved, it also vanishes because of the pseudo high-pass filtering, which eliminates the overall luminance cue. This argument is valid as long as resolution is contrast limited; in the periphery resolution may be sampling limited, resulting in better threshold values for detection than for resolution. The magnitude of the difference between the two thresholds will then depend on both optical quality and on stimulus properties.[14] To avoid this ambiguity and investigate whether eccentric refractive correction can improve resolution, the current study used separate resolution and detection tasks at high and low contrast to investigate the peripheral vision for seven subjects with severe CFL. The visual function with central refractive correction was compared with the eccentric refractive correction, optimized for the oblique viewing angle of the PRL.

METHODS

Seven subjects (A to G) with CFL and four control subjects (C1 to C4) with normal vision participated in the study. All measurements were performed monocularly, with the other eye occluded, under reduced room light conditions with natural pupils. For the CFL subjects, the study included two objective measurement techniques to assess the eccentric refraction: the PowerRefractor and a wavefront sensor. The large aberrations in these oblique angles made the eccentric refractive correction difficult to define, and therefore, both the corrections from the PowerRefractor and from the wavefront measurements were evaluated. For the control subjects, the eccentric refractive correction was only assessed with the wavefront sensor because the refraction from the PowerRefractor had proved to give worse vision for all CFL subjects except one. The refractive corrections used for the visual evaluation were normal trial lenses and the optical axis of the lens was aligned with the eccentric viewing direction, i.e., the PRL for the CFL subjects. The evaluation of the peripheral vision with the subjects' central correction and with eccentric correction was performed with two different tasks: number identification and grating detection. Before the actual acuity tests began, trials were carried out to find suitable test areas and to acquaint the subjects with the measurement techniques and the stimuli. All subjects gave informed consent before participation, and the study followed the Declaration of Helsinki and was approved by the local Research Ethics Committee. The optical and visual function measurements are described in more detail in the following sections.

Initial Clinical Examination of the CFL Subjects

All seven CFL subjects have been followed for 2 to 4 years within our research project. They have been chosen from a larger group of individuals with CFL, because of their long standing, severe, and absolute CFL on both eyes, and because of their stable eccentric viewing. Table 1 presents data for each subject. The onset of the CFL was at a relative young age and the scotomas have been stable for at least 2 years. The subjects actively used their remaining peripheral vision and had at least one stable PRL. For each CFL subject, the better eye with the most used PRL was chosen for the optical measurements and visual evaluations. The state of the CFL and the extent of the scotoma were examined with Goldman perimetry and Tangent Screen Visual Field Testing. The angle of the eccentric viewing was also confirmed with the eye trackers in the PowerRefractor and the wavefront sensor. The refractive state of the central optics of the eye (i.e., approximately where the fovea was formerly located) was assessed by the PowerRefractor and confirmed by retinoscopy. We will call the correction thereby found "the habitual central refractive correction" because many of the subjects were accustomed to this or a similar correction before our study. Only subject E and F had no earlier correction and the habitual central refractive correction therefore differed slightly (0.6 D) from what they were used to, for the other subjects the differences were <0.5 D, everything calculated in terms of power vectors.[21] No subject showed evidence of cataract.

Eccentric Refraction

The PowerRefractor is a commercial instrument and its function can be described as a combination of photorefraction and retinoscopy performed in different meridians to analyze the refractive state of the eye.[5,6] It incorporates an eye tracker to measure the pupil size and viewing angle. The distance between the subject and the PowerRefractor was 1 m. A special fixation help, in the shape of a screen with concentric rings centered on the PowerRefractor camera, was used in our study to establish a sufficiently stable eccentric viewing for subjects with CFL.[1] The subject was instructed to fixate the PowerRefractor camera, which means that the PRL was aligned with the measurement axis of the instrument. One measurement of the eccentric refraction was taken when the fixation stabilized. When the subject views eccentrically, the projection of the pupil becomes elliptical, and if the pupil is small, the projection can be too narrow to analyze. For this reason, it was not possible to use the PowerRefractor for subject D.

To assess the peripheral optics of the eye in more detail, a wavefront analyzer based on the Hartmann-Shack principle[22] has been developed for off-axis measurements (see ref. 23 for a full description). To facilitate viewing for subjects with CFL the same kind of fixation help as for the PowerRefractor was used, together with a fixation light aligned with the measurement axis of the sensor. An eye tracker was also incorporated to verify that the angle of the PRL was aligned with the measurement angle of the sensor. A number of measurements were made, and the wavefronts were reconstructed with Zernike polynomials over a circle that encircled the elliptic pupil. The Zernike coefficients were then recalculated to a 4-mm pupil. Three or more wavefronts from good quality measurements with the correct viewing angle were averaged for each subject and the part of the wavefront outside the elliptic pupil (4 mm in major diameter) was removed. The point-spread function of the eye was then calculated from this wavefront for a large number of potential spherocylindrical correction values. The eccentric refractive cor-

TABLE 1.
Data on the subjects (A–G) with central visual field loss (CFL) and the control subjects (C1–C4) with normal vision

Subject	Gender and age	Cause of visual field loss	Preferred retinal location	Age at onset of CFL	Years of unchanged impairment	Refractive corrections
A	Male 57	Juvenile macula degeneration	OD 30–35° to the left	17	20	CC +2.00 −1.00 ×25° *WF +3.00 −2.00 ×100° PR +4.00 −4.00 ×90°
B	Female 61	Juvenile macula degeneration	OS 20° to the left	31	20	CC −3.75 *WF −3.25 −1.75 ×80° PR −2.00 −3.00 ×90°
C	Male 79	Age related macula degeneration	OS 10° below	73	4	CC +0.50 −0.75 ×165° *WF +0.50 −2.50 ×5° PR +1.00 −3.75 ×170°
D	Male 42	Chronic inflammation of the uveit/retinitis	OD 20° to the left	16	5	CC −2.50 −1.00 ×25° *WF +1.75 −9.00 ×50° PR No usable results
E	Female 33	Surgery on a brain tumor in the optic nerve (chiasma)	OD 17° to the left	15	10	CC −0.25 −0.50 ×95° WF −3.25 −1.50 ×80° *PR −0.75 −2.00 ×90°
F	Male 44	Late onset juvenile macula degeneration	OD 20° to the left	40	2–3	CC −0.25 −0.50 ×75° *WF +0.50 −2.00 ×90° PR +1.50 −3.00 × 90°
G	Male 57	Leber's Opticus Atrophy	OS 20° below	22	30	CC ±0 −1.00 ×80° *WF −1.25 −0.50 ×165° PR −1.00 −1.50 ×175°
C1	Female 34	Normal vision	OD 20° to the left	—	—	CC +2.00 −0.75 ×125° WF +1.00 −1.25 ×100°
C2	Male 53	Normal vision	OD 20° to the left	—	—	CC +1.00 WF −0.50 −4.50 ×85°
C3	Male 35	Normal vision	OD 20° to the left	—	—	CC ±0 −0.50 ×70° WF +0.25 −2.50 ×90°
C4	Male 50	Normal vision	OD 20° to the left	—	—	CC ±0 WF ±0 −1.25 ×90°

The column "Preferred retinal location" shows the most used eye, right eye (OD) or left eye (OS), and the eccentric viewing angle of that eye. The viewing angle is expressed as the angle between the preferred retinal location relative to the former fovea, projected in the visual field. For example "20° below" means that the eye needs to be directed 20° upwards to have best vision for objects straight in front of the CFL subject. The last column lists the different refractive corrections evaluated in this study: CC denotes the habitual central correction, WF is the eccentric correction found with the wavefront sensor, and PR is the eccentric correction from the PowerRefractor. A * marks the refractive correction which gave best visual function for each CFL subject. The refractive corrections listed are for distant vision and +1.00 D was added to compensate for the measurement distance of 1 m.

rection from the wavefront sensor was the refraction that gave the highest maximum value of the point-spread function, i.e., the highest Strehl ratio.

Visual Function Evaluation

Specific tests of resolution and detection thresholds were carried out in both high (100%) and low (25% or 10%) contrast. For subjects A, D, E, and F, 10% contrast was not possible due to the low visual-function and 25% contrast was used instead. The test stimuli were presented on a calibrated computer screen (Eizo Flex Scan T 765 with 85 Hz and a resolution of 1024 × 768) with WinVis-software (www.neurometrics.com/winvis). The background luminance of the screen was 50 cd/m^2, the test distance was 1 m (compensated by an additional +1.00 D), and the same kind of fixation help with concentric rings as for the PowerRefractor was used.

The resolution acuity measurements involved a discrimination test with the number optotypes 5, 6, 8, and 9 exclusively (see the inset in Fig. 1). The numbers were displayed in randomized order in varying sizes, in steps of 0.05 LogMAR. Each number was presented for 2 s. High and low contrast numbers were mixed randomly. An auditory signal preceded each display. The subject's task was to identify the numbers; a mistake or "I don't know" was registered as an error. The subjects were always encouraged to guess, even if they were uncertain. One staircase method for each contrast level was used in which the numbers were displayed in decreasing size down to the point where they could no longer be identified. When an error was registered, the staircase reversed and displayed an optotype that was one step larger. The subject was required to see the stimulus on two successive trials in order for a smaller stimulus to be displayed (two-down-one-up paradigm). Eight reversals around the threshold value were made. The stair-

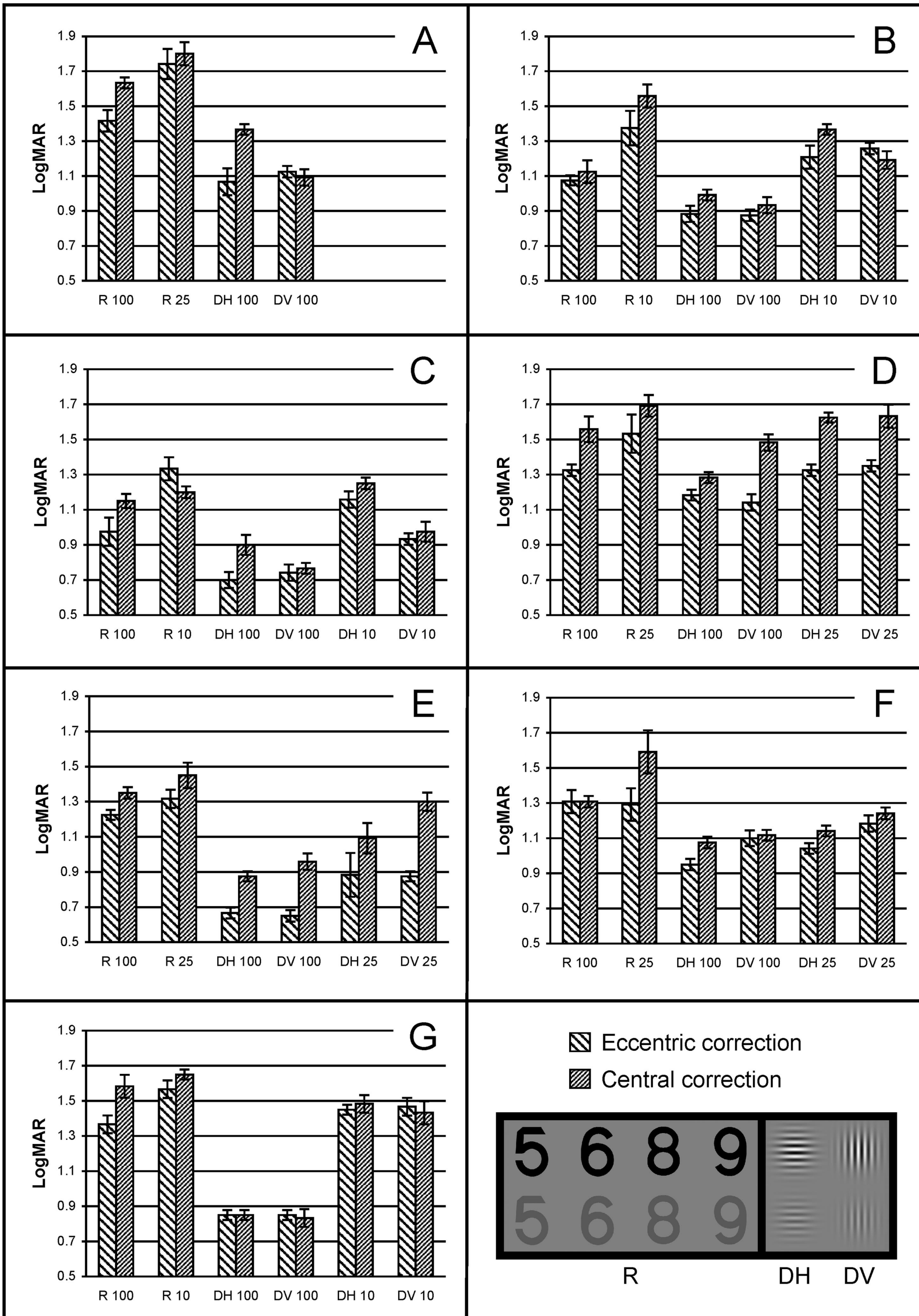

FIGURE 1.

Graphical comparison of the visual function with the best eccentric refractive correction (marked with * in Table 1) and with the habitual central refractive correction for the seven subjects with central visual field loss (A to G). The inset shows the different stimuli used. The different visual tasks are denoted as follows: R 100, resolution test with numbers in 100% contrast; R 10/25, resolution test in lower contrast (10% or 25%); DH 100 and DV 100, detection test with horizontal respective vertical gratings in 100% contrast; DH 10/25 and DV 10/25, detection tests in lower contrast (10% or 25%).

case method started with double step-size until the second reversal. The threshold value was calculated as the arithmetic mean of the last six reversals. The resolution results might depend on the subject's attention and learning effects. Therefore, the central and eccentric corrections were used in alternating order for the different subjects when the resolution thresholds were evaluated.

The detection test displayed Gabor gratings, i.e., sinusoidal gratings modulated by a Gaussian envelope, of different spatial frequencies (see the inset in Fig. 1). The circular Gaussian patches had a standard deviation of 2.5° (at this radius, the contrast was a factor $e^{-0.5}$ of the maximum value), i.e., the visible part of the grating had an approximate diameter of 5°. At low-spatial frequencies, the patch size was increased slightly to always have a minimum of six cycles of the grating visible within ±1 standard deviation from the center of the Gaussian envelope. Horizontal and vertical gratings were evaluated separately at high and low contrast. The test used a two-alternative-forced-choice paradigm with two time intervals. The subject's task was only to identify the interval in which the grating was displayed and not to determine its direction. The empty interval showed a uniformly gray screen. Each interval was displayed for 2 s and was preceded by auditory signals. In total, four interleaved staircase methods were run simultaneously in randomized order; horizontal and vertical gratings were alternated at the two contrast levels. The staircase methods used were the same as for the resolution test; starting at high-spatial frequencies and decreasing the frequency according to the two-down-one-up paradigm with a step size of 0.05 LogMAR. The subjects were encouraged to guess but could also answer that they did not see anything, which was registered as an error. The detection test took between 30 min and 45 min. Because the measurements required considerable concentration, the subject was encouraged to rest every 2 to 3 min.

Control Group

Four control subjects with normal vision were included in the study to compare the visual evaluation with earlier studies and they are presented in the four last rows of Table 1. The central refractive correction was found by subjective refraction, and the eccentric refractive correction was assessed with the wavefront sensor in 20° angle to the left in the horizontal field of view of the right eye. The visual function evaluation procedure was the same as for the CFL subject except that only eccentric refractive correction from the wavefront measurements was used and that a different fixation target was needed for the control group; instead of the fixation rings, a star (*) was used, which was located 3 m from the subject and subtended an angle of 1.6°.

RESULTS

The last column of Table 1 gives the three refractive corrections (habitual central correction, eccentric correction from the wavefront sensor, and eccentric correction from the PowerRefractor) for each subject with CFL and the two refractive corrections (central correction and eccentric correction from the wavefront sensor) for the control subjects. In Fig. 1, the visual function with the habitual central correction is graphically compared with the eccentric correction that gave best threshold values for the CFL subjects. In the graphs, the error bars for the resolution and detection tests indicate the 95% confidence interval for the mean value of the six last points of reversal of each staircase method. The reversals when the staircase procedure turned upwards and downwards are treated as observations of two separate stochastic variables (the upper and lower limit of the threshold) and the confidence interval is then calculated by the Student's t-test, i.e., $\pm t_{0.025}(4)\sqrt{((\sigma^2_{up} + \sigma^2_{down})/12)}$, where σ_{up} and σ_{down} are the measured standard deviations of the reversals upwards and downwards, respectively. In the text below, a difference between central and eccentric correction is regarded as significant only if these confidence intervals do not overlap.

As expected, all CFL subjects showed better (i.e., lower LogMAR values) detection acuity than resolution acuity at each individual contrast level, which is reasonable because resolution is a more complicated task than detection. Additionally, high-contrast targets were detected and resolved more easily than lower contrast (only subject F shows similar thresholds for high and low contrast). When central and eccentric refractive corrections are compared, it can be seen that both resolution and detection are improved by the eccentric correction in high and/or low contrast for all CFL subjects except subject G, who only showed improved resolution. Number identification is improved for five of the subjects (A, C, D, E, and G) at high contrast and for four subjects (B, E, F, and G) at low contrast. Detection of horizontal gratings is improved for six of the subjects (A, B, C, D, E, and F) in high contrast and for four subjects (B, C, D, and F) in low contrast. For vertical gratings, two subjects (D and E) showed an improved detection threshold in high and low contrasts. Altogether, the eccentric refractive correction gave significant improvements, compared with the habitual central refractive correction, for high-contrast resolution and for detection of horizontal gratings in high contrast (Wilcoxon paired-sample signed-rank test for the seven subjects, $p < 0.01$, one tailed). The threshold values have not been recalculated to account for spectacle magnification as Wang et al. did.[16] However, because all subjects, except subject A, have received a more negative eccentric correction, such a recalculation would give slightly larger improvements.

As the only departure, subject C showed a decrease in visual function with eccentric refractive correction for number identification at low contrast. Still, he subjectively experienced enough improvement to use the eccentric correction. For subject A, it was impossible to measure detection at 25% contrast, which was surprising because resolution measurements at 25% contrast were possible. One small opacity in the ocular media was found for subject D from the wavefront measurements, nevertheless, the eccentric correction gave a general improvement. All subjects, except subject E, had better threshold values with the eccentric refractive correction from the wavefront sensor than from the PowerRefractor. For subject D, it was not possible to measure the eccentric refraction with the PowerRefractor. Subjects C and F could not accept the correction from the PowerRefractor and were therefore only measured with the habitual central correction and with the eccentric correction from the wavefront sensor. During the study, the CFL subjects were also given spectacles with the eccentric refractive correction to compare with the spectacles they had before the study. Subjectively, they confirmed the results of the visual evaluation and found the eccentric refractive correction useful in their everyday life; for subjects A, D, and F primarily

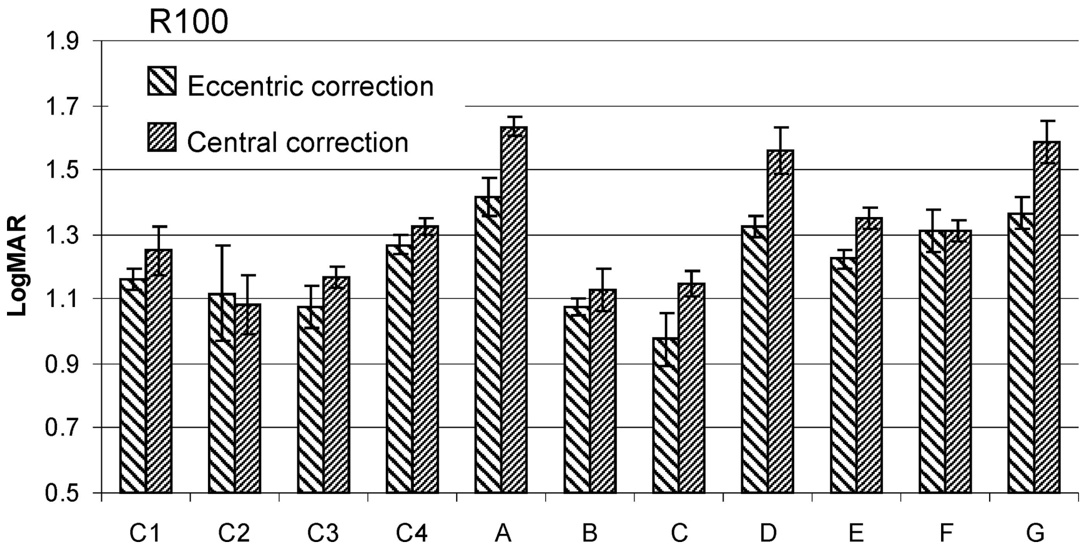

FIGURE 2.

Graphical comparison of the resolution acuity threshold in high contrast (R 100 in Fig. 1) with the eccentric refractive correction and with the central refractive correction for the four control subjects (C1 to C4) and the seven subjects with central visual field loss (A to G).

when watching television. However, we cannot exclude the possibility that this subjective response can be a placebo effect.

The control subjects were all able to perform the low-contrast tests at 10% contrast. Compared with central correction, the eccentric refractive correction gave improvements in detection acuity for all four control subjects and two subjects also showed improvements in low-contrast resolution acuity. However, no improvements in high-contrast resolution were found, which is seen in Fig. 2 (the error bars are calculated in the same manner as for Fig. 1).

DISCUSSION

Measuring the eccentric refractive error is difficult due to the large off-axis aberrations and the reduced sampling density of the peripheral retina. Although the induced astigmatism is clearly seen, the large higher order aberrations lead to a less well defined far point.[24,25] For all CFL subjects, except subject E, the eccentric refractive correction obtained by the wavefront sensor gave better visual function, which may be due to the fact that the PowerRefractor is not designed for peripheral measurements. The wavefront measurements also provide the possibility of further optical evaluation through the modulation transfer function. In the following discussion, "eccentric refractive correction" will refer to that eccentric correction, which gave best visual function for the individual CFL subject.

There are large variations in the measured threshold values between the CFL subjects. This can be explained by differences in both optical quality and in neural capacity. The difference in optical quality between the subjects is due to off-axis aberrations induced by the oblique fixation angle, and possibly small remaining refractive errors. Calculations of the wavefront with the eccentric refractive correction, e.g., show that subjects D and E have large amounts of higher order aberrations like coma, which have not been corrected in this study. The neural capacity depends on the eccentric viewing angle and on the cause of the absolute CFL, because different diagnoses affect the remaining retina differently. It is also conceivable that an adaptive change may have occurred in the visual system of some of these subjects, who for many years have had absolute CFLs in both eyes and actively used eccentric viewing.[26,27]

The results of the control group compare well with the findings of Wang et al.,[16] who investigated visual function thresholds in an angle of 20° to the left in the visual field of the right eye of three healthy subjects with intact central vision. They found that the detection threshold of sinusoidal gratings varied with the refractive correction, whereas the resolution threshold for tumbling-E discrimination was stable at about 1.0 LogMAR and only changed by 0.07 LogMAR over a range of ±3 D compared with the optimum eccentric refraction. We also found the number discrimination test to be sampling limited in high contrast for the control subjects whereas low contrast number discrimination could be, and detection acuity of sinusoidal gratings was, optically limited.

A comparison between the control subjects and the subjects with CFL is complicated by the difference in eccentric viewing angle between the subjects. However, the most noteworthy difference is that high-contrast resolution acuity was affected by the eccentric refractive correction for five of the seven subjects with CFL but not for any of the four control subjects with normal central vision. The five CFL subjects, who showed improvements (i.e., A, C, D, E, and G), seem to have worse threshold values with their habitual central correction than the control subjects (note that subject C has a PRL in only 10°). The fact that resolution acuity can improve with optical correction means that the contrast of the image on the retina is a limiting factor when these five subjects use their habitual central refractive correction. In this context, it is important to note that the changes in refractive correction are not larger for these CFL subjects than for the control group, with the exception of subject D.

It is beyond the scope of this study to explain the improved resolution acuity for five of the CFL subjects with eccentric correction. Further investigations are needed on more subjects to understand the effect of different diagnoses and any possible adaptation over time. However, we have shown that the remaining resolution acuity for some subjects with CFL can be improved with proper refractive correction. It should be noted that the CFL subjects in this study have gone through low-vision rehabilitation, including subjective refraction by experienced optometrists, without the eccentric refraction in the direction of the PRL being found. A proper optical correction is not only important for subjects with end stage CFL and a well developed PRL; eccentric correction of the optical errors in the visual angle corresponding to the best remaining part of the retina might facilitate the establishment and development of a PRL to utilize the residual vision more optimally.

CONCLUSIONS

Within this study, refractive correction has been used to improve the peripheral optical quality in the direction of the PRL for subjects with large, long standing CFL. We have shown that these eccentric refractive corrections improve the residual visual function for both resolution and detection tasks. For these subjects, the visual function is not generally limited by the neural sampling limit of the peripheral retina, as has commonly been assumed. This means that eccentric correction can be beneficial for some subjects with CFL in situations where healthy eyes are sampling limited. The conclusion of this work is therefore that eccentric optical corrections can be of practical use for subjects with large CFL.

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