CLINICAL AND EXPERIMENTAL
OPTOMETRY

RESEARCH

Self-assessment of refractive errors using a simple optical approach

Clin Exp Optom 2018; 101: 386–391 DOI:10.1111/cxo.12650

Alexander Leube* MSc
Caroline Kraft*†‡ BSc
Arne Ohlendorf*† PhD
Siegfried Wahl*† PhD

*Institute for Ophthalmic Research, Eberhard Karls University of Tuebingen, Tuebingen, Germany
†Technology and Innovation, Carl Zeiss Vision International GmbH, Aalen, Germany
‡Optometry and Vision Science, Ernst-Abbe-University of Jena, Jena, Germany
E-mail: alexander.leube@uni-tuebingen.de

Submitted: 2 June 2017
Revised: 11 November 2017
Accepted for publication: 17 November 2017

Background: This explorative study investigated procedures for the self-assessment of spherocylindrical refractive errors.
Methods: Eighteen participants with a mean age of 34.0 ± 8.8 years were enrolled. Adjustable Alvarez lenses were mounted in a rotatable ring holder and two procedures were tested for the self-adjustment: (1) rotation of the lens in three meridians: 0°, 60° and 120° and (2) rotation of the optotypes in the same meridians. Starting from maximum positive power, the participants were required to decrease the power of the Alvarez lens until the optotypes (0.0 logMAR) appeared to be clear the first time. Best-corrected visual acuity (BVA) was measured using a psychophysical staircase procedure. Bland–Altmann analysis was carried out in order to calculate the limits of agreement between the self-refraction method and the standard subjective refraction.
Results: Using procedure 1, 77 per cent of the subjects achieved a VA ≥ 0.1 logMAR (6/7.5) and the same was true for 88 per cent of the subjects using procedure 2. Using procedure 1, a significantly worse BVA was found, when compared to subjective refraction (ΔVA = −0.15 logMAR, $F_{3,140} = 7.11$, $p = 0.046$, median test). Analysis of variance (ANOVA) analysis showed a significant influence of the refraction method on the oblique astigmatism component J_{45} but not for the spherical equivalent M and the straight astigmatism component J_0 (M: $F_{3,140} = 0.532$, $p = 0.661$; J_0: $F_{3,140} = 0.056$, $p = 0.983$; J_{45}: $F_{3,140} = 13.97$, $p < 0.001$; ANOVA). The limits of agreement for the spherical equivalent error M were ± 1.10 D and ± 1.20 D and for the astigmatic components J_0 ± 0.78 D and ± 0.59 D and for J_{45} ± 0.62 D and ± 0.54 D, for procedure 1 and procedure 2, respectively.
Conclusions: Fixed adjustable Alvarez lenses and rotatable stimuli can provide a fast and precise self-assessment method to measure the spherocylindrical error of the eye.

Key words: Alvarez lenses, refractive errors, self-refraction, visual acuity

According to the World Health Organization, uncorrected refractive errors such as myopia, hyperopia and astigmatism can lead to severe blurred vision and are still the leading cause of visual impairment (42 per cent), followed by cataract (33 per cent).[1] A recent review from Naidoo et al.[2] reveals that uncorrected refractive error is the most frequent cause of moderate and severe visual impairment (MSVI, visual acuity [VA] between < 6/18 [0.51 logMAR] and > 3/60 [1.3 logMAR]) worldwide, affecting 52.9 per cent of people, while 20.9 per cent are graded as blind (VA < 3/60), caused by uncorrected refractive errors.

There is a need for easy and cheap solutions not just to correct refractive errors, but also for development of novel solutions to assess the refractive error without professional training or involvement of a trained optometrist. Especially in rural areas in the developing world, the access to eye care professionals is limited and the cost of common correction possibilities, such as spectacles, is high.[3,4]

Liquid-filled glasses (AdSpecs, Adaptive Eyecare Ltd, Oxford, UK) can provide acceptable results in the assessment of the spherical equivalent refractive error M. Surveys by Gudlavalleti et al.[3] and Ilechie et al.[5] found a significant difference between refraction results for self-assessed refraction using liquid-filled glasses and cycloplegic subjective refraction ($\Delta M = -0.44$ D, $p < 0.001$, t-test), but 85.2 per cent of 203 school children reach a VA of better than 0.10 logMAR (6/7.5 Snellen notation). Other studies showed that 92 per cent[6] of school children from Boston, USA and nearly 87 per cent[7] from Chaoshan, China reached a monocular VA that was better than 0.10 logMAR (6/7.5) after self-refraction and also while correcting the spherical equivalent refractive error.

Next to liquid-filled self-adjustable glasses, Alvarez lenses[8] can be used to achieve self-assessment of refractive errors and are available commercially (AdLens, AdLens Ltd, Oxford, UK). These are a set of two lenses with a cubic surface definition that produces a combined optical power which can be adjusted by lateral shifts between the lenses (Figure 1).[9]

Current self-adjustable spectacles, like liquid-filled glasses (AdSpecs) or Alvarez lenses (FocusSpecs), provide a moderate agreement, when compared to conventional refraction techniques for the correction of the spherical refractive error (95 per cent limits of agreement [LoA]:

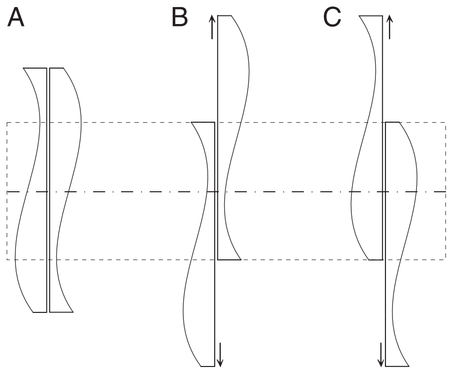

Figure 1. The Alvarez principle. A: Represents the zero power alignment of the lenses. B: The lateral shift between the two lenses results in a negative power, whereas the opposite lateral translation in C: results in a positive power of the lens.

± 1.43 D,[5] ± 1.31 D,[6] ± 1.56 D[10]). However, there are limitations while using liquid-filled glasses, for example the correction and assessment of astigmatism.[3] The purpose of the current pilot study was to develop test procedures and to determine the accuracy of self-refraction for the assessment of spherocylindrical refractive errors (sphere, cylinder and its axis) using adjustable Alvarez lenses.

METHODS

Participants

A prospective, randomised study was carried out at the University of Tuebingen, Germany. Eighteen participants were enrolled with a mean age of 34.0 ± 8.8 years (range 26–54) and a mean spherical equivalent refractive error of −0.61 ± 1.2 D (range from −4.6 D to 2.4 D). The cylindrical ametropia ranged from −0.25 D to −1.75 D with a mean value of −0.58 ± 0.38 D (Table 1).

Participants were recruited from students and employees of the University eye clinic and were made familiar with the procedure of the self-refraction technique to ensure that they perform equally well.

Inclusion criteria for participation were: a refractive error between −5.00 D and +2.50 D of spherical ametropia, less than 2.00 D of astigmatism and best-corrected VA of minimum 0.1 logMAR (6/7.5), assessed on a printed eye chart. Subjects with known ocular diseases were excluded. The study was approved by the Ethics Commission of the Medical Faculty of the University of Tuebingen. The research followed the tenets of the Declaration of Helsinki. Informed consent was obtained from all subjects after explaining the nature and possible consequences of the study.

Participant	Eye	Subjective refraction			Monocular visual acuity (logMAR)	Binocular visual acuity (logMAR)
		Sphere (D)	Cylinder (D)	Axis (°)		
1	OD	−0.25	−0.25	0	−0.25	−0.16
	OS	+1.00	−0.50	90	−0.25	
2	OD	−2.75	−0.25	151	−0.26	−0.30
	OS	−1.75	−0.5	27	−0.26	
3	OD	−0.5	−0.25	168	−0.21	−0.26
	OS	−0.75	−0.75	4	−0.13	
4	OD	0.25	0.00	0	−0.24	−0.30
	OS	0.00	0.00	0	−0.12	
5	OD	−0.5	−0.75	103	−0.24	−0.21
	OS	0.00	−1.00	71	−0.01	
6	OD	−2.00	−0.75	78	−0.26	−0.30
	OS	−1.5	−1.75	72	−0.26	
7	OD	−0.25	−0.25	176	−0.14	0.00
	OS	−0.5	−0.5	20	−0.12	
8	OD	0.00	−0.25	142	−0.30	−0.30
	OS	−0.5	0.00	0	−0.21	
9	OD	0.25	−1.5	104	−0.09	−0.23
	OS	1.5	−0.75	73	−0.04	
10	OD	0.00	−0.50	12	−0.05	−0.18
	OS	0.25	−1.25	6	0.13	
11	OD	1.50	−0.25	150	−0.12	−0.08
	OS	2.50	−0.25	10	−0.01	
12	OD	−0.50	−0.25	75	−0.17	−0.19
	OS	−0.50	−0.25	36	−0.23	
13	OD	0.50	0.00	0	0.11	−0.05
	OS	0.50	−0.25	149	−0.20	
14	OD	1.25	−0.75	78	0.01	−0.28
	OS	0.00	−0.50	84	−0.25	
15	OD	1.25	−0.75	162	0.07	−0.14
	OS	1.00	−0.50	9	0.11	
16	OD	0.25	−0.25	37	−0.25	−0.28
	OS	0.25	−0.25	0	−0.15	
17	OD	−2.00	0.00	0	−0.22	−0.18
	OS	−1.75	−0.5	176	−0.10	
18	OD	−4.00	−1.00	11	−0.22	—

OD: right eye, OS, left eye.

Table 1. Subjective spherocylindrical ametropia (D) and best-corrected monocular and binocular visual acuity (logMAR) for each participant

Self-assessment of the spherocylindrical refractive errors using an Alvarez-based lens

Monocular spherocyclindrical refractive errors were measured using a novel self-refraction method (SfR) that used adjustable glasses (AdLens, AdLens Ltd)

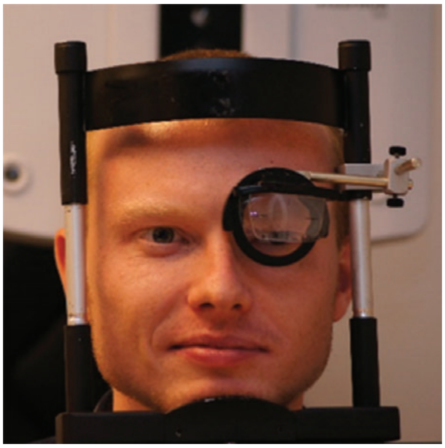

Figure 2. Adjustable Alvarez lens mounted on a ring holder and an adjustment set-up

mounted in a ring holder (Figure 2). In contrast to the original formulation by Alvarez,[8] it was recently shown that these lenses have a moderate amount of astigmatism in the central optical area[11] and it is therefore possible to separate different meridians of interest.

To measure the spherocylindrical refractive errors, two different procedures were tested: (1) rotation of the lens in three meridians: 0°, 60° and 120°, and (2) no rotation of the lens, but a rotation of the optotypes in the same meridians as in procedure 1 (Figure 3). A standard PC Monitor (DELL S2316H, Dell Inc., Austin, Texas, USA) was used to display optotypes at a distance of 5 m.

The meridians were chosen from the procedure to measure refractive errors, using eccentric photorefraction.[12] As described by Gekeler et al.,[12] the ametropia of an eye changes over the pupil meridians and the technique used follows two basic assumptions: (i) that the two principle meridians, with the highest difference in power, are perpendicular, and (ii) that the change over the pupil meridians follows a sine-squared function.

To fit this function, measurements of at least three meridians are necessary. To determine both the spherical and the astigmatic error of the eye using either one of the procedures of the self-refraction method, the participant was asked to adjust the power of the Alvarez lens, starting from maximum positive power (to avoid unwanted accommodation) until the 0.0 logMAR (6/6) line of a letter chart (adopted from the EDTRS[13] chart) was visible for the first time. This procedure was repeated for the three different meridians and three times for each meridian.

The relationship between spherical power change and the relative lateral shift between the lenses was calibrated prior to the experiment (Power (D) = 0.64 * Shift (mm) −1.37, $R^2 = 0.995$), resulting in an accuracy of 0.25 D for the reading of the self-adjusted power.

The participants were placed in a chin and head rest to minimise misalignments between the lens and the eye (Figure 2). All measurements were performed by a single optometrist (CK) at a 5 m distance using one eye, while the fellow eye was covered with an eye patch. The results were corrected for the difference in vertex distances between the self-refraction and the subjective refraction.

The measurement sequence was randomised with respect to the orientation (0°, 60° or 120°) and to the procedure (1 or 2). The spherocylindrical correction (Sph = Sphere, Cyl = Cylinder, Axis) was calculated from power vectors[14] obtained from the measurements of the three meridians R(orientation), according to the following formulas (1)–(6).[12]

$$M = \frac{R(0^\circ) + R(60^\circ) + R(120^\circ)}{3} \qquad [1]$$

$$J_0 = \frac{2 \cdot R(0^\circ) - R(60^\circ) - R(120^\circ)}{3} \qquad [2]$$

$$J_{45} = \frac{R(60^\circ) - R(120^\circ)}{\sqrt{3}} \qquad [3]$$

$$Sph = M + \sqrt{J_0^2 + J_{45}^2} \qquad [4]$$

$$Cyl = -2 \cdot \sqrt{J_0^2 + J_{45}^2} \qquad [5]$$

$$Axis = 0.5 \tan^{-1} \frac{J_{45}}{J_0} \qquad [6]$$

To test monocular and binocular VA, which were achieved using either one of the self-refraction procedures, the corrections were placed in a trial frame and the VA was tested psychophysically using a Best-PEST adaptive staircase procedure (FrACT, Freiburg Acuity and Contrast Test).[15]

Standard procedure for the assessment of refractive errors

In order to compare the spherocylindrical refractions using both self-refraction procedures, the monocular, non-cycloplegic refraction was assessed objectively (OR) using a wavefront aberrometer (i.Profiler plus, Carl Zeiss Vision GmbH, Aalen, Germany) and subjectively, using a standard subjective refraction (SuR)[16] procedure (Subjective Refraction Unit, Carl Zeiss Vision GmbH). The objective refraction was measured three times and the median value from the readings was calculated for a 3 mm pupil. Subjective refraction was assessed using SLOAN-optotypes in an EDTRS layout following the rule: 'most positive power with highest visual acuity'. Monocular and binocular visual acuity was noted for each of the standard procedures, using the same method as for the self-refraction procedure.[15]

Statistical analysis

Data from the different refraction methods was converted to the power vector notation[14] and separately analysed for the three components (M, J_0 and J_{45}). Statistical analyses were performed with a statistics software package (IBM SPSS Statistics 22, IBM, Armonk, New York, USA). Normality of data was investigated using the Shapiro–Wilk test.

To test if there was an influence of the refraction method (CR versus SuR versus SfR) on the VA and the correction value, a multivariate analysis of variance (ANOVA) and Bonferroni post hoc correction was performed. The agreement between the three methods of refraction was tested using a Bland–Altmann[17] analysis, which determined the 95 per cent limits of agreement (LoA) as the product of 1.96 and the standard deviation of the difference between the methods.

RESULTS

Visual acuity

The VA was tested monocularly and binocularly and the testing order was randomised according the refraction method. Ninety-one per cent of the participants had a VA equal or better than 0.10 logMAR (6/7.5) after correction of refractive errors which were obtained either with the objective or subjective prescription. In contrast, VA obtained from the prescriptions after procedure 1 (self-refraction with rotating the lens) was 0.1 logMAR or better in 60 per cent of the subjects, while this was the case for 80 per cent of the subjects with procedure 2 (rotating the optotypes).

Non-parametric testing revealed a statistically significant difference between monocular VA from self-assessed spherocylindrical refraction and objective as well as subjective refraction ($F_{3,140}$ = 22.88, $p < 0.001$, median test). Post hoc analysis showed that the monocular VA was worse when the lens was rotated (ΔVA = −0.20 logMAR, $F_{3,140}$ = 16.51, $p < 0.001$, median test). When procedure 2 of the self-refraction method was used, the median VA between subjective refraction and self-assessed refraction was not different (ΔVA = −0.13 logMAR, $F_{3,140}$ = 8.24, p = 0.062, median test). Pearson correlation revealed no significant correlation between the visual acuities of the different refraction methods ($p > 0.05$, Pearson).

Visual acuity, tested under binocular conditions (BVA), was better than 0.10 logMAR (6/7.5) in all participants, when refractive errors were corrected either with objective or with subjective measurements. Using procedure 1, 77 per cent of the subjects and 88 per cent of the subjects in the case of procedure 2, achieved a BVA better than 0.1 logMAR (6/7.5). BVA was significantly different between the refraction methods ($F_{3,140}$ = 13.96, p = 0.003, median test). Post hoc analysis revealed no difference between rotated optotypes (procedure 2) compared to objective (ΔVA = −0.13 logMAR, $F_{3,140}$ = 5.60, p = 0.108, median test) and subjective refraction (ΔVA = −0.11 logMAR, $F_{3,140}$ = 2.79, p = 0.570, median test). Using procedure 1 (rotated lens), a significantly worse BVA was found, when compared to objective refraction (ΔVA = −0.16 logMAR, $F_{3,140}$ = 11.11, p = 0.005, median test) and subjective refraction (ΔVA = −0.15 logMAR, $F_{3,140}$ = 7.11, p = 0.046, median test). Again, there was no significant correlation between the VA of the different refraction methods ($p > 0.05$, Pearson).

Refractive components under monocular conditions

Multivariate ANOVA showed a significant influence of the refraction method on the oblique astigmatism component J_{45} but not for the spherical equivalent M and the straight astigmatism component J_0 (M: $F_{3,140}$ = 0.532, p = 0.661; J_0: $F_{3,140}$ = 0.056, p = 0.983; J_{45}: $F_{3,140}$ = 13.97, $p < 0.001$; ANOVA). A post hoc test revealed a significant difference between J_{45} for procedure 1 of the self-refraction method ($p < 0.001$), but not for procedure 2 (p = 1.00). Furthermore, the agreement between both self-refraction procedures and the subjective as well as the objective refraction was analysed.

		Mean difference (D)	95% limits of agreement (D)	95% CI for upper limit (D) From	95% CI for upper limit (D) To	95% CI for lower limit (D) From	95% CI for lower limit (D) To
Objective versus SfR (rotated lens)	M	−0.26	±0.89	0.89	0.35	−0.87	−1.41
	J_0	0.01	±0.87	1.13	0.61	−0.59	−1.11
	J_{45}	0.28	±0.70	1.20	0.77	−0.21	−0.64
Objective versus SfR (rotated optotypes)	M	−0.29	±1.09	1.14	0.47	−1.05	−1.72
	J_0	0.02	±0.66	0.89	0.48	−0.44	−0.85
	J_{45}	0.04	±0.59	0.81	0.45	−0.37	−0.73
Subjective versus SfR (rotated lens)	M	0.08	±1.10	1.51	0.84	−0.68	−1.35
	J_0	−0.01	±0.78	1.01	0.54	−0.56	−1.03
	J_{45}	0.31	±0.62	1.13	0.75	−0.13	−0.51
Subjective versus SfR (rotated optotypes)	M	0.06	±1.20	1.62	0.89	−0.77	−1.50
	J_0	0.01	±0.59	0.78	0.42	−0.40	−0.76
	J_{45}	0.07	±0.54	0.76	0.44	−0.30	−0.62

CI: confidence interval, SfR: self-refraction.

Table 2. Descriptive data from Bland–Altmann analysis for the comparison of the objective and subjective refraction to the self-refraction for the three refractive components

The results of the Bland–Altmann analysis are shown in Table 2. In Figure 4A–C the difference versus mean plots are shown for the comparison of the self-refraction method using rotated optotypes (procedure 2) and the subjective refraction for M and J_0, J_{45}.

The mean difference in M for the comparison of self-refraction procedures and the subjective refraction shows small positive values (+0.08 D for rotated lens and +0.06 D for rotated optotypes), whereas the comparison of both procedures to the objective refraction results in mean difference of −0.26 D (procedure 1) and −0.29 D (procedure 2) for the spherical equivalent error. The 95 per cent confidence intervals (CI) of the 95 per cent LoA are around ± 0.35 D for M and ± 0.25 D for the cylindrical components of the refraction. This result shows that the precision of the estimation of the 95 per cent LoA is the range of the precision of a clinical standard refraction (± 0.25 D), even for this small sample size.

Significant correlations were found between the spherical equivalent error (M) assessed during both the self-refraction procedures and the subjective refraction (rotated optotypes: r = 0.743, $p < 0.05$; rotated lens: r = 0.773, $p < 0.05$; Spearman). The correlations for the astigmatic components were weak and showed no significance (J_0: rotated optotypes: r = 0.309, p = 0.07; rotated lens: r = 0.042, p = 0.81; Spearman; J_{45}: rotated optotypes: r = −0.137, p = 0,432; rotated lens: r = 0.156, p = 0.36; Spearman).

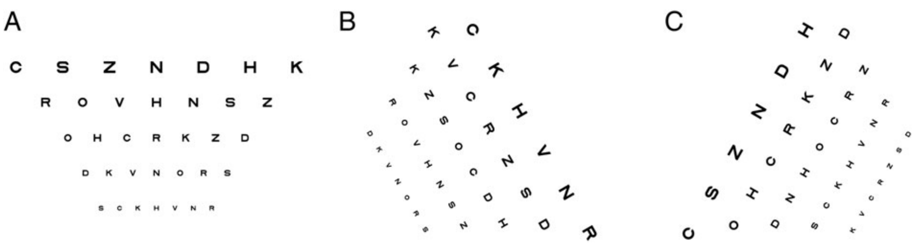

Figure 3. Optotype presentation during self-refraction. A: Orientation 0°, B: orientation 60° and C: orientation 120° for the measurement of three meridians.

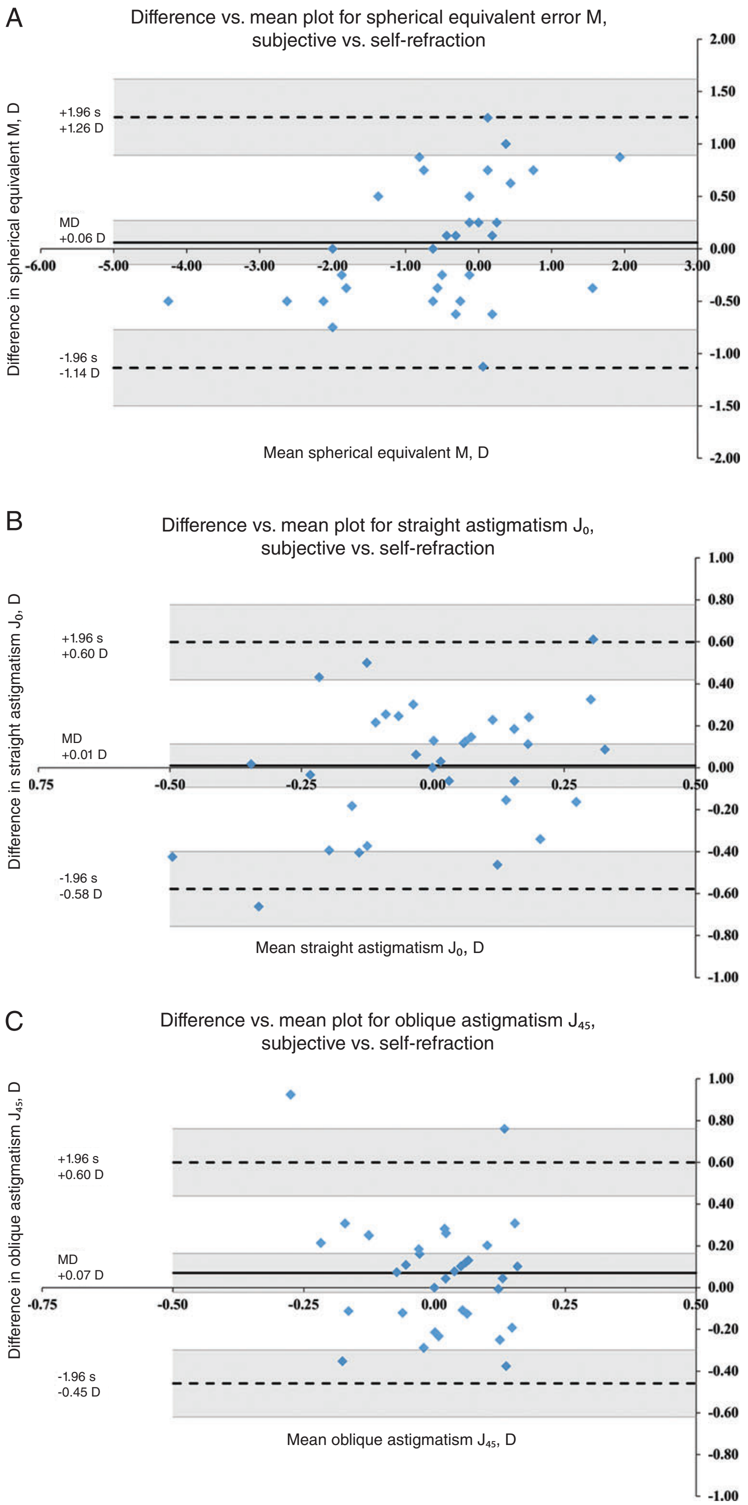

Figure 4. A–C: Difference versus mean plots for the comparison of the subjective refraction and the self-refraction (rotated optotypes) to determine A: the spherical equivalent refractive error (M), B: the straight astigmatism (J_0) and C: the oblique astigmatism (J_{45}). MD: mean difference, S: standard deviation. Shaded areas present 95 per cent CI limits for the mean difference and 95 per cent limits of agreement.

DISCUSSION

Studies regarding the self-assessment of the refractive errors of the eye are currently focused on the measurement of the spherical equivalent error and ignore the assessment of the astigmatic error of the eye and its axis. The results of the present study provide two test procedures for self-refraction in order to self-assess the spherocylindrical refractive errors, using adjustable Alvarez lenses.

Visual acuity

Compared to studies that used liquid-filled adjustable glasses and assessed the spherical equivalent error, without compensating for the astigmatism, the number of subjects that achieved 0.10 logMAR was higher (92 per cent[6] and 87 per cent[7]). Since VA measurements from the current study protocol are attributed to the spherocylindrical correction – and due to the low correlations between the astigmatic components from standard and self-refraction – the VA that was reached with either one of the self-refraction procedures can be expected to be worse. However, there was a reported difference in VA range in the order of repeatability (± 0.2 logMAR, 95 per cent CI) of an acuity assessment using the FrACT.[18] To increase the accuracy of the astigmatism measurement, an assessment of the optical power in the principal meridians of the astigmatic eye can be conducted. A paradigm could be used which incorporates an adjustment of the best spherical lens in the 0° meridian and a self-adjustment of the axis of the Alvarez lens until maximum blur occurs. A spherical adjustment in this meridian would follow and result as the difference in power adjustments as the value for the cylindrical ametropia.

Bland–Altman analysis

The 95 per cent LoA for the spherical equivalent error (Figure 4A) from the present study (± 1.10 D and ± 1.20 D, for rotated lens and rotated optotypes) can be compared to those of others studies (LoA = ± 1.43 D,[5] LoA = ± 1.31 D[6] and LoA = ± 1.56 D[10]) with larger sample sizes (n = 203,[5] n = 350[6] and n = 556[10] school children). The reported LoA from the current investigation are slightly lower, which results in good agreement of Alvarez-based self-refraction with already established subjective and objective procedures.

For the agreement of the cylindrical components (Figures 4B and 4C), a significant increase was found in the difference between the methods with higher astigmatic ametropia for the straight astigmatism J_0 (r = 0.358, p = 0.035, Pearson) but not for the oblique component J_{45} (r = –0.246, p = 0.155, Pearson). However, it should be noted that the maximum extent of the straight astigmatism J_0 component was only 0.71 D.

Two individuals were outside the 95 per cent CIs of LoA for J_{45}, which reflects high individual scatter. The main reason for this scattering was the high ametropia of the participants, since one participant had a spherical refractive error of –4.50 D and the second participant had an astigmatic error of −1.75 D. When these two participants were excluded from the correlation analysis, no significant correlations between the mean and the difference between the methods were present. However, the accuracy of the self-refraction procedure needs to be validated in study groups with a higher amount of astigmatism.

Comparison between both self-refraction procedures

Rotating the optotypes (procedure 2) instead of rotating the lens itself (procedure 1) resulted in higher correlation co-efficients and similar agreement, when compared to the subjective refraction, especially for the astigmatic components of the refractive vectors. This can be explained in two ways. First, the rotation of the lens was not precise enough and small changes in the axis occurred during the power adjustment of the Alvarez lenses. Second, the rotation of the Alvarez lenses changed the gaze point within the lens for every meridian and led to a change in the optical errors. Barbero et al.[9] showed that the combination of two simple Alvarez lenses results in a large amount of optical aberrations, up to 1.25 D, since small changes in gaze position are enabled. This limits the use of Alvarez-based adjustable glasses for the purpose of the self-assessment of refraction. However, the authors proposed a lens design with reduced optical aberrations and enhanced image quality, where a dynamic range of the optical power up to 4.50 D is possible with a lateral displacement between the lenses of ± 3.0 mm. In future applications of the Alvarez-based self-refraction, an optimised lens design based on the higher range in optical power with reasonable optical properties in combination with rotatable stimuli presentation should be used.

Limitations of the study

To account for unwanted accommodation, which is a known problem during subjective refraction, the study protocol required that measurement of the self-assessed refraction for both procedures commenced from maximum positive power until the 0.0 logMAR (6/6) line of optotypes was visible (readable) for the first time. In contrast to the current study, other studies that assessed self-refraction in school children used a cycloplegic agent in order to block accommodation.[3,5–7,10] Since the current study protocol and the protocols from earlier studies are not comparable, it is uncertain if the present results would have been different if a cycloplegic agent would have been used. Future studies should include cycloplegic refractions to assess the accuracy of the self-refraction in order to control accommodation.

The current study was designed as a pilot study to investigate the feasibility of Alvarez lenses in combination with rotatable optotypes for a self-assessment of the refraction of the eye. Therefore, the number of participants included in the trial was limited. Future investigations need to validate the reported methods and larger cohorts with a broader range of astigmatic errors are required. Cycoplegic refraction should be used. Furthermore, alternative stimuli could be used such as non-Latin letters or other geometrical patterns to enable the use of the self-assessment techniques in rural areas.

Self-refraction methods in general involve self-judgement of optical blur, which requires a basic understanding of the refraction procedure. When a standard refraction is conducted, the optometrist supervises the response of the patient and judges and interprets the responses. For self-refraction to succeed, easily understandable instructions must be issued to the participant. To overcome this difficulty, the method adopted in this study could be incorporated into virtual reality or augmented reality glasses and combined with smart software to guide the participant.

ACKNOWLEDGEMENTS

This work was done in an industry-on-campus co-operation between the University of Tuebingen and Carl Zeiss Vision International GmbH. The work was supported by third-party funding (ZUK 63). This study was conducted by the Institute for Ophthalmic Research, University of Tuebingen. A. Ohlendorf and S. Wahl are employees of Carl Zeiss Vision International GmbH.

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