Design and validation of a scanning Shack Hartmann aberrometer for measurements of the eye over a wide field of view

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Abstract: Peripheral vision and off-axis aberrations not only play an important role in daily visual tasks but may also influence eye growth and refractive development. Thus it is important to measure off-axis wavefront aberrations of human eyes objectively. To achieve efficient measurement, we incorporated a double-pass scanning system with a Shack Hartmann wavefront sensor (SHWS) to develop a scanning Shack Hartmann aberrometer (SSHA). The prototype SSHA successfully measured the off-axis wavefront aberrations over +/- 15 degree visual field within 7 seconds. In two validation experiments with a wide angle model eye, it measured change in defocus aberration accurately (<0.02 µm, 4mm pupil) and precisely (<0.03 µm, 4mm pupil). A preliminary experiment with a human subject suggests its feasibility in clinical applications.

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Peripheral vision plays an indispensable role in daily visual tasks such as driving [1, 2] and locomotion [3]. Although visual acuity for spatial resolution tasks declines rapidly in the peripheral visual field, visual acuity for detecting spatial patterns and objects declines only slightly in the periphery [4, 5]. Spatial acuity for detecting peripheral patterns is optically limited since it can be enhanced by improving peripheral optical quality [6, 7]. Moreover, clinical interest in peripheral vision has increased recently because peripheral optical aberrations (especially defocus) might be important for emmetropization and myopia development [8–12]. Taken together, these studies demonstrate the importance of peripheral vision has increased recently because peripheral optical aberrations (especially defocus) might be important for emmetropization and myopia development [8–12]. Taken together, these studies demonstrate the importance of peripheral vision.
of the eye to measure the aberrations on the second pass through the eye’s optical system. The double-pass apparatus that incorporates the SHWS as a sub-system is called a SH aberrometer. The typical SH aberrometer is designed to measure along the eye’s primary line of sight, and therefore is optimized for measuring central vision.

More recently, the SH aberrometer was adapted by Atchison [14, 15] and Lunstrom [16] to measure off-axis wavefront aberrations associated with peripheral vision. In their studies, subjects were directed to fixate a target displaced from the aberrometer’s measurement axis. With eccentric fixation, the SH axis becomes oblique to the primary (foveal) line-of-sight (LoS) thus enabling measurements of the off-axis wavefront aberrations along a secondary LoS [14, 17]. Obtaining a series of measurements along multiple LoS to survey a large area of the visual field requires the subject to fixate a sequence of targets. This is a time-consuming process that may inadvertently introduce measurement variability due to temporal instability of the eye [18]. Thus there is a need for an expedient method to measure the off-axis wavefront aberrations of the eye in a more efficient manner.

To meet this need, we have combined the SH aberrometer with a scanning system to sequentially measure the off-axis wavefront aberrations across the central 30° visual field. This system is named as scanning Shack Hartmann aberrometer (SSHA). With our system, the eye fixates a single target while the entering probe beam rotates about the center of the entrance pupil to place the laser beacon in a sequence of locations in the peripheral retina. Light reflected from the eye is de-scanned by the same system for measurement by a fixed SHWS. The resulting increase of efficiency enables measurement of a significant field of view in a few seconds. The purpose of this paper is to report the design and validation of the instrument and technique.

The basic Shack-Hartmann wavefront aberrometer has been extensively validated for on-axis use [19–21]. Those validation studies have shown that test cases involving lower-order aberrations (e.g. defocus and prism) are sufficient to demonstrate that the instrument correctly measures wavefront slope and therefore the instrument is valid for measuring ocular wavefront aberrations in general. Validating a wide-field aberrometer introduces a more challenging problem of verifying the requirement for tight alignment of the eye to the instrument. Unlike axial aberrometry, a sequence off-axis wavefront aberration measurement is very sensitive to misalignment of the test eye. Sensitivity to misalignment is a common problem in optical testing that typically requires an indirect approach to validation. Accordingly, we report the results of two experiments using differential defocus plus an analysis of the positional stability of the data image during the scanning operation.

2. Methods

2.1 Instrument design

The schematic diagram of the apparatus is shown in Fig. 1. To incorporate the scanning mirrors with SHWS, the lenslet plane of SHWS and the scanning axes of the X-Y mirrors are co-aligned optically onto planes conjugated with the entrance pupil (EP) of the tested eye [22]. This is done using three relay telescopes DPS1-2, DPS3-4, and L5-6. In the incoming path, the scanning axes of X-Y mirrors form a scanning center via DPS3-4. This scanning center is further conjugated with the EP center of the eye via DPS1-2. When a spatially filtered and collimated narrow NIR laser beam (850nm, 1mm in diameter) is introduced into the system via a beam splitter (BS1), the beam intersects with the scanning axes of X-Y mirrors and entrance pupil center of the eye. As the X-Y scanning mirrors rotate, the beam rotates about a pivot point lying at the center of the eye’s EP, thereby injecting the probe beam along different LoS specified in angular dimensions in object space (Fig. 2). In the eye’s image space, this beam scans across the retina and forms a sequence of retinal spots when the scan pauses briefly (50 milliseconds) to acquire a wavefront measurement. These spots serve as beacons that radiate light for a second pass through the eye’s pupil. Thus, for each position
of the scanning mirrors, a wavefront originating from the retinal spot is modulated by the ocular structures (e.g., lens and cornea) and emerges at EP as shown by the outgoing path in Fig. 1. As the emerging wavefront propagates back through the system, it is de-scanned by the X-Y scanning mirrors and then sampled by an array of 0.3-mm-diameter micro-lenses of focal length 9 mm in the SHWS.

![Fig. 1. Scanning Shack Hartmann aberrometer (SSHA) apparatus. BS1-3, beam splitters; DPS1-4, Double pass scanning lenses; L5-9, Lenses; SHWS, Shack Hartmann Wavefront sensor; Aperture A1, limiting aperture.](image1)

![Fig. 2. Scanning pattern of SSHA apparatus. As the scanning mirrors rotate, the mirrors direct the beam along different LoS in sequence. Each data point in the figure indicates a particular LoS in test eyes' object space. The associated numbers represent the sequential order. It took 8 seconds for SSHA to scan the whole visual field.](image2)

The critical element for achieving the design goals specified above, in both incoming and outgoing paths, is the custom-designed, three-element, double-pass scanning-lens (DPS1-4 in Fig. 1). In the incoming direction, the relay telescope DPS3-4 conjugates the rotation axes of X & Y scanning mirrors and forms a compact scanning center for field angles up to 15° in all meridians. This scanning center is further conjugated to the EP center of the eye over the 15° field via telescope DPS 1-2 as shown in Fig. 3(a). The DPS lenses [22] were designed so that the mirrors could scan an incoming, narrow, collimated laser beam over the full 15° field yet the beam enters the eye near the EP center. Our DPS design goal was to ensure this pupil...
entry point was no more than 55µm from the pupil center. In the reverse direction (outgoing path in Fig. 3(b)), the off-axis wavefronts propagate through different parts of the two telescopes as the LoS changes. This could cause variation in the instrumental aberrations that would complicate the interpretation of aberration measurements. Therefore, our DPS design balanced the inherent aberrations of the individual lenses so that the telescope achieved diffraction limited performance along all paths of interest for a 6mm EP. To validate our DPS design when incorporated in the aberrometer, we used Zemax [23] to simulate the complete system including a wide angle schematic eye [24]. According to the simulation result, the aberrometer measures the off-axis wavefront aberrations of the model eye accurately over the designed visual field (+/− 15 deg).

Fig. 3. The relay scanning pair. (a) Incoming direction, the scanning relay pair DPS 1-2 focus the incoming narrow laser beams to the center of entrance pupil (EP) from the scanning center; (b) In the outgoing direction, the DPS design minimizes and balance the instrumental aberration along different paths.

In addition to hardware design, we developed a software package to process the raw data from the SHWS. As the wavefront encounters the lenslet array in SHWS, it is subdivided into many small beams, each of which forms spot image on the CCD sensor. The relative position of the spot centroid to its reference location is proportional to the local gradient of the detected wavefront by a factor of lenslet focal length [13, 25]. Since the off-axis wavefronts propagate along different paths through the DPS telescopes as the X-Y mirrors scan across the visual field, it was necessary to acquire a series of reference images to compensate for the small aberrations associated with each LoS. By matching the centroid image sampled along a particular LoS with the corresponding reference image, the local gradients can be readily calculated. In general, these gradients are defined over an elliptical pupil because the measurement axis for oblique LoS intersects the plane of the iris aperture obliquely. Reconstructing the wavefront from measured gradients within an ellipse is non-trivial. To solve this problem, we have developed several wavefront reconstruction methods based on Zernike polynomials and Fourier series [26]. In the present study we used the direct method and scaling method described previously [14, 16, 25, 26].

Relay telescope L7-8 conjugates the EP plane and the bulls-eye alignment ring with the image plane of a small f/# pupil camera, which ensures the eye is positioned correctly in three dimensions. Lens L9 introduces a fixation target consisting of one central and several peripheral fixation targets, which allows subjects to fixate obliquely as described in previous studies [14–16]. By combining peripheral fixation targets with a scanning aberrometer, the accessible field of view goes well beyond the central 30°. Relay telescope (L5-6) anterior to the SHWS includes a Badal system [27, 28] (not shown in Fig. 1) that removes the bulk of the defocus before the wavefront enters the SHWS in order to reserve the dynamic range of the SHWS for measuring astigmatism and higher-order aberrations. Aperture A1 is conjugated with the retina and is kept as small as possible to attenuate the corneal reflection while letting the wavefront originating from the retinal spot to pass through to the SHWS. The laser safety
issue was addressed by ensuring that the radiant flux in the pupil plane was under 50 micro-watts, which is far below the recommended limits to retinal exposure [29].

2.2 Instrument validation on a model eye

A physical wide angle model eye was used as a test case for instrument validation. The model eye consisted of a 4mm-pupil aperture (EP), a doublet lens (LAO 787 doublet from Melles Griot Inc.), and an extended plane retina. The optical axis of the model eye was aligned coincident with the measurement axis of the aberrometer in the 0° scanning position. The instrument was aligned such that the EP of the model eye was conjugate to the scanning center and to the lenslet array in the SHWS. The radiant flux at the pupil plane was 22 micro-watts. Wavefront measurements were obtained along multiple LoS over +/-15 degree 2-dimensional visual field sequentially (Fig. 2). We designed two experiments to test accuracy and precision by verifying the SSHA’s ability to detect changes in defocus. In the first experiment, a well-calibrated Badal system inserted between lenses L5 and L6 was used to add three levels of $Z_0$ defocus (0.64µm, 1.28µm, and 1.92µm) to the aberrations of the model eye. In the second experiment, the retina of the model eye was axially translated (+1 mm, +5mm) from an emmetropic to a myopic state to introduce two levels of $Z_0$ defocus over the whole visual field of the model eye. The measured defocus changes from the two experiments were then compared with theoretical predictions.

2.3 Instrument evaluation with human eyes

Besides validating with a wide angle model eye, we also tested a human subject since the light efficiency and scattering properties of the wide angle model eye are different from human eyes. The experimental protocol was approved by Indiana University Institutional Review Board and complied with the requirements of the Declaration of Helsinki. An emmetropic subject with healthy normal eyes was tested without cycloplegic or other pharmacological agents. An on-axis fixation target was set beyond the eye’s far point to encourage relaxation of accommodation. A dental impression was used to stabilize the subject’s head position. With the aid of the pupil camera, bulls-eye target and translation stage, the entrance pupil of the eye was aligned to the instrument. The radiant flux at the cornea was 42 micro-watts. The full sequence of 37 off-axis aberration measurements was repeated five times with realignment of eye to instrument between each measurement. To represent the wavefront deviation among the five measurements, the point-by-point wavefront difference between the individual trials and the mean wavefront over 5 trials was calculated. The root-mean-square error of such deviations (RMSDev) in Eq. (1) [30] provides a metric of the repeatability of the five measurements.

\[
RMSDev = \frac{1}{5} \sum_{i=1}^{5} \left( \frac{1}{N} \sum_{k=1}^{N} (W_i(x_k, y_k) - W_{\text{mean}}(x_k, y_k))^2 \right)
\]

where $W_i$ is the i’th trial wavefront, $W_{\text{mean}}$ is the mean wavefront over 5 trials, $(x_k, y_k)$ is the k’th sampling point of the wavefront maps, and $N$ is the total number of sampling points within the elliptical pupil.

3. Results

3.1 Instrument validation on a model eye

For the first experiment, the changes in measured wavefront defocus produced by known amounts of defocus introduced by the Badal system are shown in Fig. 4(a). Strong backward scattering of light from the probe beam prevented measurements for 0° field angle and along the horizontal meridian. For the remaining 30 field positions, the mean defocus change was 0.66µm, 1.30 µm, and 1.92 µm for Badal defocus levels of 0.64µm, 1.28µm, and 1.92µm.
Thus the inaccuracy for measuring change in aberrations is 0.02 µm or less. Measurement precision, as specified by the standard deviations of the measured defocus change, was 0.02 µm, 0.03 µm, and 0.03 µm respectively. These precision values are larger than those reported for a commercial, non-scanning aberrometer [28] but are of the same order of magnitude as the variability in human eye measurements taken under comparable conditions [18].

Similarly for the second experiment, the changes in measured defocus produced by translating the model retina axially are compared with the ray-tracing prediction in Fig. 4(b). According to the prediction, translating the retina axially at +1 mm and +5 mm from its emmetropic position introduces approximately 0.23 µm and 0.85 µm defocus along every LoS within +/−15 degree visual field. For both defocus levels (after excluding any LoS with scattering artifacts), the measurements are accurate to within 0.01 µm and precision is better than and 0.03 µm.

![Fig. 4. Defocus measurements of SSHA along all LoS at various field angles. Horizontal axis indicates the scanning sequence of LoS; vertical axis indicates the magnitude of defocus terms (Z20) over 4 mm pupil. (a) Comparison of the defocus measurements (black dot) with the defocus introduced by the Badal lens (horizontal dash line) along multiple LoS. The masked LoS are those suffered from backward scattering. (b) Comparison of the defocus measurements (black dot) with the defocus introduced by retinal translation (horizontal dashed line) along multiple LoS. The masked LoS are those suffered from backward scattering.](image)

3.2 Instrument evaluation with human eyes

For each scan, it took less than 8 seconds to measure the eye’s wavefront aberrations along 37 LoS over the central 30° visual field. Due to the strong backward reflection from the system and cornea, the SSHA failed to measure the wavefront aberrations along the LoS along the horizontal visual field. The mean wavefront maps of the five measurements are shown over the actual elliptical entrance pupils (5 mm major diameter) in Fig. 5. The repeatability was also tracked across the five measurements along every LoS. The RMSDev value computed over the elliptical pupil is annotated above the corresponding wavefront map in Fig. 5. When excluding the artifact-prone horizontal LoS, the mean RMSDev along all other LoS is 0.14 µm.
4. Discussion

The scanning aberrometer designed and implemented for this study efficiently measured the off-axis wavefront aberrations of human eyes along 37 different lines-of-sight in 8 seconds. Measurements of an induced change in focus of a model eye (Fig. 4) indicated the instrument has good precision ($\leq 0.03\mu$m, 4mm pupil) and accuracy ($\leq 0.02\mu$m, 4mm pupil). These values are equivalent to less than 0.03 diopters of defocus which is neither clinically nor functionally significant. Furthermore, in the evaluation experiment with a human eye, the mean RMSDev of the five repetitive measurements across the non-horizontal LoS is 0.14 $\mu$m. This low value suggests that SSHA is a feasible and reliable instrument to be applied in clinical research and diagnosis.

We validated our instrument using a differential-focus experimental-design because it excludes other potential sources of error such as misalignment of the test eye to the instrument. The mean and standard deviation of the differential measurements across multiple LoS can be regarded as the accuracy and precision of the aberrometer itself. Although it was convenient to evaluate the instrument using defocus, the results may be generalized to other aberration modes since wavefront slope is measured with the same accuracy and precision at every point in the pupil. Besides validating the SSHA with the defocus wavefront aberration of the model eye, we also measured the centers of the SH data images from different frames. Since the entrance pupil center of the test eye is conjugated with the rotational center of the scanning mirrors and the SH lenslet plane, the wavefronts emerging at the entrance pupil along different LoS should be sampled at the same location on the lenslet plane as the scanning mirrors (X&Y) scan. Correspondingly, the center of the SH centroid images of
different frames should be fixed at the same location on the camera CCD plane. With the well-aligned model eye, we found that this center is very stable as the mirrors scan across the whole designed visual field (±15 degrees, excluding the horizontal LoS): the standard deviation of the center drift of the SH centroid images was 48 microns (horizontal) and 55 microns (vertical) on the CCD plane.

Back scatter of light from the laser probe beam from multiple surfaces (24 surfaces) in the multi-element scanning lenses (DPS 1-4 in Fig. 1) can enter the SHWS and corrupt measurements. Particularly when the system directs the probe beam along the horizontal LoS, the vertical scanning mirror (X) aims the laser beam along the optical axis of the first scanning relay pair (DPS 3-4). Since the refractive surfaces of these lenses are normal to the incoming laser, their reflectance introduces strong scattering, which contaminates the measurements along the horizontal LoS. We attempted to mitigate this effect by placing aperture A1 at the foci plane between the last relay pair (L5-6). Although this aperture reduces the backward scattering significantly, it also has the undesirable effect of limiting dynamic range of the SHWS. Polarization techniques can be used to reduce backscatter, but we have not yet implemented that idea. A software innovation that iteratively finds the centroids of the SHWS spots based on the compactness, peak and mean brightness of the spots also excludes spots contaminated by backward scattering. The exclusion of a few contaminated spots is tolerable for the modal wavefront reconstruction methods [26], provided there are enough measured gradients to perform a satisfactory least-squares fit. When measuring the model eye, for example, a reasonable wavefront estimation was possible even for those LoS that suffered from moderate backward scattering. In the presence of strong backward scattering, wavefront reconstruction fails which explains the absence of wavefront measurement along certain LoS (Fig. 5).

Performance of the scanning aberrometer is also limited by scanning speed, the accessible visual field, and pupil size. For example, it takes 8 seconds for the scanning mirrors X&Y to cover the central 30° visual field using the scanning pattern in Fig. 2. This duration is limited by the time required for the mirrors to accelerate, decelerate, and stabilize. High speed scanning is an advantage when measuring subjects with unstable tear films. Some individuals cannot refrain from blinking for 8 seconds, and even for those who can suppress blinking during the scan the tear film changes rapidly between blinks [31, 32]. One solution is to break the scan into two or more sequences, but faster scanning mirrors would be a better option. The range of visual field locations accessible in one scan is limited by the size of the DPS lenses. As the f-number of these lenses is already small (f/1.8), it may be impractical to expect more than ±15 degrees of scanning angle for a single fixation target. Our approach to extending the accessible visual field is to change the eye’s fixation between scans. By overlapping the scanned areas, internal checks based on repeatability become possible. The dynamic range of the SHWS also limits the range of visual field that can be examined in one scan. The human eye has significant field curvature and oblique astigmatism that threaten to exceed the sensor’s dynamic range. Our design goal of ±15° was guided by theoretical analysis of the variation in aberrations of a wide angle schematic eye [24], which are within the dynamic range of the current SH lenslet array used in our instrument. Yet another limitation is imposed by the limited size of the beam splitter placed immediately in front of the subject’s eye (BS2 in Fig. 1). The largest pupil size our instrument can measure is 6 mm for emmetropic subjects.

Although this report focuses mainly on the hardware implementation of a scanning aberrometer, it is worth noting that the development of off-axis wavefront reconstruction over elliptical pupil is also an important aspect of system development. These wavefront reconstruction methods have been summarized elsewhere [26]. The choice of method for off-axis wavefront reconstruction and representation is application dependent. For example, the Fourier series based methods are generally more efficient computationally than the Zernike polynomial based methods. While for some clinical or scientific applications, the Zernike based method are preferred because the derived Zernike polynomials provide a succinct...
description of the system in terms that are easily understood, for other applications the best description of the data might be a model eye that reproduces the data [17]. Two Zernike-based methods are used in our system. For display and reporting, we used Lundstrom’s ‘direct method’ [16, 26]. It applies classical least-squares fitting of the derivatives of Zernike circle polynomials to gradient data over a circumscribed circular pupil, the radius of which equals the major radius of the elliptical pupil. The absence of gradient data in the region between the ellipse and the circle does not defeat the least-squares method because practical systems are typically over-determined. The obtained wavefront map is preferred for purposes of interpreting a given optical path length (OPL) map as a prescription for a correcting lens. However, for purpose of data management, we found it more convenient to map points in the elliptical entrance pupil to the circular physical pupil, which stretches the OPL map anisotropically as described by Atchison [25, 26]. The advantage of this stretching is that all the maps have a circular domain with the same diameter, which makes it easy to represent the wavefront with a conventional vector of Zernike aberration coefficients. In this way, data management is simplified, which is important for a system that generates a large amount of data quickly.

Our system incorporates dual scanning mirrors with a fixed SHWS to efficiently measure the off-axis wavefront aberrations of human eyes over a large field of view. In principal, other scanning system designs and sensing techniques could be used instead. For example, replacing our scanning lenses with reflective mirrors might reduce backward scattering and improve performance. Another improvement might be to incorporate other sensing techniques with larger dynamic range. Potential candidates might be laser ray tracing [33], double pass measurement [34], and Hartmann Moire wavefront sensor [35]. These techniques have the potential to grant the instrument much larger dynamic range for wavefront sensing as well as increased range of accessible visual field.

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