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Design and Validation of an Infrared Badal Optometer for Laser Speckle (IBOLS)

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Abstract

Purpose—To validate the design of an infrared wavefront aberrometer with a Badal optometer employing the principle of laser speckle generated by a spinning disk and infrared light. The instrument was designed for subjective meridional refraction in infrared light by human patients.

Methods—Validation employed a model eye with known refractive error determined with an objective infrared wavefront aberrometer. The model eye was used to produce a speckle pattern on an artificial retina with controlled amounts of ametropia introduced with auxiliary ophthalmic lenses. A human observer performed the psychophysical task of observing the speckle pattern (with the aid of a video camera sensitive to infrared radiation) formed on the artificial retina. Refraction was performed by adjusting the vergence of incident light with the Badal optometer to nullify the motion of laser speckle. Validation of the method was performed for different levels of spherical ametropia and for various configurations of an astigmatic model eye.

Results—Subjective measurements of meridional refractive error over the range $-4D$ to $+4D$ agreed with astigmatic refractive errors predicted by the power of the model eye in the meridian of motion of the spinning disk.

Conclusions—Use of a Badal optometer to control laser speckle is a valid method for determining subjective refractive error at infrared wavelengths. Such an instrument will be useful for comparing objective measures of refractive error obtained for the human eye with autorefractors and wavefront aberrometers that employ infrared radiation.

Keywords

objective refraction; subjective refraction; laser speckle optometer; aberrometer; instrument calibration

Despite technical advances in the design of autorefractors and wavefront aberrometers, the gold standard for prescribing spectacles and contact lenses remains the subjective refraction.^{1, 2} This is because there is often a discrepancy between objective determinations of refractive error and the definitive, subjective preferences of the patient. This discrepancy has been attributed to many variables, including accommodative status during the objective measurement^{3–6}, the difference in the retinal reference plane measured between the techniques,^{7, 8} the Stiles-Crawford effect^{9, 10} and noise in the objective technique.^{6, 11} However, promising new methods of objective refraction based on analysis of retinal image

quality have the potential to achieve improved levels of accuracy and precision that may supplant the subjective refraction in the future.²

To investigate the sources of discrepancy between subjective and objective refractions in the human eye it is important to devise and validate instrumentation that specifically controls for the above variables. To this end, a new instrument was built that combined a clinically available aberrometer based on Shack-Hartmann (SH) principles¹² with the implementation of an earlier described¹³ design of a subjective laser speckle optometer that also uses infrared radiation. By using nearly the same wavelengths for both measurements we avoid the uncertainties associated with ocular chromatic aberration that arise when converting measurements from infrared to visible wavelengths. This Combined Objective and Subjective Optometer (COSO, Wavefront Sciences Inc.) measures both objective and subjective refractive errors using equivalent wavelengths of light, along the same optical axis and in close temporal proximity. The purpose of this report is to describe an experimental validation of the instrument using a model eye with known optical characteristics.

DESIGN OF INSTRUMENTATION

The Wavefront Aberrometer

A second generation, Complete Ophthalmic Analysis System (COAS model G-200) was used to measure the refractive error of a model eye objectively. The COAS is a commercially available instrument (Wavefront Sciences, Inc) which uses the Shack-Hartmann (SH) technique to measure higher and lower order aberrations.¹² It has been validated separately elsewhere.¹⁴ Light scattered from the focused fundus image of a super-luminescent laser diode (835nm, wavelength spread about ± 15 nm at half maximum energy) acts as the point source ("fundus beacon") for the optical analysis system. A telescope relay system images the wavefront exiting from the eye onto a micro lenslet array with 210 microns effective lenslet pitch. This lenslet array images the fundus beacon into a multitude of spots formed on a CCD detector. Displacements of these spots from their expected, aberration-free locations allow calculation of the shape of the wavefront exiting the eye. The diameter and separation of each lenslet is such that the instrument samples the wavefront with a spatial resolution of 0.21mm in the pupil plane. For a 3mm diameter pupil approximately 160 spots are analyzed.

The alignment of the eye under examination is facilitated by a real-time display of the pupil image and by real time calculations of how the pupil is centered on the detector array (x and y coordinates of the pupil image center). A third camera shows the appearance of the fundus beacon and can be used to determine whether any reflections from other optical surfaces are likely to interfere with analysis.

Infrared Badal Optometer for Laser Speckle (IBOLS)

In the early 1960's it was observed that laser light reflected from a matte surface caused an interference pattern at the retina that was perceived by an observer as a speckle pattern.^{15, 16} The apparent motion of this speckle pattern was seen to accompany movement of the observer's head and could be correlated with the observer's ametropia.¹⁷ To exploit this phenomenon for clinical measurement of ametropia, the fixed matte surface was replaced by the surface of a rotating drum mounted on a gimbal that permitted measurements in different meridians.¹⁷ From these clinical beginnings, the rotating drum laser speckle optometer developed, which has been utilized in various forms in almost all subsequent laser refraction studies.^{17–25} As the subjective task for a laser speckle optometer is simple, requiring only that the observer report the direction of movement of the speckle pattern, applications

include measurement of subjective refractive error and also investigation of aspects of accommodation.²⁶

Two significant drawbacks of drum-based optometers, especially when a compact design is desired, are that (i) the so-called “plane of stationarity” (the surface that is optically conjugate to the retina when speckle motion ceases) is not actually a plane but is a curved surface, and (ii) the position of this curved surface lies behind the surface of the rotating drum at a distance that is dependent on the curvature of the drum.^{22, 25} This becomes a problem especially when a relatively large speckle field is being generated by a drum with a short radius of curvature such as may occur in a compact Badal optometer. The fact that the plane of stationarity is curved²⁷ means that a drum based laser speckle system can never provide an extended field of stationary speckles at the refractive end point. Because the field of speckles will not all be stationary at one time, observers using the system will be less certain of their settings and the results will have poorer repeatability. To allow for the instrument to maintain a compact size and to avoid the problems created by field curvature, we built a laser speckle optometer designed in which a flat rotating diffusive disc with a high IR transmittance was utilized to generate the laser speckle pattern (provisional patent withdrawn).²⁸

The laser speckle disc optometer that was built for IBOLS is similar in principle to a concept described by Ohzu.¹³ As illustrated in Figure 1, if a coherent point source (SOPS) is viewed through a small area (5mm diameter for this set up) near the rim of a slowly rotating diffuser plate (2.6 rpm) then moving speckle patterns are generated on the patient's retina. The apparent velocity of the speckles in the pattern is determined by the distance between the plane of stationarity and the plane of focus of the eye.²⁹ In a myopic eye the speckle pattern appears to move in the same direction as the moving screen; for hyperopic eyes the opposite direction of motion is observed. If the point source is adjusted axially until it is conjugate with the retinal plane, then the speckle will not appear to be moving in any consistent direction; rather it will appear to “boil” regardless of the velocity or axial location of the diffusing plate. The spherical refractive error of the eye is equal to the vergence of the light entering the eye when motion is nulled.

For the IBOLS design it was convenient to control the vergence of light entering the eye using the principle of a Badal optometer, as illustrated in Figure 2. The SOPS is located at a distance x from the first focal plane of the Badal lens ($L1$) and its image is located at distance x' from the second focal plane. Thus the vergence of light as it passes through the second focal plane is $V = 1/x'$. Combining this formula with Newton's relationship $xx' = ff'$ we have

$$V = \frac{1}{x'} = \frac{x}{ff'} = \frac{x}{f^2} \quad (1)$$

A relay telescope makes the second focal plane of the Badal lens optically conjugate to the eye's cornea so the vergence of light entering the eye is also V . The diffusing plate is positioned near the back focal plane of the Badal lens, but its exact location is not critical. In summary, the refractive error of the eye is equal to V when motion is nulled. Experimental verification of eqn. (1) for our instrument is described in a later section.

Combined Objective and Subjective Optometer (COSO) Instrument Design

The combined instrument (Figure 3; see Table 1 for details) uses a Badal optometer lens ($L1$, $f=75\text{mm}$) and a laser diode source (820nm) to generate a wavefront with vergence at the cornea that is proportional to the axial distance of the speckle optometer point source (SOPS) from the first focal point of the Badal lens ($L1$). The laser and a focusing lens ($L0$,

$f=100\text{mm}$) were placed on a motorized translational stage (MTS) of 0.01mm (0.0017D) resolution. The image of the laser source is formed 100mm downstream from the focusing lens and is the moveable object in the Badal system. In order to combine the IBOLS subsystem with a stock COAS aberrometer, additional distance is required between the usual cornea position of the eye and the first element of the COAS. This was achieved using a unit-magnification relay-telescope (L4, L5) that images the usual cornea position (CP1) onto the new cornea position (CP2). This relay telescope is a unit-magnification, four focal length system. The lenses L4 and L5 are arranged so the more curved sides face toward each other to minimize the aberration of field curvature between CP1 and CP2. The optical axes of the COAS and the Badal Laser optometer were carefully aligned and superimposed with the beam-splitter BS10.

In order for the laser disc optometer to be located at a convenient position, the observer's eye was optically relocated using another unit-magnification relay-telescope (L2, L3) so that the corneal vertex is at the focal point (CP3) of the Badal lens. This is also the position of the rotating disc (HDW, holographic diffusing wheel). We confirmed experimentally that calibration of the instrument is not affected by shifting the diffusing wheel along the optical axis. This fact matches the prediction by Ohzu¹³ that the wheel location did not matter in the perception of the plane of stationarity.

The focal length of lens L0 that generates the speckle optometer point source (SOPS) does not affect the instrument calibration as it simply creates the object for the Badal optometer. However the focal length of the lens L0 does have to be chosen with some care, as it will affect the luminance of the speckle pattern. It is desirable to use a short focal length lens to expand the light pattern on the diffusing wheel and to keep the beam uniformly illuminated. If the focal length of L0 is made too short, this results in the loss of light to the eye and thus the luminance of the speckles is reduced, making it harder for observers to judge the direction of speckle motion. If the focal length of L0 is too long, the speckle pattern appears noticeably brighter in the middle than on the edges.

Our system produced a fully developed speckle pattern. The contrast of a fully developed speckle pattern is defined to be unity.³⁰ This is based on the assumption that the amplitudes as well as the phase relations of the secondary wave-fields are entirely random.²² Visual inspection also confirmed that the speckles had high contrast and were clearly visible.

According to Ingelstam and Ragnarsson,²¹ the angular widths of the speckles are constant and thus the size of the speckles appear constant, independent of the focus plane of the observing system (e.g. human eye). The minimum distance between the speckles can be shown to be of the order of λ/d , where d is the diameter of the exit pupil.²² The minimum separation between speckles for our application ($\lambda = 820\text{ nm}$, $d = 3\text{ mm}$) is estimated to be 0.94 arcmin .

The observer uses a computer keyboard to control the motorized translation stage to position the SOPS in relation to the Badal Optometer lens L1 so that stationarity of the laser speckle pattern is established. When this occurs, SOPS is conjugate with the entrance apertures of the photoreceptors of the observer's retina and the eye's refractive error is given by eqn. 1.

In the standard COAS instrument the first element in front of the observer is a polarizing optic (a quarter wave plate) that prevents unwanted reflections internal to COAS from the laser source that produces the fundus beacon from interfering with the wavefront sensor. In the combined instrument, the laser speckle optometer and COAS share the additional relay telescope lenses and it is possible that the laser speckle source could create reflections that might interfere with the wavefront sensor. For these reasons, in the COSO instrument, the quarter wave plate was removed from the COAS part of the system and was replaced with a

slightly larger quarter wave plate, QWP2, positioned in front of lens L5. The speckle laser was turned off during the objective refraction to eliminate any possibility of interference.

Visibility and Safety of Infrared light in the Combined Instrument

The IBOLS subsystem uses a narrow bandwidth, 820 nm laser as its light source. Although this wavelength is normally considered invisible, the human eye is not completely insensitive to near infrared light. The human visual system has a luminous efficiency of approximately 1×10^{-5} for 820nm light.³¹ Such low sensitivity of the human visual system at this wavelength requires that the source be of sufficient power to elicit a visual response but also the source must be safe for viewing. Prior to any direct or chance human observations with this instrument, laser safety was assessed. The laser source in the IBOLS speckle sub system was treated as an extended source because it subtends a visual angle of ~ 2.5 degrees. The power measured for this source was 130 μ W (Orion PD-300-BB power meter, Ophir Optronics) at the corneal plane (CP1, Figure 3), and this is more than 20 times below the maximum permissible exposure (MPE) for continuous intrabeam viewing of extended sources recommended by ANSI Z-136-2000³² We also measured the power of the COAS SLD at the corneal plane (CP1, Figure 3) to be 90 μ W, which is 7 times below the MPE for continuous intrabeam viewing of a point source recommended by ANSI Z-136-2000.³² Therefore, our instrument was considered safe for use with human subjects. For these power levels the speckle pattern and COAS laser source were both clearly visible to the human eye as observed by the experimenters.

To verify that no other wavelengths for which the eye is more sensitive might be emitted by the laser, we examined the visibility of this source through bandpass (10 nm wide) filters with center wavelengths of 780, 790, 800, 810, 820, 830 and 840 nm. When the 820 nm filter was used, the laser was clearly visible to human observers. When the 810 or the 830 nm filters were used, the laser was barely visible. When the 780, 790, 800 and 810 nm filters were used, the laser was no longer visible. This experiment confirmed that the visible red speckle pattern produced by the laser diode was at a wavelength of 820nm.

Verification of COAS Calibration

The COAS subsystem was calibrated by the manufacturer using standard production methods. We verified that shipment of the instrument to Indiana University did not invalidate the factory calibration by externally injecting a collimated laser beam (810 nm) into the COAS in place of the usual reflected wavefront from an eye. Using a 5mm analysis diameter and with the COAS chromatic aberration correction switched off, a refractive error reading of $-0.03\text{DS} / -0.07\text{DC} \times 006$ (RMS) was measured. This was accompanied by an insignificant amount of coma and fluctuations in defocus of $\pm 0.04\text{D}$ in real time. Inspection of the pattern of spots in the Shack-Hartmann image revealed no indications of instrument misalignment.

Model Eye

Given the complexity of the human eye, and its many unknown optical features, it is important to independently calibrate and validate new instrumentation on a known system prior to deployment in scientific investigations. For this purpose we constructed a model eye from a +10 D glass lens behind a 3 mm diameter aperture to minimize the effect of any higher order aberrations on speckle motion. The aperture was positioned axially near the vertex of the lens and was carefully aligned to the optical axis of the model eye by minimizing the model's astigmatism and coma as measured by the COAS aberrometer. The refractive error of the model eye was controlled by adjusting the axial separation between lens and model retina. Sphero-cylindrical refractive errors were introduced with ophthalmic lenses placed immediately in front of the model eye. The retina of the model eye was

composed of a gently stretched, white plastic membrane 20 microns thick that was negligible compared to the model eye's axial length. The speckle pattern formed on the anterior surface of the model retina was observed using a video camera sensitive to infrared light, with a close focusing lens that viewed the retina from the anterior side via a mirror that was positioned just beside the lens of the model eye. By interposing the video camera between the model eye and our human observer's eye we were assured that the speckle pattern was formed on the model retina, not on the human retina.

The refractive error of the model eye was determined objectively with the COAS aberrometer using two different methods (Zernike and Seidel) for deriving the spherical equivalent refractive error M from the Zernike aberration coefficients of a wavefront aberration map,

$$M = \frac{-c_2^0 4 \sqrt{3}}{r^2} \text{ (Zernike)} \quad (2)$$

$$M = \frac{-c_2^0 4 \sqrt{3} + c_4^0 12 \sqrt{5}}{r^2} \text{ (Seidel)} \quad (3)$$

where c_2^0 and c_4^0 are the Zernike coefficients for defocus and spherical aberration, respectively, and r is pupil radius.³³ The Seidel method is paraxial since it determines M solely on the basis of wavefront curvature at the pupil center. By comparison, the Zernike method adjusts for the presence of spherical aberration by minimizing wavefront variance computed over the whole pupil. These two methods are identical in the absence of spherical aberration. The orthogonal components of astigmatic refractive error, J_0 and J_{45} in power vector notation,³⁴ are computed from the Zernike coefficients using the formulas

$$J_0 = \frac{-c_2^2 2 \sqrt{6}}{r^2}, \quad J_{45} = \frac{-c_2^{-2} 2 \sqrt{6}}{r^2} \quad (4)$$

VALIDATION OF SPECKLE MERIDIONAL REFRACTOMETRY

This section describes the empirical testing of a fundamental hypothesis about how the IBOLS instrument will behave when measuring an astigmatic system. If an eye has an astigmatic refractive error, the direction of speckle motion is expected to be at an angle to the direction of motion of the diffusing surface.^{22, 35, 36} Ingelstam and Ragnarsson (1972)²² describe a method for calculating the direction of speckle motion in which the velocity vector of the diffusing surface is resolved into two other vectors lying in the principal meridians of the astigmatism. These two orthogonal vectors are then analyzed separately, taking into account the refractive errors in these meridians, to determine the speed of motion in the principle directions. A vector sum of these components yields the apparent motion of the speckle pattern.

An alternative approach, which leads more directly to the notion of meridional refractometry, is to conceive of the astigmatism as a power vector that can be resolved into two orthogonal components. One of these components is parallel to the direction of motion of the diffusing screen and the other is orthogonal to the screen's motion. The component parallel to the screen's motion is responsible for the degree to which the apparent motion has a component in the same, or opposite, direction as the moving screen. This is the component of astigmatic refractive error the IBOLS instrument was designed to measure.

In our instrument the laser light passes through an area of the diffusing screen near the top of the spinning disk (Figure 1) and therefore the direction of motion of the screen is horizontal. Accordingly, we instructed the observer of the speckle pattern formed on the model eye retina, and captured by the infrared video camera, to attend only to the leftward or rightward components of motion and disregard motion in other directions. We reasoned that if the apparent motion was neither rightward nor leftward, then the motion had been nulled in the horizontal meridian of motion of the diffusing screen. Thus the instrument is seen to be a meridional refractometer that determines the refractive error of the eye in the horizontal meridian. To confirm this reasoning, we devised the following experiment.

Methods

We configured the axial length of the model eye for emmetropia and placed a +2.00D cylindrical lens in front of the model eye to produce a -2.00D astigmatic refractive error. The spherical component of refractive error was manipulated with spherical lenses placed in front of the astigmatic lens. The independent variables were axis of the cylindrical lens (rotated it in 22.5° steps from 0° to 157.5° in random order) and power of the spherical lenses (1D steps from 1DS to -2DS). In each of these test conditions we measured the total sphero-cylindrical refractive error of the model eye plus auxiliary lenses *in situ* with the COAS aberrometer. Care was taken to avoid reflections in the COAS raw image and multiple measurements were interleaved with speckle measurements throughout the experiment.

A method-of-limits psychophysical paradigm was used for the speckle optometer measurements to determine subjectively the refractive error of the model eye in the horizontal meridian. To begin each trial, the experimenter displaced the motorized translation stage in a random direction by an amount sufficient to produce an obvious speckle pattern moving noticeably left or right. The observer then re-positioned the motorized stage until the speckle pattern appeared to be moving with a velocity component that was just noticeably in the opposite direction. A total of 6 just noticeably left and 6 just noticeably right speckle movement thresholds were determined and the mean position was converted to a vergence value using eqn. 1. The variation of vergence measured by this procedure, as a function of axis of the astigmatic refractive error, was analyzed using Fourier analysis. Our expectation, based on the theory of meridional refractometry, is that vergence V should vary with meridian θ and astigmatism axis α according to the formula

$$V(\alpha) = M + J \cos(2(\theta - \alpha)) = S + \frac{C}{2} - \frac{C}{2} \cos(2(\theta - \alpha)), \quad (5)$$

where S is the spherical component of refractive error, C (a negative number) is the cylindrical component of refractive error, $M = S + C/2$ is the spherical equivalent refractive error, $J = -C/2$ is the magnitude of astigmatism in power vector notation, α is the axis of the astigmatism, and θ is the meridian-of-measurement oriented parallel to the direction of motion of the diffusing screen (nominally 180 degrees).

Results

Figure 4 shows refractive error (measured subjectively with the IBOLS instrument) as a function of the axis of the cylindrical lens used to induce astigmatism into the model eye. The power of the cylindrical lens was +2D and an additional -1D spherical lens was included to make the spherical equivalent refractive error zero. Thus the expected refractive error of the model eye in this configuration was +1DS, -2DC axis α , where α is the axis of the cylindrical lens. The equivalent prescription in power vector notation is 0DM, +1DJ, axis α . Thus, according to eqn. (5), meridional refractive error in the θ meridian should vary

as $V = +1 \cos(2(\theta - \alpha))$. The IBOLS instrument was designed to measure power in the $\theta = 180^\circ$ meridian, in which case $V = \cos(2\alpha)$ as shown in Figure 4 by the dashed curve. However, the measured refractive error, shown by symbols in Figure 4, deviated systematically from this curve which suggested the meridian-of-measurement was not exactly 180° . To determine the true meridian-of-measurement, the data were fit with a cosine function using Fourier analysis. The result, shown by the solid curve in Figure 4, revealed that the meridian-of-measurement for our instrument was 168° rather than the expected 180° meridian. This small discrepancy was later traced to the fact that the laser beam did not penetrate the exact top of the spinning disk and consequently the direction of motion of the moving screen was tilted slightly from the horizontal. From physical measurements of the instrument we estimated the tilt to be about 16° , which is close to the 12° tilt derived from Figure 4. This small tilt was not large enough to warrant a change in the psychophysical method (e.g. the instructions to observe rightward or leftward motion), but for quantitative purposes all subsequent analysis assumed the IBOLS instrument measured power along the 168° meridian.

To gather further evidence that our IBOLS instrument measures refractive error in the 168° meridian, we repeated the preceding experiment for a range of configurations of the astigmatic model eye described in Methods. In each case we computed the refractive error of the model eye in the 168° meridian from objective COAS measurements for comparison with the subjective measurements obtained with IBOLS. The results, shown in Figure 5, indicate a close correlation ($r = 0.9967$; $p < 0.0001$, $df = 26$) between the objective and subjective results. The least-squares regression passes through the origin and has slope that is only slightly different from unity (95% confidence interval = 0.932 to 0.995) indicating there may be a slight bias as refractive error changes. To investigate this possible bias further, the results are also shown in a bias plot³⁷, Figure 6. This plot reveals an outlier that may be contributing to possible bias and indicating that there is a slight ($-0.096D$) systematic difference between the two methods. The slope of the least square regression line is not significantly different from zero ($p = 0.059$; $df = 25$) when the outlier is removed and only a weak statistical significance results when it is included in the analysis ($p = 0.041$; $df = 26$). We attribute the possible bias and the slight systematic difference in Fig. 6, to the fact that the focal length of the Badal lens ($f = 75\text{mm}$) was slightly less than specified by the manufacturer (see Discussion).

CALIBRATION OF IBOLS

The analysis of data reported above required a calibration of the IBOLS instrument. A nominal calibration is obtained from eqn. 1 and knowledge that the stock Badal lens has focal length 75mm,

$$V = \frac{x}{f^2} = \frac{x(m)}{(0.075m)^2} = 178D/m = 0.178D/mm \quad (6)$$

We confirmed this calibration constant with the following experiment.

Methods

The model eye with 3mm pupil diameter was positioned at CP2 and aligned so that the image of the COAS super-luminescent diode beam was well centered on the model retina. Spherical refractive errors of the model eye were introduced by varying the axial distance between lens and model retina. Additional ophthalmic lenses were used to achieve the largest refractive errors tested ($+3.00\text{ DS}$, -2.00 DS and -3.00 DS), and in this case care was taken to eliminate reflections and monitor the raw image throughout each trial. The COAS aberrometer was used as our measurement standard to determine the refractive error (*per*

eqn. 2, eqn. 3) of the model eye *in situ* for each configuration of the model eye. The chromatic correction facility of COAS software was disabled so that the refractive errors reported were for the measurement wavelength (835nm). From the mean of 4 repeated measurements we derived the refractive error in the 168° meridian. Interleaved with these COAS measurements we determined refractive error subjectively with the IBOLS using the protocol below. A graph of refractive error (from COAS) as a function of position of the SOPS (from IBOLS) was expected (according to eqn. 6) to be linear with slope equal to the calibration constant 0.178D/mm.

For IBOLS measurements, a human observer viewed the speckle pattern formed on the model retina, detected by a video camera, and displayed on a video monitor. The same psychophysical procedure described above in the section *Validation of speckle meridional refractometry* was followed. The experiment was performed by two well-trained observers, each of whom determined 27 just noticeably left and 27 just noticeably right speckle movement thresholds for each refractive configuration of the model eye. The mean of these 27 settings was taken as a measure of x , the position of the motorized stage for stationarity of the speckle pattern.

Results

The calibration results are shown in Figure 7 for both Zernike and Seidel methods of wavefront refraction. We performed least-squares regression on the results for the two data sets separately and then compared them for equality of their slopes and intercepts. This analysis³⁸ revealed no significant differences between the results from the two observers ($p = 0.711$ and $p = 0.196$ for slope and intercept respectively; $df = 1, 24$) nor was there a significant difference in slopes of the best fitting lines obtained for the two methods of refraction ($p = 0.116$; $df = 1, 24$). However there was a noticeable offset between Zernike (RMS) and Seidel methods of objective refraction, resulting in a significant difference in their y-intercepts ($p < 0.0001$; $df = 1, 24$). We pursued this result by evaluating the two data sets (Seidel and Zernike) separately and compared each to theory. The slope for Zernike refractions was 5.75 mm/D (0.174 D/mm) and was not significantly different ($p = 0.29$; $df = 1, 24$) from the design value of 5.62 mm/D (0.178 D/mm) nor was its intercept significantly different ($p = 0.555$; $df = 1, 24$) from zero. The regression slope for Seidel refractions was 5.39 D/mm (0.186 mm/D). Although this slope was not significantly different from the design value ($p = 0.231$; $df = 1, 24$), the y-intercept was significantly different ($p < .0001$; $df = 1, 24$) from zero. We attributed this non-zero y-intercept to the presence of spherical aberration in the model eye (see Discussion). On the basis of these results, we chose the Zernike(RMS) refraction method as the more appropriate calibration for use with IBOLS in the present series of experiments. The results, using Zernike (RMS) refraction only, are also shown in a Bland-Altman³⁷ bias plot in Figure 8, confirming that there is no systematic discrepancies between refractive error measurements (mean difference = -0.02). Least squares regression reveals a line that is not significantly different than zero ($p = 0.90$; $df = 12$) indicating no bias.

DISCUSSION

This study demonstrates experimentally that an infrared laser speckle optometer can be used to measure the meridional refractive error of a model eye. Calibration of the Badal optometer, based on the manufacturers specification of the focal length of the Badal lens ($f = 75\text{mm}$), agreed closely with measurements of refractive error obtained with the COAS wavefront aberrometer (Fig.7). However, when that calibration was used to verify measurements of astigmatism, a slight discrepancy emerged (slope of regression line in Fig. 5 was slightly less than 1) that appears to be due to residual uncertainty in the calibration of the Badal optometer. The focal length of the Badal lens can deviate from 74.25 mm to 75.75

mm based on the manufacturers (Thorlabs, Inc) reported focal length tolerance of 1%. Another source of calibration uncertainty could be attributed to the meridian-of-measurement for the IBOLS instrument. Although we found the average meridian of measurement to be 168° , it could deviate by $\pm 2^\circ$ for repeated measurements. Using this knowledge, we applied both sources of uncertainty to our data separately and found that 0.5 mm change in the focal length of the Badal lens had a much higher impact on our data than did a change of 2° in choice of meridian. A focal length of 74.5 mm would result in the regression line in Figure 5 with a slope that is not significantly different from unity. Therefore, we attribute the slight discrepancy in slope from unity in Figure 5 to a slightly shorter focal length of the Badal lens rather than an error in choice of meridian. However, this discrepancy is less than the manufacturers tolerance and is functionally insignificant, and therefore should not affect human subject results. Thus we reaffirm our conclusion from experiments with an astigmatic model eye that the meridian-of-measurement is parallel to the tangential direction of motion near the rim of the rotating diffuser interposed between the eye and a coherent point source. Additional experiments confirmed that a Badal optometer can be used to adjust the vergence of the coherent point source to null the speckle motion and that the resulting vergence equals the eye's meridional refractive error. These observations are in agreement with the theory of meridional refractometry using laser speckle developed by Ingalstam and Ragnarsson²² expressed in optometric terms by text eqn. 5.

Calibration of our IBOLS instrument revealed that subjective measurements of refractive error using laser speckle agrees closely with objective calibration of the model eye using wavefront aberrometry and the Zernike method for determining refractive error by minimizing RMS wavefront error. However, a systematic discrepancy resulted when the model eye was calibrated using the Seidel method of wavefront refraction. This discrepancy was caused by small amounts of positive spherical aberration (0.0391 ± 0.018 microns) in the model eye and auxiliary lenses used to induce refractive errors. Although we designed our experiment to avoid spherical aberration by using a 3mm artificial pupil, the experimental results demonstrated that even small amounts of spherical aberration can have a significant effect on measurements of refractive error. The magnitude of this effect is predicted quantitatively by text equation 2 and equation 3 and is explained by the difference in criteria used in the two methods for determining when an eye is optimally focused. According to the Zernike definition of emmetropia, neither the marginal nor the paraxial rays from infinity are well focused on the retina.² Instead, emmetropia occurs when the sum of squared ray errors over the entire pupil is minimized. By comparison, Seidel emmetropia means that rays near the pupil center are optimally focused, regardless of rays passing through other points in the pupil.

In the subjective IBOLS instrument, the observer makes judgments about the direction of speckle motion that arises from light entering all points of the pupil. There is no opportunity for the observer to restrict the rays to the paraxial region and therefore it is unlikely that the subjective results will agree with the Seidel method. Instead, the overall pattern of motion must be assessed even if motion is ambiguous due to the presence of higher-order aberrations, such as spherical aberration. While there is no reason to suppose *a priori* that the human observer makes motion judgments that minimize the RMS wavefront error, present results show that under the conditions of our experiment that is indeed what happened when judging speckle motion in a model eye with small amounts of spherical aberration. It is possible that a different result will be obtained when the instrument is used to measure refractive error in a human eye since the observer must make judgments about speckle patterns formed directly on her own retina. Such speckle patterns are expected to be influenced by the Stiles-Crawford effect that will attenuate the effectiveness of rays passing through the margins of the pupil relative to central rays. In this case the Seidel refraction method, or perhaps some other method, might predict subjective results more accurately.

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APPENDIX

The appendix is available online at www.optvissci.com.

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Figure 1.

Principle of the spinning disk speckle optometer. The coherent source is moved axially to be conjugate to the retina (here shown for a myopic eye) at which position motion of the speckle ceases. The reciprocal distance from the speckle optometer point source (SOPS) to the cornea ($-1/L2$) is the refractive state of the eye for the meridian of motion of the isolated region of the diffusing disk. The rotating diffuser is normal to the direction of the light entering the eye.

Figure 2.

Principle of the IBOLS design. Badal lens L1 uses the speckle optometer point source (SOPS) to produce a wavefront of vergence $V=1/x'=x/ff'$ in its back focal plane. This vergence is also present at the eye's cornea because the relay telescope (L2, L3) renders the second focal plane of the Badal lens conjugate to the cornea with unit magnification. The spinning disk D is located near the second focal plane of the Badal lens.

Figure 3.

The Combined Instrument Optical Schematic (COSO, Design View). The ray paths in this figure are shown for the case of an eye that is emmetropic for the wavelength of the laser diode. CP1 is the normal location of the eye's cornea with the commercially available COAS. CP2 is the actual location of the cornea for the COSO. CP3 is conjugate with CP2 and CP1. Point source SOPS is shown at an axial position that is conjugate to the retina and therefore will result in the appearance of a stationary speckle pattern.

Figure 4.

Effect of axis of cylindrical lens (abscissa) on measured refractive error (ordinate) for an astigmatic model eye. Symbols show the experimental results. The solid curve shows the best-fitting sinusoidal function determined by Fourier analysis of the measurements. For reference, the dashed curve shows the expected result assuming the IBOLS instrument measures refractive error in the 180th meridian. The phase shift between the two curves is -11.67 degrees.

Figure 5.

Verification of IBOLS as a meridional refractometer. Symbols show the correlation between objective refractive error of the model eye in the 168° meridian (abscissa) as measured by the COAS aberrometer with subjective refractive error (ordinate) as measured with IBOLS. Symbol type indicates the axis of the cylindrical lens used to induce astigmatism in the model eye. The dashed line $y=x$ represents perfect agreement. Error bars represent ± 1 SD and in most cases are smaller than the diameter of the symbol.

Figure 6.

Bland-Altman bias plot of the difference between the refractive error measurements of an astigmatic model eye taken by IBOLS against their mean. Ignoring one outlier, the slope of the regression line is not significantly different from 0 indicating no bias. The dark dashed line represents the mean difference between the instrument measurements and the two dotted lines represent the 95% confidence limits.

Figure 7.

Experimental calibration of IBOLS. Symbols (observer 1, open symbols and observer 2, closed symbols) show the correlation between objective refractive error of the model eye (abscissa) as measured by the COAS aberrometer with axial position of SOPS (ordinate) determined subjectively with IBOLS. Error bars represent ± 1 standard deviation and in most cases are smaller than the diameter of the symbol. Spherical refractive error of the model eye was manipulated with trial lenses and measured by COAS using two algorithms (RMS, circles and Seidel, squares). Dashed line is the expected calibration based on the theory of Badal optometers

Figure 8.

Bland-Altman bias plot of the difference between the refractive error measurements, for a model eye, by COAS and IBOLS against their mean (Observer 1, closed symbols and observer 2, open symbols). COAS measurements are based on RMS wavefront refraction and a calibration 0.174 D/mm for IBOLS. The dashed line shows the mean bias (-2.44×10^{-6}), and the dotted lines show the 95% limits of agreement (± 0.29 D).

Table 1

Description of Labels for Combined Objective Subjective Optometer Instrument

Label	Description
L4	IR achromatic lens, f=75mm
L5	IR achromatic lens, f=75mm
L3	IR achromatic lens, f=50mm
L2	IR achromatic lens, f=50mm
L1	IR achromatic lens, f=75mm the Badal Optometer lens
L0	IR achromatic lens, f=100mm mounted on the motorized translation stage
MTS	Motorized translation stage on which L15 and Laser 10 are mounted.MTS moves the position of SOPS with respect to the Badal lens
HDW	Holographic Diffusing Wheel (disc) that transmits near IR light to produce the speckle pattern
BS10	Near IR beam splitter
820 nm Laser diode	820 nm collimated laser diode, 8 mW
QWP2	Zero order quarter wave plate
CP1	Position the cornea of an eye under examination would occupy in an original COAS system. Virtual position of the cornea of the eye under examination in the COCO system
CP2	Position of the cornea of the eye under examination in the COSO system
CP3	Virtual position of the cornea of the eye under examination in the Laser Disc Optometer arm of the COSO system