Measurement of ocular aberrations in downward gaze using a modified clinical aberrometer

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Abstract: Changes in corneal optics have been measured after downward gaze. However, ocular aberrations during downward gaze have not been previously measured. A commercial Shack-Hartmann aberrometer (COAS-HD) was modified by adding a relay lens system and a rotatable beam splitter to allow on-axis aberration measurements in primary gaze and downward gaze with binocular fixation. Measurements with the modified aberrometer (COAS-HD relay system) in primary and downward gaze were validated against a conventional aberrometer. In human eyes, there were significant changes ($p<0.05$) in defocus C(2,0), primary astigmatism C(2,2) and vertical coma C(3,–1) in downward gaze (25 degrees) compared to primary gaze, indicating the potential influence of biomechanical forces on the optics of the eye in downward gaze. To demonstrate a further clinical application of this modified aberrometer, we measured ocular aberrations when wearing a progressive addition lens (PAL) in primary gaze (0 degree), 15 degrees downward gaze and 25 degrees downward gaze.

OCIS codes: (330.7327) Visual optics, ophthalmic instrumentation; (330.4460) Ophthalmic optics and devices; (330.5370) Physiological optics.

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1. Introduction

The measurement of ocular aberrations provides important information in both ophthalmic research and clinical practice. Over the past few decades, several techniques have been developed to measure ocular wavefront aberrations. Early methods involved subjective techniques to measure ocular aberrations [1]. Recently, objective methods such as the Shack-Hartmann wavefront sensor have been introduced as reliable and practical techniques to measure ocular aberrations [2]. The principle and measurement technique of this device are explained in detail elsewhere [3,4]. The complete ophthalmic analysis system (COAS-HD, Wavefront Sciences, USA) is a commercially available aberrometer, based on the Shack-Hartmann principle that has been validated for the purpose of clinical use with both human and model eyes [5].

There are a range of different clinical and research applications for the measurement of wavefront aberrations including quantifying the optical quality of normal eyes, clinically abnormal eyes (e.g. dry eye, keratoconus), determining the optical effect of refractive corrections (e.g. contact lenses, spectacle lenses, refractive surgery) and designing optimized refractive corrections [3].

Ocular wavefront aberrations measurements are usually captured from one eye in primary (horizontal) gaze viewing a far target. However, this does not replicate the natural viewing conditions of human eyes for many tasks such as near work or reading that typically involve binocular viewing and near focus (accommodation) in downward gaze. A number of studies [6–8] have shown that changes in horizontal gaze have no significant influence on the optics of the eye compared to primary gaze, however these studies have not investigated changes in ocular optics in downward gaze. A range of biomechanical changes may occur when we adopt a downward gaze that could result in changes of ocular aberrations. The eyelid aperture has been shown to narrow in downward gaze leading to changes in corneal aberrations [9]. Cyclotorsion is a rotation of the eye around the visual axis and this can change with vertical eye movements [10] and when changing from monocular to binocular viewing [11]. It is also conceivable that gravitational forces could alter the shape or alignment of the optical components of the eye during downward gaze [12,13].

Given that many normal visual tasks are performed binocularly in downward gaze, it is of interest to be able to measure ocular aberrations under these natural viewing conditions. To achieve this, we have modified a commercially available aberrometer (COAS-HD) with a relay lens system and a rotatable beam splitter (hot mirror) to allow measures of aberrations of human eyes in both primary and downward gaze and to allow subjects to fixate an open field target with both eyes (binocularly) during the wavefront measurements.

2. Methods

2.1 Experimental setup

A commercial Shack-Hartmann aberrometer (COAS-HD) was modified by adding a relay lens to allow measurement of ocular aberrations along the visual axis (on-axis) in primary and downward gaze under natural binocular viewing conditions. A schematic diagram of this optical system is shown in Fig. 1. The first component of this system, a gold coated mirror (**M1**) [95% reflectivity of infrared light ranging from 800 to 1000 nm] was placed in front of the wavefront sensor with an angle of 45 degrees to reflect the infrared measurement beam (840 nm) from the wavefront sensor. To increase the working distance of the system, a pair of achromatic doublet lenses ($\mathbf{L_1}$ and $\mathbf{L_2}$) with focal lengths of 100 mm were placed after **M1** to maintain the afocal optical system and relay the emerging wavefront to the next optical surface, a wide band hot mirror (**M2**) [> 85% transmissibility of visible light ranging from 450 to 645 nm and > 90% reflectivity of infrared light ranging from 750 to 1200 nm]. The distance between the centre of **L1** and **L2** (200 mm) determined the magnification of the pupil, which was 1 × in our optical design. These lenses had an anti-reflection coating (for wavelengths from 600 to 1050 nm) in order to reduce the risk of energy loss of the wavefront sensor's measurement beam.

The infrared measurement beam travelling from the wavefront sensor through the relay lens system was then redirected towards the subject's left eye (OS) by a wide band hot mirror (**M2**) placed in front of the subject's left eye at an angle of 45 degrees. Both mirrors (**M1** and **M2**) were placed parallel to each other to avoid inducing any lateral compression of the wavefront measured using this modified COAS-HD. However, an accurate subjective adjustment of the free space target was necessary to maintain co-axial alignment of the subject and COAS-HD. As our aim was to measure wavefront aberrations with binocular fixation of a free space target, lens holders were attached behind the hot mirror and outside of the measurement beam to allow optimum sphero-cylinder refractive correction of both eyes.

Along with primary gaze measures, this instrument was also modified to measure aberrations in downward gaze. The hot mirror (**M2**) was mounted on a custom built mirror mount (Fig. 1C). This mount was fixed with a vertical rotatable scale in such a way that the

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geometrical centre of the hot mirror (**M2**) rotated along the axis of the measurement beam. With a downward rotation of the mirror **M2**, there was a upward rotation of the measurement beam reflected from the hot mirror surface (**M2**). The eye had to rotate in a downward direction (similar angle of rotation of **M2**) to align the visual axis and measurement beam. This technique allowed the measurement of on-axis aberrations of the rotated eye in downward gaze.

A chin rest was placed on an XYZ translation stage so that we could align the subject's visual axis and measurement axis and maintain the conjugate focal plane of the optical system with the relay system. The eye was visible on the COAS-HD video screen through the addition of an infrared LED light source (940 nm) which was mounted near the tested eye. This arrangement allowed the use of normal COAS-HD focusing and alignment techniques during the measurements. The level of energy of the measurement beam from the original COAS-HD and from the COAS-HD relay system were measured by a power meter (Newport, model 1815) and the difference was not significant (less than 10 microwatts).

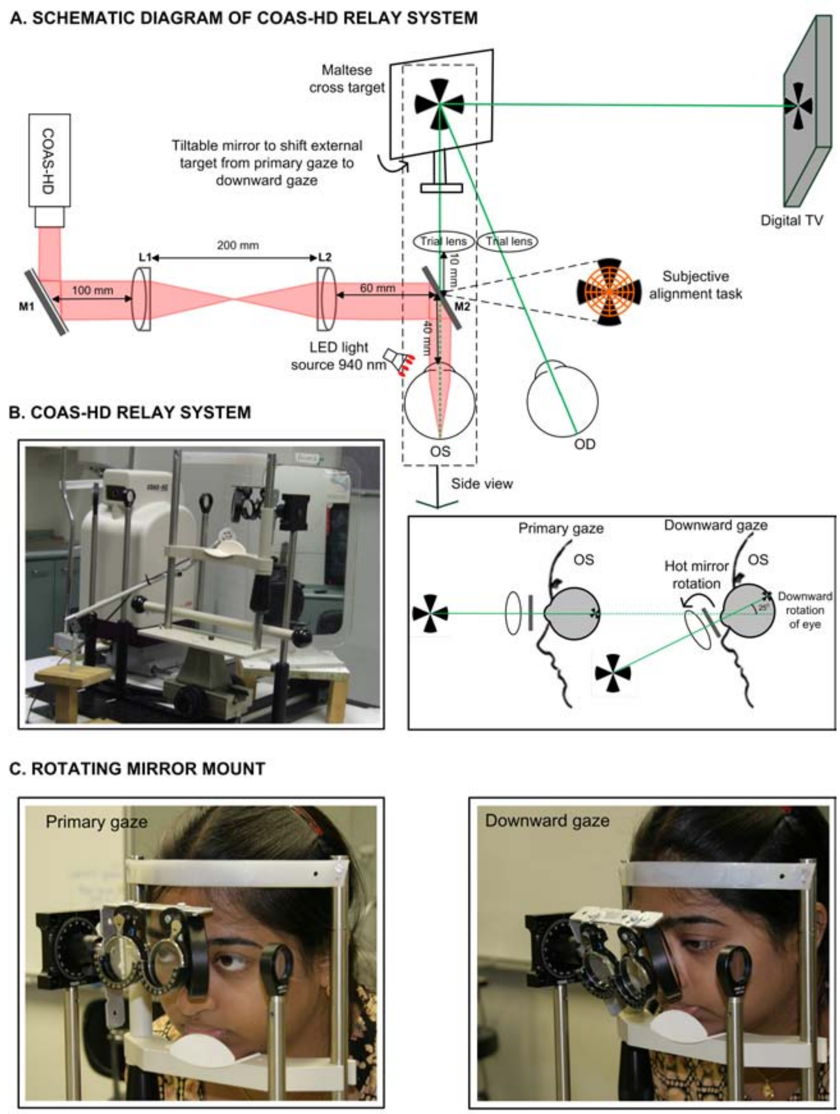

Fig. 1. Schematic diagram (A) and photographs (B and C) of COAS-HD relay system.

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2.2 Validation

Nine young adult subjects aged between 25 and 32 years (mean age 28 years) were recruited for this study. All subjects were free of any significant ocular diseases and had no history of eye surgery. Approval was obtained from the university human research ethics committee prior to the commencement of the study. Subjects were treated in accordance with the declaration of Helsinki. All subjects had best corrected visual acuity of logMAR 0.00 or better in both eyes. Mean (± SD) spherical equivalent refraction was −0.85 ± 1.67 DS (range from + 0.25 to −4.75 DS). None of the subjects had anisometropia greater than 1.00 DS, or astigmatism greater than 0.75 DC. Wavefront aberrations of each subject's left eye were measured using the conventional aberrometer and the COAS-HD relay system in primary gaze. Subjects were given their full distance refractive error correction (sphero-cylinder) during wavefront measurements, taking into account the vertex distance of the trial lenses. All measurements were performed through the subjects' natural pupils. During the measurement with the relay system, the subject was asked to look at a distant (5 m) Maltese cross target with both eyes. The chin rest position was then adjusted (vertically and horizontally) until the centre of the cross target coincided with the centre of the COAS-HD fixation target that was visible via the hot mirror surface. Therefore, the centre of the COAS-HD target and the centre of the Maltese cross were coaxial with the visual axis of the subject's tested left eye (OS). This alignment ensured that we were measuring the on-axis aberrations of the subject's left eye. The chin rest and COAS-HD (if necessary) were then moved back and forth to focus the wavefront sensor on the iris plane, thus maintaining a conjugate focal relationship between the subject's entrance pupil and the optical system of the COAS-HD. Finally, wavefront measurements were taken of the subject's left eye in the unaccommodated condition, fixating on the distant (5 m) free space high contrast Maltese cross target.

We were also interested to measure ocular aberrations in downward gaze. The hot mirror (**M2**) was secured to a custom built mirror mount and a vertical rotating scale, so that the geometric centre of the hot mirror (**M2**) rotated along the axis of the measurement beam. The downward rotation of the hot mirror **M2**, produced an upward rotation of the measurement beam. The hot mirror was rotated by 25 degrees so that the subject looked down at this angle and to keep alignment between the visual axis, internal target of the aberrometer and centre of the external target (Maltese cross), the chinrest was shifted (in upward and inward directions). The external Maltese cross target was visible via a mirror. The vertical axis of this mirror was rotated to shift the Maltese cross target from primary to downward gaze (Fig. 1). Similar to the primary gaze technique, subjects had to align the internal and external targets before taking measurements in downward gaze to ensure on-axis measurements were acquired.

While studies have shown no significant variation in ocular aberrations with horizontal gaze [6], we hypothesize that downward gaze might be different due to lid pressure [9,14–16], gravitational effects [12,13], or perhaps some differences in the biomechanical force from the extraocular muscles. So along with the human eyes, we also measured aberrations from a model eye in primary gaze and downward gaze using the relay lens system to verify that the changes in aberrations found in human eyes in downward gaze were real effects (i.e., optical and physiological changes) rather than representing artefacts induced from the measurement technique. Known spherical and cylindrical lenses of three different combinations of powers and axes (Lens A = −2.50DS/−3.00 DC × 180; Lens B = −3.5DS/-1.25DC × 130; Lens C = + 2.00DS / −3.00DC × 30) were added to the model eye. We placed the model eye on a rotational stage which was fixed to the chinrest of the COAS-HD relay system. During the downward gaze measurements the model eye was rotated 25 degrees in the downward direction to simulate the measurements taken with real eyes.

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2.3 Analysis

As the wavefront aberrations of the eye exhibit temporal microfluctuations [17] we collected multiple wavefront measurements (4 × 25 frames) from each subject for primary and downward gaze. Each set of 25 measurements takes about 2.5 seconds (i.e., ~10 Hz measurement frequency). For both human and model eyes, Zernike polynomials up to the 8th radial order were fit to the wavefront measurements by the COAS software using the nomenclature recommended by the Optical Society of America (OSA) [18]. We rescaled the wavefront data for a fixed 5.0 mm pupil diameter using the method of Schwiegerling [19]. A Matlab based algorithm was used to detect artefacts in the Zernike polynomial fit coefficients [20]. Sources of these artefacts could include blinking, poor stability of the subject's head and poor tear film quality. The time span of a typical blink for the healthy eye of a subject is about 250 msec [21]. In this study, short term continuous measurements of wavefront aberrations (2.5 secs) reduced the possibility of substantial artefacts in the time course of the Zernike polynomial terms.

The presence of the relay lens system caused the wavefront to be inverted in primary gaze. In downward gaze, there was an additional rotation of the wavefront because of the hot mirror rotation. Therefore, we rotated the wavefront [22] to its original position using custom written software (Matlab based) and then compared this with the data obtained from original COAS-HD system.

For human eyes, in order to correct any cyclotorsion in downward gaze, the iris images from the wavefront sensor in primary and downward gaze were analysed for each subject. Initially, to determine correspondence of the images, a set of uniquely identifiable control points (iris landmarks), were manually selected from each image by the operator. We denote the coordinates in the primary gaze as (x, y) and in the downward gaze image as (X, Y). Three sets of control points were selected from the two images, followed by a similarity image transformation:

$$\begin{aligned} X &= s(x\cos\theta - y\sin\theta) \\ Y &= s(x\sin\theta + y\cos\theta) \end{aligned} \tag{1}$$

where s, θ, are scaling and rotational differences between the images, respectively. The final values of scaling and rotation were obtained as the mean values of all three points. An overview of the rotation of the human eye's wavefronts obtained from the COAS-HD relay system in primary and in downward gaze is shown in Fig. 2.

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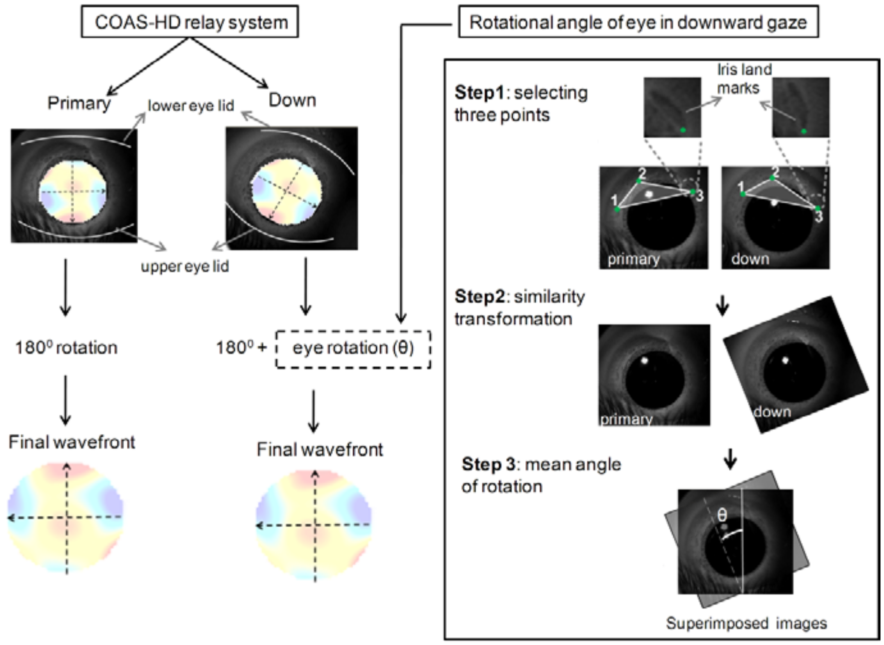

Fig. 2. Flow chart of wavefront rotation technique to compensate for an inverted image through the COAS-HD relay system, eye rotation due to hot mirror tilt and a unique cyclotorsion of the eye associated with downward gaze.

3. Results

3.1 Primary gaze

The orthogonal refractive power vector components (M, J0 and J45) were determined from the refractive Zernike power polynomials [23]. For human eyes, the mean differences between the measurements of refractive components obtained from the conventional aberrometer and from the COAS-HD relay system in primary gaze were small: spherical equivalent (M) –0.09 ± 0.17 D, horizontal / vertical astigmatism (J0) –0.02 ± 0.05 D and oblique astigmatism (J45) –0.03 ± 0.03 D. Figure 3 shows the results of correlation of data obtained with the conventional aberrometer and the COAS-HD relay system in terms of refractive components (M, J0 and J45) from the 9 eyes.

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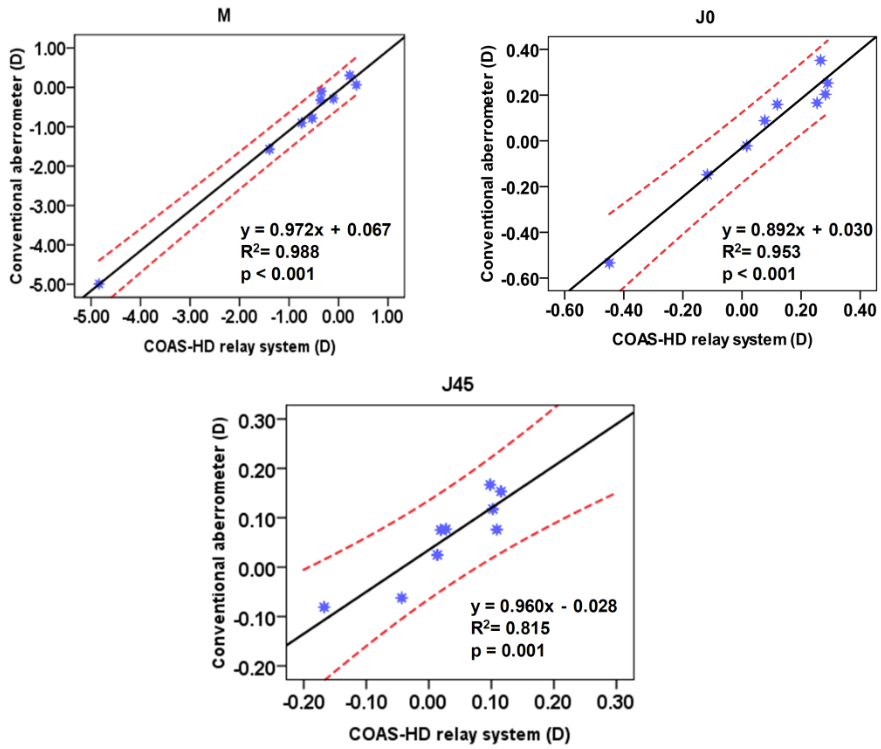

Fig. 3. Correlations between the refractive components obtained from the conventional aberrometer and from the COAS-HD relay system in primary gaze. Solid black lines represent the linear regression and dashed red lines represent the 95% confidence bounds.

The mean differences of the major higher order coefficients between the measurements obtained from the conventional aberrometer and the COAS-HD relay system were also small: vertical trefoil C(3,–3) 0.020 ± 0.034 µm (R^2 = 0.919, p = 0.004), horizontal trefoil C(3,3) 0.014 ± 0.020 µm ((R^2 = 0.978, p < 0.001), vertical coma C(3,–1) –0.014 ± 0.031 µm (R^2 = 0.980, p < 0.001) horizontal coma C(3,1) –0.020 ± 0.035 µm (R^2 = 0.924, p = 0.003) and primary spherical aberration C(4,0) –0.013 ± 0.027 µm (R^2 = 0.944, p < 0.001).

We also examined the test-retest repeatability of the measurements with the relay system by taking 6 independent measures (10 frames per measure) on the same three subjects in primary gaze after deliberately misaligning and realigning the instrument between each measure. We found small mean differences and strong correlations between the two sets of measurements. As examples, the mean differences of defocus C(2,0), spherical aberration C(4,0) and total higher order RMS between the two sets of measurements were –0.014 µm (R^2 = 0.999), –0.004 µm (R^2 = 0.892) and –0.002 µm (R^2 = 0.947), respectively.

3.2 Downward gaze

3.2.1 Model eye

As we were interested to measure aberrations in downward gaze, it was important to ensure that rotation of the hot mirror during downward gaze measurement did not lead to any potential error in lower or higher order wavefront terms. Therefore, we calculated Pearson's correlation of second order and major higher order coefficients between the measurements obtained from the COAS-HD relay system in primary and downward gaze for the model eye (Table 1).

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Strong correlations were found between the measurements obtained through the relay system in primary and downward gaze indicating that the hot mirror rotation did not introduce any unwanted astigmatism or coma (Table 1). As we maintained the distance between the hot mirror and the corneal apex, there were no significant changes in defocus between the primary and downward gaze measurements.

Table 1. Mean differences (MD), standard deviation (SD) and Pearson's correlation (R^2) of major refractive components of the model eye between primary and downward gaze (25 degrees) obtained through COAS-HD relay system

Coefficients	Mean differences (µm)	SD (µm)	R^2
Oblique astigmatism C(2,–2)	–0.013	0.009	1.000
Defocus C(2,0)	–0.003	0.002	0.997
WTR/ATR astigmatism C(2,2)	0.028	0.020	0.996
Vertical coma C(3,–1)	0.004	0.003	0.787
Horizontal coma C(3,1)	–0.001	0.001	0.839
Spherical aberration C(4,0)	<0.000	<0.000	0.996

3.2.2 Human eyes

Analysis of ocular wavefronts revealed that three wavefront coefficients were significantly different from primary gaze to downward gaze (Fig. 4). Of the lower order aberrations, defocus C(2,0) was shifted in the myopic direction (mean difference ± SD 0.150 ± 0.199 µm, paired t-test p = 0.04) and primary astigmatism C(2,2) was shifted in the direction of against-the-rule (ATR) astigmatism (mean difference ± SD –0.088 ± 0.101 µm, paired t-test p = 0.030). Changes in higher order aberrations (HOAs) were smaller compared to the changes in lower order aberrations. Of the HOAs, a statistically significant change was observed only in vertical coma C(3,–1) (mean difference ± SD 0.0181 ± 0.020 µm, paired t-test p = 0.028) in downward gaze compared to primary gaze.

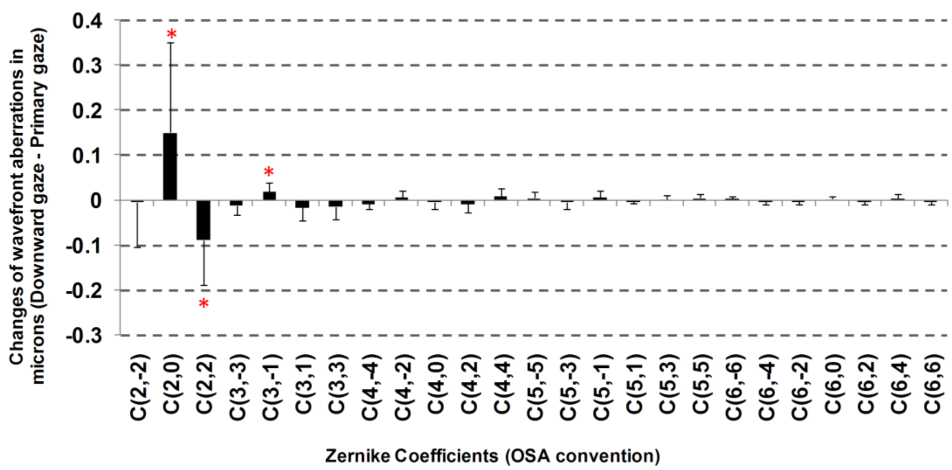

Fig. 4. Group mean ± SD (n = 9) changes of ocular aberrations in downward gaze (25 degrees) compared to primary gaze for 5.0 mm fixed pupil diameter. ***** = Paired t-test (<0.05).

4. Clinical application of COAS-HD relay system

To illustrate the potential application of the COAS-HD relay system, the optical properties of an ophthalmic correction were tested by measuring wavefront aberrations of a human eye using a commercially available progressive addition lens (PAL) [soft design] with distance

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power plano (± 0.00 D) and near addition + 2.00 DS in primary gaze (corresponding to the distance zone of the PAL), in 15 degrees downward gaze (corresponding to the intermediate zone of the PAL) and in 25 degrees downward gaze (corresponding to the near or reading zone of the PAL).

Progressive addition lenses are designed for presbyopic subjects (who have age related reduction in their amplitude of accommodation) to provide adequate vision for all distances with a gradual increment of positive power from the distance zone (above centre) of the lens to the near zone (towards the bottom). The wavefront aberrations of the bare eye (eye only) in primary gaze and downward gaze with two different viewing angles (15 degrees and 25 degrees) were initially measured as baseline (control) measurements with a natural pupil diameter using the COAS-HD relay system. The wavefront aberrations of the same PAL wearing eye in primary, intermediate (15 degrees) and downward gaze (25 degrees) were then also measured. The aberrations of the isolated PAL were derived in Eq. (2).

$$\Delta W(\rho,\theta)_{Lensonly} = W(\rho,\theta)_{Lensoneye} - W(\rho,\theta)_{Bareeye} \tag{2}$$

Wavefront maps representing the higher order aberration distributions (in microns) of different optical zones (distance, intermediate and near) of 'lens only' (PAL) across a 5.0 mm pupil diameter are illustrated in Fig. 5. Total higher order RMS (HORMS) for each condition was also calculated to compare the optical image quality during distance, intermediate and near viewing with the PAL. The magnitude of total HORMS increased in the intermediate zone (0.192 µm) and in the near zone of the lens (0.154 µm) to be considerably more than the magnitude through the distance zone (0.083 µm) (Fig. 5). Comparing the distance zone and intermediate zone of the PAL, the largest changes occurred in vertical trefoil C(3,–3) [mean difference –0.142 µm] followed by vertical coma C(3,–1) [mean difference –0.088 µm]. In the near zone the greatest changes occurred in vertical coma C(3,–1) [mean difference –0.105 µm] followed by vertical trefoil C(3,–3) [mean difference –0.091 µm] compared to the distance zone.

To provide an illustration of the changes in retinal image quality through the different optical zones of the tested PAL, the measured higher order aberrations were used to calculate the point spread function (PSF) and Visual Strehl ratio based on optical transfer function (VSOTF) for a fixed 5.0 mm pupil (Fig. 5). Presently, the VSOTF is considered to be one of the best image quality metrics which is highly correlated with subjective visual acuity [24]. The numerical calculation of VSOTF is discussed in [25]. Small reductions in image quality are evident in the intermediate and near zones compared to the distance zone with the PAL (Fig. 5).

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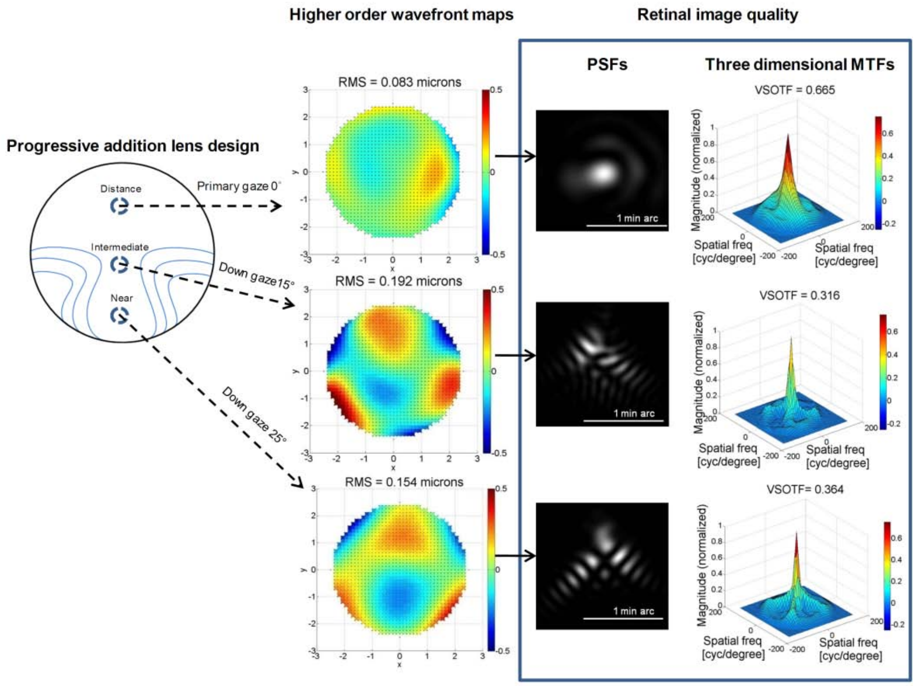

Fig. 5. Higher order wavefront maps and retinal image quality [point spread functions and three dimensional modulation transfer functions (MTFs)] at different optical zones of a progressive addition lens (lens only) across 5.0 mm fixed pupil diameter. Average VSOTF is shown at the top of each plot.

5. Discussion

We have developed a new technique to measure wavefront aberrations with open field binocular fixation, in both primary and downward gaze, by modifying a commercially available Shack-Hartmann wavefront sensor (COAS-HD) with a relay lens system. The lower and higher order aberrations from human eyes and a model eye measured with the COAS-HD relay system were comparable with those measured with the conventional COAS-HD aberrometer. We found that the COAS-HD relay system could reliably and repeatably measure defocus, astigmatism and higher order aberrations both in primary and downward gaze.

To better understand the optical characteristics of the human eye during reading it is necessary to measure ocular aberrations of the eye in downward gaze. In this study, we found small but statistically significant changes in lower order and higher order aberrations of the eye in downward gaze compared to primary gaze. In agreement with a previous study of ocular aberrations after reading [9] we also observed changes of defocus [C(2,0)], primary astigmatism [C(2,2)] and vertical coma [C(3,–1)] during downward gaze.

We have also demonstrated the potential application of measuring ocular aberrations in downward gaze with spectacle corrections such as PALs. Similar to previous studies [26,27], the results of our study also suggest that PALs introduce higher order aberrations, in particular coma and trefoil in the intermediate and near zones (Fig. 5). Optical bench methods [28–30] or mathematical models [31–35] can measure or estimate the optical quality of PALs in isolation from the optics of the eye. However the interaction between the optics of the human eye and the ophthalmic corrective lenses will produce unique aberration profiles.

Measurements through the COAS-HD relay system may also be useful to determine the optical performance of contact lenses in downward gaze. During downward gaze, a contact

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lens might be slightly decentred from its original position by biomechanical forces or gravity. Mcllraith et al [36] examined the stability of soft toric contact lenses in different viewing gazes and found an infero-nasal rotation of contact lenses in downward gaze. Translating soft and rigid bifocal contact lenses are designed so that a near vision lens segment shifts across the pupil in downward gaze. The COAS-HD relay system would also potentially be useful in assessing the on-eye optical performance of these translating lenses in primary and downward gaze. Another potential clinical application of the COAS-HD relay system is the assessment of the optical performance of accommodating intra-ocular lenses (IOLs) during a near task in downward gaze.

6. Conclusion

We have modified a commercially available Shack-Hartmann wavefront sensor to allow measurement of wavefront aberrations in downward gaze under natural viewing conditions. We have validated the measurements of this modified wavefront sensor against a conventional wavefront sensor. We found small but statistically significant changes in lower and higher order aberrations of the human eye in downward gaze compared to primary gaze. Additionally, a clinical example with a progressive addition lens has been presented to illustrate the potential application of measuring the combined effects of ocular and ophthalmic correction aberrations in downward gaze. Future studies extending this work will provide insight into the performance of ophthalmic corrective lenses *in situ* and the optical properties of the human eye in downward gaze under natural viewing conditions.

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