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ORIGINAL ARTICLE

Peripheral Refraction Profiles in Subjects with Low Foveal Refractive Errors

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ABSTRACT

Purpose. To study the variability of peripheral refraction in a population of 43 subjects with low foveal refractive errors.

Methods. A scan of the refractive error in the vertical pupil meridian of the right eye of 43 subjects (age range, 18 to 80 years, foveal spherical equivalent, $<\pm2.5$ diopter) over the central $\pm45°$ of the visual field was performed using a recently developed angular scanning photorefractor. Refraction profiles across the visual field were fitted with four different models: (1) "flat model" (refractions about constant across the visual field), (2) "parabolic model" (refractions follow about a parabolic function), (3) "bi-linear model" (linear change of refractions with eccentricity from the fovea to the periphery), and (4) "box model" ("flat" central area with a linear change in refraction from a certain peripheral angle). Based on the minimal residuals of each fit, the subjects were classified into one of the four models.

Results. The "box model" accurately described the peripheral refractions in about 50% of the subjects. Peripheral refractions in six subjects were better characterized by a "linear model," in eight subjects by a "flat model," and in eight by the "parabolic model." Even after assignment to one of the models, the variability remained strikingly large, ranging from -0.75 to 6 diopter in the temporal retina at 45° eccentricity.

Conclusions. The most common peripheral refraction profile (observed in nearly 50% of our population) was best described by the "box model." The high variability among subjects may limit attempts to reduce myopia progression with a uniform lens design and may rather call for a customized approach.
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Key Words: physiological optics, peripheral refraction, myopia, ophthalmic instrumentation, spectacle design

Recent studies in animal models and humans suggest that hyperopic defocus, imposed in the periphery of the visual field, may promote the development of foveal myopia.[1–4] The recent observation that axial length in the human eye undergoes a small but measurable change to compensate for imposed defocus of either sign after only 1 h additionally supports the notion that defocus is a relevant factor in refractive development in humans.[5] If defocus is a key stimulus for emmetropization, peripheral refractive errors cannot be neglected when optical correction is attempted but designed only for the fovea. Previous work showed that single vision spectacles induce some levels of peripheral hyperopia.[6,7] The new requirement for the peripheral retina (correction of peripheral hyperopia and/or generation of peripheral myopia) represent an open challenge to spectacle lens designers. Recently, examples of how spectacles can be designed and manufactured to impose myopic refractive errors to the periphery have been presented.[6] However, wearing comfort of such lenses can be limited because of the distortions in the periphery and the astigmatism that they generate, raising ergonomical issues.[8] An optimum solution would be to minimize distortion using the amount of induced peripheral myopia and the central area with null optical power as optimization variables, both for spectacles or contact lens designs.[6]

The idea that peripheral refractions control foveal refractive development is not supported by all published studies. For instance, Mutti et al.[9] found only a negligible association between peripheral hyperopia and the progression of myopia in the Collaborative Longitudinal Evaluation of Ethnicity and Refractive Error (CLEERE) study [0.024 diopter (D) myopia progression per year per diopter of relative peripheral hyperopia]. A clinical trial in Chinese children wearing spectacles with modified designs to induce peripheral myopia did not detect any significant inhibition of myopia progression, relative to the progres-

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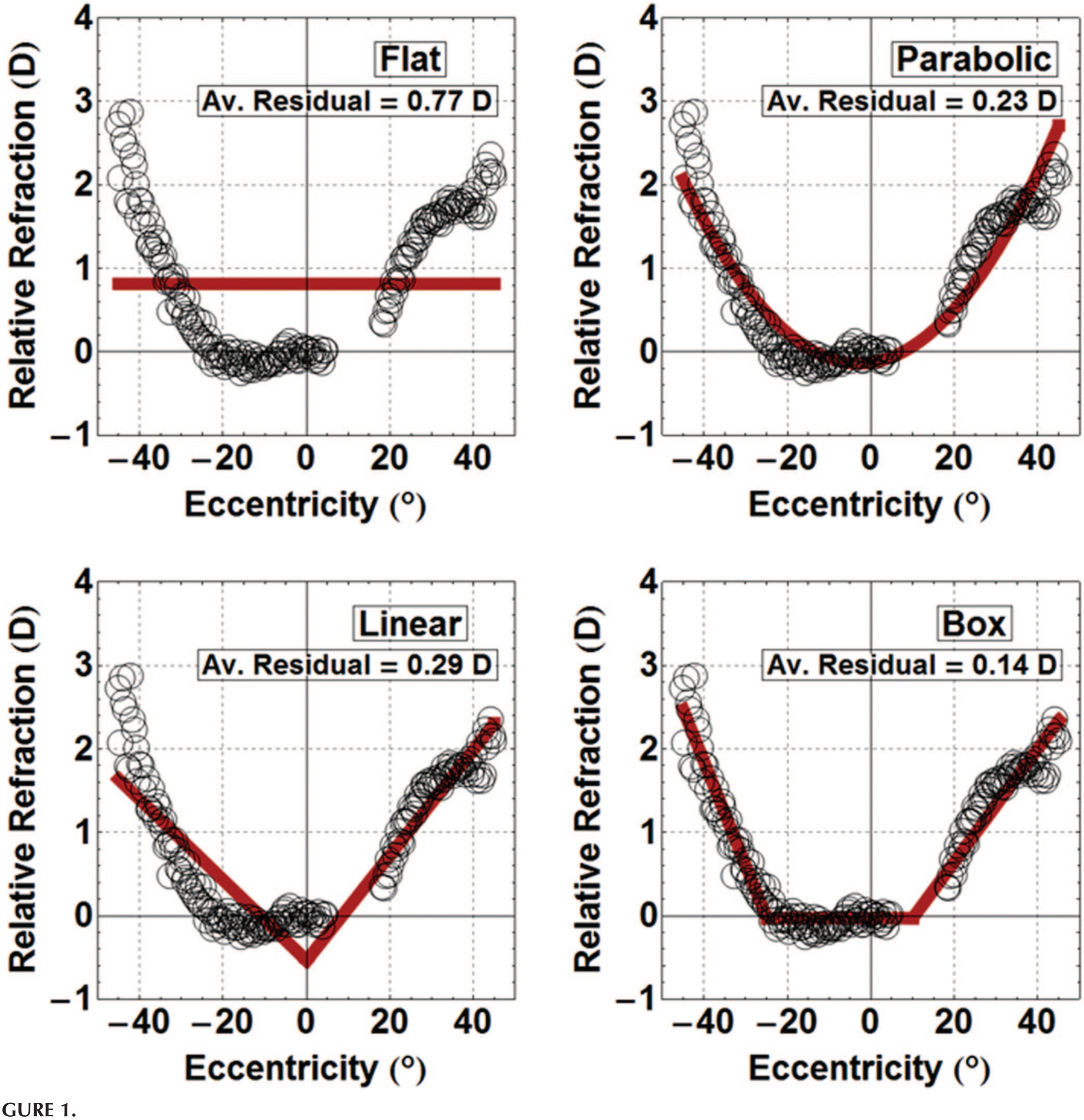

FIGURE 1.

Example of the classification procedure in a subject. Four different fits were performed, according to the proposed models (discussed in text). Positive eccentricity means nasal side of the retina. In this particular subject, the best description was achieved with the "box model." A color version of this figure is available online at www.optvissci.com.

sion in a control group wearing conventional spectacles during the initial 12-month phase.[10] An effect was only seen if the analysis was confined to the youngest participating children with parental history of myopia. These equivocal results may in part be explained by the fact that the patterns of imposed relative peripheral myopia were also highly variable, depending on the individual peripheral refraction profiles. To better describe the normal distribution of the relative peripheral refractive errors in a sample of human subjects with low central refractive errors, a newly developed scanning photorefractor was used.[11,12] The advantage of this device is that semicontinuous scans (0.4° angular resolution) can be performed over the central ±45° degree horizontal field in about 4 s, while the subject keeps the eye in a steady position. Previous studies had more coarse angular resolution, with sampling intervals between 5 and 20°, and they often required the subject to change gaze position for the individual measurements.[13–17]

METHODS

Subjects

Forty-three subjects were enrolled in the study, with a wide range of ages from 18 to 80 years (mean, 47.8 years; standard deviation, 19.2 years). Inclusion criterion for participation was a central refractive error of <2.5 D spherical equivalent (myopic or hyperopic). All subjects were measured after topical application of phenylephrine and tropicamide for cyclopegia, which was applied in the course of other examinations at the University Eye Hospital of Tuebingen. Informed consent was obtained from all participants before the measurements, and permission for the study was obtained from the Institutional Review Board of the Medical Faculty of the University of Tuebingen. The study protocol was in accordance with the guidelines of the Declaration of Helsinki.

Measurements

At least six scans of the peripheral refractions in the horizontal direction (from −45 to 45°) were performed in each subject, using a custom-built scanning photorefractor. The details of the refractor have been described elsewhere.[11,12] Briefly, the instrument consists of an infrared photoretinoscope attached to a charged-coupled device camera via a USB cable.[18] Infrared light from the photoretinoscope is reflected off of hot mirror onto the retina, that is rotated and translated simultaneously along a linear stage by two stepping motors. The path of movement is calculated to make it possible to scan the peripheral retina in the horizontal plane from −45 to 45° in steps of 0.4°. The procedure takes about 4 s per scan. Because of the stationary position of the photoretinoscope, only the vertical pupil meridian is refracted. Astigmatism remains unknown. Nevertheless, these measurements permit comparisons of refraction profiles across the horizontal visual field among different subjects.

Data Analysis and Refraction Profile Classification

For each subject, the average refractive profile as a function of the angular eccentricities was obtained from a total of six scans. To better visualize the peripheral differences or similarities, all profiles were normalized to 0 in the fixation axis. Excluding the refraction data at the optic nerve head excavation (detected between 5 and 20° in the nasal retina), each subject's data were fitted to four different mathematical models: (1) "flat model" (refraction constant across the visual field), (2) "parabolic model" (refraction profile follows a parabolic function), (3) "linear model" (refraction changes linearly with eccentricity from the fovea to the periphery), and (4) "box model" (no significant changes of refraction in the central area, and a linear change in refraction in the periphery, starting at a certain peripheral angle). Subjects were assigned to one of four profiles based on the model fit that minimized the average residual value. Fig. 1 shows an example of the classification procedure in one subject. In this case, the function with least residual error followed the "box model" (lower graph on the right panel of Fig. 1). All calculations were performed using custom and built-in functions written in Mathematica software (Mathematica, Wolfram Research, Champaign, IL).

RESULTS

The high variability of the individual refraction profiles in the 43 subjects can be inferred from Fig. 2. Here, the refractions were normalized to 0 refractive error in the fovea. Relative peripheral refractive errors still ranged from −0.75 to around 6 D on the temporal side of the retina (negative eccentricity angles) at 45°. On the nasal retinal side, the variability was slightly less, perhaps because of the fact that the optical axis is tilted toward this side (angle kappa). The average relative refraction of all subjects (thick red line) showed little changes between 0 and −20°, followed by an increase in relative hyperopia to 2 D or more at 45°.

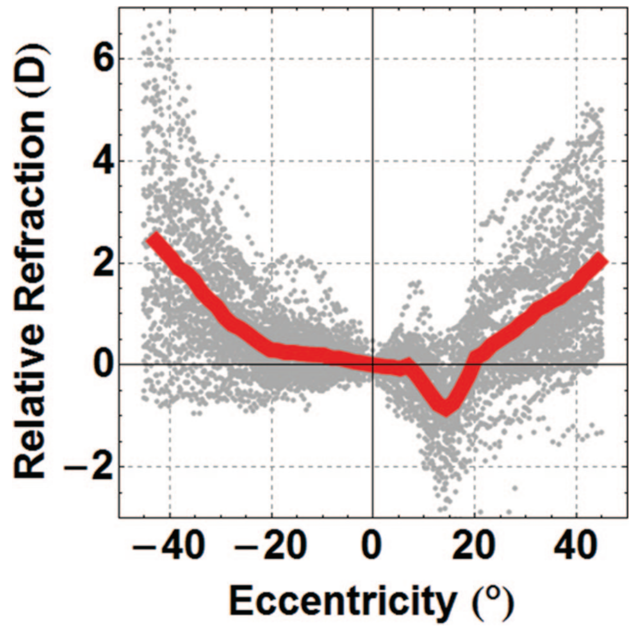

FIGURE 2.
Refractive errors in the vertical pupil meridian of the right eyes of all 43 subjects, plotted across the central 90° of the horizontal visual field after normalization to 0 refractive error in the fovea. The thick (red) line represents the average refraction of all subjects. A color version of this figure is available online at www.optvissci.com.

The optic disc could be recognized as an area with more relative myopic refractions, located at about +15° from the fovea (Fig. 2). The average "dioptric depth" of the optic disc was around 1 D, equivalent to about a third of a millimeter.[19]

Fig. 3 shows the results of the data classification according to the procedure described in the methods section. Almost one-half the population (20 of 43) was classified into the "box model" with little change of the refraction over the central ±20°, and an almost linear increase in relative hyperopia more peripherally. The remaining subjects were about equally distributed among the other three models. One subject had an irregular refractive profile (fitting quality was mathematically poor for any of the models, presenting high residual amounts) that could not be included as any of the proposed models.

To illustrate the effect of lenses designed to impose relative peripheral myopia, we estimated the refractive profile that an eye wearing a lens with a parabolic increase in refractive power from 0 in the center to +2 D at 45° would have in each of the four classifications. Two diopters were chosen based on lens designs described in the literature.[10,6] The dashed lines in Fig. 3 showed the resulting peripheral refraction profiles in the eye after the mathematical subtraction of the spectacle profile to the average profile of the group. It can be seen that 2 D of peripheral plus power is not sufficient to cancel relative peripheral hyperopia in the case of the parabolic model. Such a lens would have the desired effect primarily in the case of the "flat model."

Finally, we studied whether the central refractive errors differed between the four models. Fig. 4 shows the amounts of central refraction in each subject (i.e., the central refraction along the

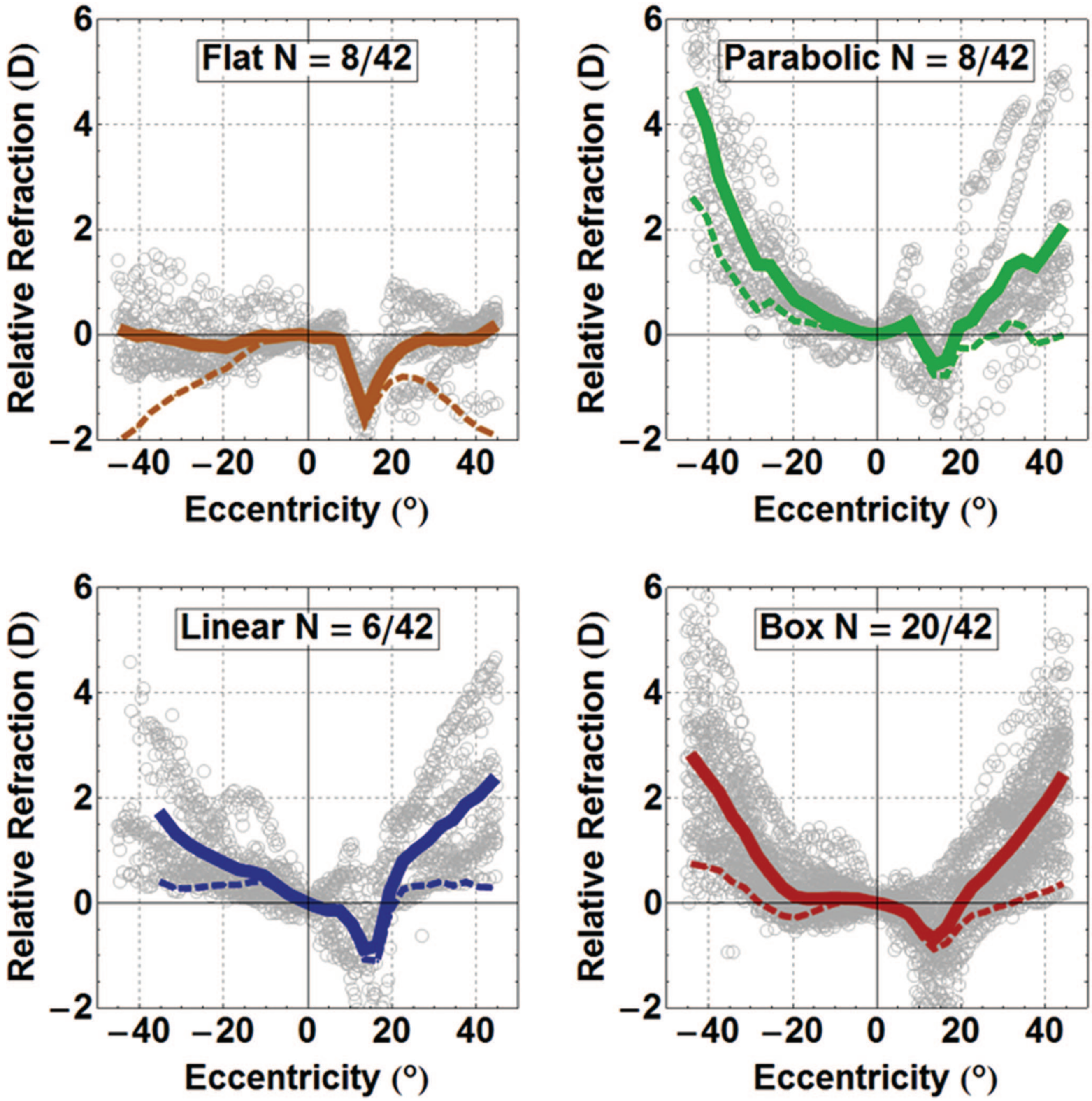

FIGURE 3.
Classification of the subjects' peripheral refractions according to the four models proposed above (Fig. 1). Data plotted as empty light gray circles reflect original data, normalized to 0 in the fixation axis. Positive eccentricity means nasal side of the retina. Thick color lines reflect numerical averages, separately for the four classifications. Dashed lines denote the average refractions if a spectacle is worn with a positive radial refractive gradient, generating a power addition of 2 D at 45° (discussed in text). A color version of this figure is available online at www.optvissci.com.

vertical meridian measured objectively with our instrument) assigned to each of the four models. A one way analysis of variance revealed no statistically significant differences ($p > 0.10$) in the central refraction among the four groups. This is likely because of the distribution of the foveal refractive values of our population (most of them were clustered in the proximity of 0 refractive error; mean, −0.3 D; standard deviation, 0.9 D) and also because of the relatively small number of subjects for performing this kind of study (a higher number of subjects equally distributed according to the central refractive error would be required).

DISCUSSION

Why Such a Large Variability of Peripheral Refraction Profiles?

The large variability of the relative peripheral refractions in subjects with low refractive errors is unexpected. If emmetropization acts locally in the retina, one would expect that, over time, refractive state is adjusted all over the visual field. There are several speculations possible why this did not happen:

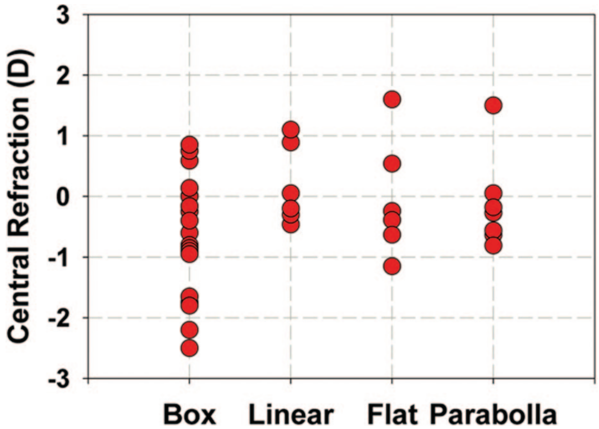

FIGURE 4.
Central refraction of the 43 subjects participating in the study clustered according to the four different models of peripheral refraction profiles proposed in this work. A color version of this figure is available online at www.optvissci.com.

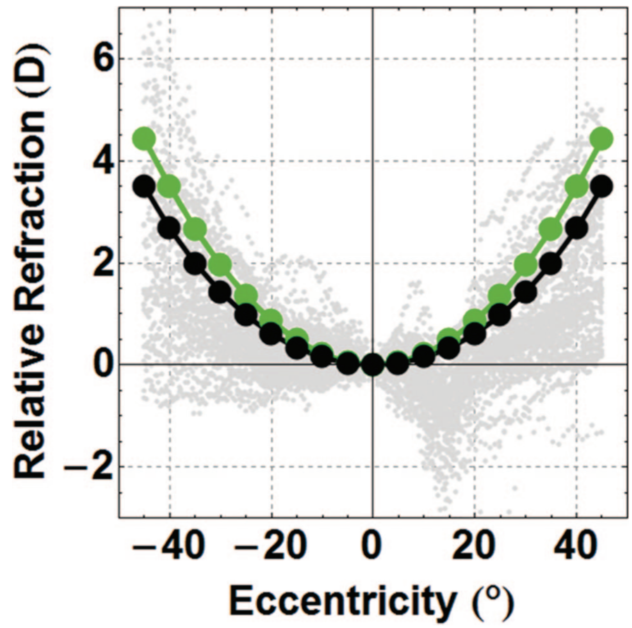

FIGURE 5.
Filled circles show the refractive error along the vertical pupil meridian as a function of the horizontal eccentricity angle as predicted from two different schematic eye models (data in green and black correspond, respectively, to the Escudero-Navarro eye model and to the Liou-Brennan eye model). On the background (light gray dots), the data from the subjects participating in this study is shown. A color version of this figure is available online at www.optvissci.com.

(1) every subject may have different requirements for the peripheral refraction profile, because of differences in accommodation patterns, or differences in peripheral spatial resolution or spatial processing in the retina; however, this does not seem very likely; (2) the peripheral refraction profile is random because of the large depth of focus. This is also not very likely because it has been shown that local corrections of peripheral refractive errors can improve visual acuity[20]; (3) the interactions of peripheral and central refractions is different in different subjects, but the mechanism is not understood—this is difficult to prove; (4) the pattern of higher order aberrations in cornea and lens (not measured in the present study) is predetermined in each subject, perhaps randomly or by genetics, and generates a specific individual refraction profile that represents the best match of image plane and retinal plane. This is also not a good explanation because the wavefront errors from higher order aberrations are small compared with the variability observed here (except perhaps for astigmatism); and (5) the setpoints of emmetropization may be different in different subjects, generating different peripheral refraction profiles that are necessary to approach these setpoints.[21] However, this issue would require long-term studies.

All these considerations do not rule out the possibility that artificially generated peripheral refractive errors may be a way to manipulate foveal refractive development. However, given the high variability of relative peripheral refractions, the amounts of peripheral myopia required to control foveal myopia development needs more detailed studies. A uniform lens design may not be successful, and this may perhaps be an explanation for the limited success of current clinical trials.[10] Customized lens designs, according to the individual peripheral refractive profiles might enhance the effects of such lenses. However, it is still uncertain whether the same variability presented in our population of nearly emmetropic subjects exists in myopic eyes. This might also influence the design of potential spectacles to control myopia and reflects the need for further research on the topic.

Why are Subjects Often More Hyperopic in the Periphery?

It is striking that the subjects tended to become more relatively hyperopic in the vertical meridian in the horizontal peripheral visual field. Compared with the classical data of Rempt et al.,[13] our measurements would correspond to the data they plotted as dots in Fig. 3 of their article in which measurements were performed with a subjective assessment technique every 20° in the horizontal field. They showed that the vertical meridian had mostly hyperopic refractions in the periphery. To confirm that relative hyperopia should be expected in the vertical meridian, we performed ray-tracing simulations in two different eye models (the Liou-Brennan and Escudero-Navarro schematic eye model).[22,23] Results are shown in Fig. 5. The Escudero-Navarro eye model (black filled circles, Fig. 5) is essentially the same as the Navarro model but incorporates a retinal surface of −12 mm of radii of curvature useful to study off-axis optical quality of an average eye.[24] The lens refractive index was constant, as opposed to the Liou-Brennan eye model (green filled circles, Fig. 5) that incorporates a refractive gradient index for the crystalline lens. The calculations were performed using ray-tracing software (ZEMAX Development Corporation, Bellevue, WA). The predictions from the Navarro eye model were slightly more myopic compared with the Liou-Brennan eye model, probably induced by the lack of a gradient index structure in the crystalline lens of the first model.

Predicted refractions were also slightly more hyperopic than the mean refractions of the population. However, it should be noted that a slight variation in the shape of the retina would substantially change the values of peripheral refractive errors. The eye models assume a perfectly spherical retinal shape, which may not reflect the reality.[25,26]

Nevertheless, a limitation of this work comes from the fact that only the vertical meridian is refracted. The scope of our results is strictly restricted to this meridian although, in terms of spherical equivalent, the validity of the classification would depend on the interaction of peripheral astigmatism and sphere. This kind of study can only be approached with an improved version of our instrument. To simply replicate the study of Rempt et al.,[13] measuring vertical and horizontal meridians, the operator would have to rotate manually the illumination LEDs of the photoretinoscope after taking one vertical meridian scan. In addition, the analysis should take into account pupil ellipticity because the change in the dimensions of the horizontal pupil meridian would quickly vary with eccentricity. In practice, this approach would require double time for each measurement. However, only two orthogonal refractions would be obtained, requiring manual intervention from the operator. It would be more ambitious to use an automated rotating photoretinoscope (as in the PowerRefractor commercial instrument) synchronized with the mirror movement. However, the synchronization of the two stepping motors and the LEDs rotation might be a demanding task that would surely slow down the scanning time. A sequential but automatic approach (different meridians refracted each in different scans, one after the other) might provide a good balance between scanning time and complexity.

Finally, it should be noted that the measurements with the scanning photorefractor are representative: a recent comparison of the photorefractor to a custom-built scanning Hartmann-Shack wavefront sensor provided similar values for the peripheral refraction in the vertical pupil meridian.[27] However, the lack of a gold standard instrument is obvious.

In conclusion, the most common refraction profile in the vertical pupil meridian in this study sample can be best fitted by the "box model," with little change over the $\pm 20°$ of the central field, followed by a linear increase of hyperopia further in the periphery. These results might help to improve, optimize, or customize future lens designs that are developed to slow down the progression of myopia.

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