The Spatially Resolved Refractometer

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ABSTRACT

PURPOSE: To investigate factors controlling the aberrations of the eye, including accommodation, wavelength, and the apodization of the optics of the eye by cone directional selectivity.

METHODS: We constructed a new implementation of the Spatially Resolved Refractometer (SRR). This is an instrument, based on the Scheiner principle, that allows the rapid psychophysical measurement of the complete wavefront aberrations of the eye. We have investigated both the reproducibility of the measurements, and the effect of static accommodation and wavelength on the wavefront aberrations of the eye. In addition we combined the wave front aberrations with cone photoreceptor directionality to compute the modulation transfer function of the eye, at the retinal level.

RESULTS: The SRR measurements were rapid (4 minutes per measurements, 12 minutes per patient) and reproducible. There are significant changes in wavefront quality with accommodation, with optimal image quality near the resting point of accommodation. Image quality for polychromatic (white) light is strongly affected by both longitudinal and transverse chromatic aberration. Finally, we find that incorporating the effects of cone directionality into the calculation of image quality can increase image quality by up to 50%.

CONCLUSION: Calculation of a simple "optimal surgical shape" for wave-front guided refractive surgery will depend on improved understanding of the interplay between the biological and physical properties of the eye. [*J Refract Surg* 2000;16: S566-S569]

The ability of the eye to form an image on the retina depends on the quality of the optics of the eye. If the optics of the eye are poor, a low quality image is formed on the retina and the image is blurred. If the optics are relatively good, a sharp image is formed on the retina. The simplest forms of image blur arise from the errors in the refractive state of the eye. Images are simply out of focus, and these out of focus images can be partially corrected by the use of corrective lenses combining spherical and astigmatic corrections. However, even if the sphere and astigmatism are perfectly corrected, then retinal images are still blurred more than predicted by diffraction from the edges of the pupil. This blur arises from higher orders of imperfections in the optical properties of the eye, different regions of the pupil direct light to different places on the retina, even when the eye is optimally corrected with glasses or contact lenses. The total image forming ability of the eye (ignoring scatter) can be described mathematically by the eye's pupil function. This pupil function has two components, an intensity apodization function, and a phase function, which is commonly called the wavefront aberration of the eye. The wavefront aberrations of the eye represent the angular deviation of a ray of light from ideal as it passes through the optics of the eye. An ideal optical system would have a uniform wavefront aberration, that is, all values would be equal. The most familiar form for the apodization function is the pupil size. The image on the retina depends on the size of the pupil. For small pupils, refractive errors are not very important, because the wavefront aberration of normal eyes does not vary rapidly across the pupil, but diffraction from the edges of the pupil are important. At the end of the current paper we describe how the cone photoreceptors also contribute to the apodization of the eye, but for the majority of the paper we will be discussing the wavefront aberrations.

In principle the wavefront aberrations of the eye can be measured by passing the image of a light source through each point in the pupil and determining where that ray strikes the retina. In a simplified form this is the technique described by Scheiner to measure the refractive error of the eye. We use a more complicated form of a Scheiner optometer, the Spatially Resolved Refractometer[1-3] to measure the deviation of a ray of light for 35 different entry locations within the eye's pupil. The current paper describes an implementation of the spatially resolved refractometer and gives sample results.

METHODS

The principles of the apparatus have been described in detail[1] previously. In our current

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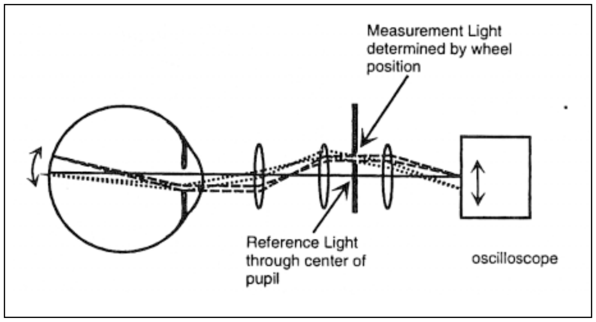

Figure 1. Example of how the spatially resolved refractometer (SRR) varies the angle of light impinging on the eye, without changing the location.

implementation the gimballed mirror described in that publication has been replaced with an oscilloscope screen. Briefly, the apparatus works by collecting light emitted from an illuminated point on an oscilloscope. The light is passed through a wheel mounted on a stepper motor. This wheel is optically conjugate to the eye's pupil, and the wheel has a series of 1 mm diameter precision drilled holes. By rotating the stepper motor to a series of preset positions, the holes are scanned across the pupil in 1 mm steps. Thus, the subject sees the illuminated point on the oscilloscope through each point in the pupil. If the eye had no aberrations, then every point on the pupil would project to the same point on the retina. The eye does have aberrations however, so the position of the oscilloscope point on the retina changes for each pupil entry position. By moving the oscilloscope point with a joystick, the retinal location is moved (Fig 1). If it is moved so it aligns visually with a reference mark (the image of a cross provided by another optical channel), then the aberrations for that location in the pupil can be cancelled (Fig 1). The angle required to null the aberrations at each pupil position represents the slope of the wavefront at that location. Since the task for the subject is simply to use a joystick to align a spot (viewed in random order, one at a time through each pupil location) to a cross (always viewed through the center of the pupil), it is extremely simple and fast. A single run takes about 4 minutes, and we generally collect three separate runs, for a total measurement time of 12 to 15 minutes. We then use a standard fitting procedure[4,5] to fit the slope measurements to a set of Zernike polynomials.[6,7] The resulting Zernike expansion is an estimate of the wave-front height. The advantages of the Zernike polynomials for this purpose have been discussed elsewhere.[6-11]

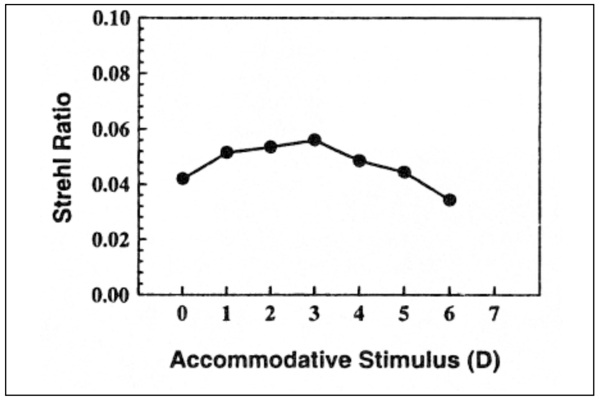

Figure 2. The average Strehl ration (6 s's) as a function of the accommodative stimulus. Data are from He et al, 1999. Most subjects have the best optical quality near the resting point of accommodation.

RESULTS

Reproducibility

Overall reproducibility is good.[1] We find that subjects can reliably measure ray aberrations with a standard error of the mean of .27 milliradians, which is equal to the ray deviation produced by 0.09 diopters (D) of blur at the edge of a 6 mm pupil. This is about the minimum resolvable blur for the human eye, providing a good match between the measurements and the visual capacity of the subjects. We also find that the results are stable over a time spans of months.

Changes in Wavefront With Static Accommodation

We have used the SRR to measure the change in the wavefront with static accommodation.[12] We find that there are systematic changes that occur in the wavefront quality of the eye with accommodation (Fig 2). In general subjects tend to have the lowest wavefront aberration when they are accommodating about 1 to 2 D in from their far point.

Changes in the Wavefront With Mydriatics

We have also made a series of measurements of the wavefront aberrations of the eye under various pharmacological states. In general there are small but consistent changes in the wavefront aberrations of the eye when pharmaceutical agents are applied. These differences are consistent and varied between types of agent. An example is shown in reference #1.

Effect of Wavelength

Up to this point we have talked about the aberrations that occur for monochromatic light. However, the largest aberrations in the eye are actually those that occur with polychromatic (white) light. The polychromatic aberrations occur because the eye does not have an identical index of refraction for all wavelengths. This causes changes in both the refractive power of the eye with wavelength, and changes in the magnification of images with wavelength. Almost all studies agree that the refractive power of the eye varies by about two diopters across the visible spectrum.[13-16] As a result, if the eye is focused on an image in the green region of the spectrum, shorter wavelengths are considerably out of focus. In addition to this difference in refractive power, there is also a difference in where the images at different wavelengths fall on the retina. This occurs because the fovea of the eye is not on the optical axis of the eye, and as a result, the magnification changes that occur with wavelength, result in wavelength dependent displacements. This change in the position of an image is commonly called the transverse chromatic aberration (TCA). TCA varies from subject to subject.[14] In addition the actual perceived TCA varies considerably whether one accounts for the influence of the cones (the Stiles-Crawford effect[17]) or not.[14]

Role of Photoreceptors

The Stiles-Crawford Effect also plays an important role in determining the optical quality of the eye for monochromatic aberrations. We mentioned that the pupil function has two components, the phase component, which is represented by the wavefront aberrations, and an intensity component. Most analyses have simply used the entire pupil. However, the differential sensitivity of the cones to light from different points in the pupil can have an important influence on the aberrations of the eye.[18,19] Recently we have shown that when the actual wavefront aberrations and the cone directionality are measured[20] in the same subjects, the cones can improve the retinal image quality.[21] Figure 3 shows results for one subject.

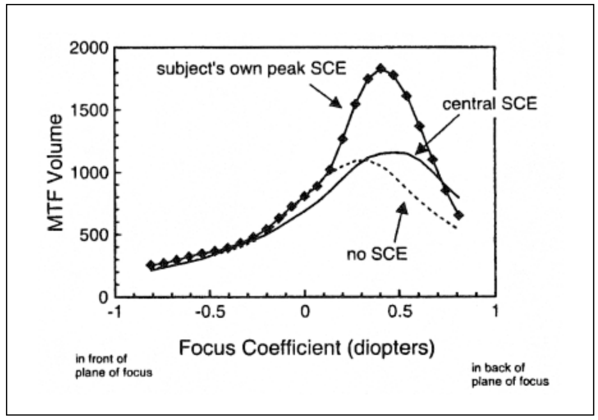

Figure 3. The change in the volume of the two-dimensional modulation transfer function (MTF) with the addition of the cone directionality. The dashed line shows the whole pupil (6 mm) MTF volume for various positions around the small pupil focus. The addition of a central Stiles-Crawford Effect (SCE) improves the imaging for hyperopic defocus (solid line). Placing the Stiles-Crawford peak at this subject's own optimal location greatly increases the image quality (solid lines plus symbols).

DISCUSSION

The current version of the SRR has been quite valuable for our basic investigations of the imaging properties of the eye. We have been able to test individuals ranging in age from 20 to over 60 years of age. Other researchers have successfully applied the device to both pediatric (at the New England College of Optometry[22]) and clinical (at the Emory Vision Correction center[23]) populations. The current system does have some limitations, mainly in that it has three separate optical channels that require very careful alignment. However it is possible to further simplify the system.[24]

Our work has identified a number of factors which may affect the ability of wavefront guided refractive surgery to improve vision. We have shown that in young observers accommodation is an important factor. Wavefront aberrations are at a minimum at the resting point of accommodation, and this needs to be factored into the surgical decisions. We have also shown that chromatic aberrations are very important, and in some observers transverse chromatic aberration can be both large, and change dynamically with pupil size. Finally, the pharmacological state of the pupil is important. Although we have published results for the effects of mild mydriatics[1], we have also observed that other cyclopelegic drugs also alter the wavefront aberrations. Although these pharmacological effects were not particularly large in any members of our small population, they do require better understanding of the causes before we can properly talk about eliminating wavefront aberrations.

Finally, there are also important issues introduced by the apodization of the pupil by the cone photoreceptors. We have shown[21] that the actual position within the pupil towards which the photoreceptors are oriented can play an important role in the image quality of the eye. Since there is considerable individual variation in photoreceptor alignment in the normal population[20,25], this factor can be important for some individuals.

The spatially resolved refractometer has been shown to be a reliable, reproducible technique for measuring the wavefront aberrations of the human eye. Working with Navarro and colleagues[26] we find that the spatially resolved refractometer gives essentially identical estimates of the wavefront aberrations to measurements in the same eye using either a Hartmann-Shack wavefront sensor or a laser ray tracing technique.[27] It has both strengths and weaknesses related to other techniques. For instance, because it uses the subject's own visual system to determine the wavefront, it is truly a single pass measurement and makes no assumptions about the reflecting layers in the eye. As a result, the subjective technique may give a better estimate of the true subjective higher order refraction. The SRR technique is also a sequential technique, which means that the patient's pupil can be sampled in a way that is more optimal for measuring aberrations. Finally, the SRR allows us to have the patient confirm the adequacy of the measurements by "replaying" each pupil entry position, and asking the patient to confirm that all measurements project to the same retinal location. More significantly, the Zernike fit to the data could be used to generate the replayed points, allowing the patient to quickly assess whether the least squares fit to the data adequately described their own aberrations. The subjective approach also has the limitation that it is slower than the optical measurements and requires a cooperative subject. We can currently obtain a full measurement in three to four minutes, and there is room to reduce this further. However techniques such as the Hartmann-Shack can be performed in less than a second.

Using the spatially resolved refractometer, we have been able to directly measure all the major aberrations of the eye at the fovea, that is, the monochromatic wavefront aberrations, as well as both the longitudinal and transverse chromatic aberration. Initial patient work indicates that the technique can be readily applied in a clinical setting as well.

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