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Measurement of ocular counter-roll using iris images during binocular fixation and head tilt

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Abstract

Objective: To compare the ocular counter-roll (OCR) measured using iris images during binocular fixation and head tilt with OCR measured via fundus photography.

Methods: Fifty-three healthy college students participated in this study. The mean OCR was measured by collection of iris images and fundus images under seven head tilt conditions (0 degrees; 10, 20, and 30 degrees right; and 10, 20, and 30 degrees left). Three iris images (crossed pupil center, pupil center, and pupil periphery) were taken using a slit-lamp biomicroscope with an ophthalmic camera and a half-silvered mirror; fundus images were collected via fundus photography. The mean OCR values were compared between images taken with each method.

Results: No iris images or head tilt conditions revealed any significant differences in mean OCR comparison with fundus images. The mean difference in OCR was smallest, and the correlation was greatest, between the crossed pupil center and fundus images.

Conclusion: A half-silvered mirror and iris images can replace fundus photography for the measurement of OCR.

Keywords

Ocular counter-roll, iris image, binocular fixation, slit-lamp biomicroscope, half-silvered mirror, pupil, fundoscopy, ophthalmological diagnostic technique

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Introduction

The ocular counter-roll (OCR) is a compensatory torsional eye movement that stabilizes images on the retina. It is mainly generated by the vestibular ocular reflex (VOR) during head movement.[1,2] Peripheral sensory organs involved in the VOR each generate an angular VOR (corresponding to head rotational movements) and a linear VOR (corresponding to linear motion and gravity).[3] The motor output of the VOR is performed by extraocular muscles, based on signals from the vestibular system; the OCR is mainly generated by superior and inferior oblique muscles.[4]

OCR measurement methods are subjective (e.g., double Maddox rod and Lancaster screen tests[5,6]) or objective (e.g., ophthalmoscopy and the use of specialized instruments,[7] fundus photography,[8] video camera collection of iris pattern images,[9] and cornea-centered photography[10]). Fluur[11] reported that objective methods for OCR measurement are more reliable and reproducible than subjective methods.

Fundus photography is the most common method for measuring ocular torsion,[12–15] via measurement of the fovea–optic disk center tangent[16] or use of an angle-measuring program.[17] Most fundus photography methods measure ocular torsion with the head and eyes in a static posture.[18,19] However, it is difficult to measure ocular torsion using a dynamic posture or fixation distance. If a patient's pupil is extremely small, pharmacologic dilation or dark adaptation approaches may be necessary; cataracts may also cause measurement difficulty.[20,21]

Proposed alternatives to fundus photography include image collection with a smartphone[22,23] and ocular torsion measurement using a digital camera and image analysis program.[24] Slit-lamp biomicroscopy with a 90-diopter aspheric lens is reportedly a useful approach, but its correlation with fundus photography is weak.[15] In patients with strabismus, OCR measurement using a digital camera and image analysis program revealed results similar to those of fundus photography; moreover, digital cameras were less complicated and more economical than fundus photography.[25] Hussein and Coats[26] reported that iris patterns may be useful for the analysis of OCR associated with head tilt. Several other methods for measuring ocular torsion using an iris image have been reported, but were complicated or did not include any head tilt condition; moreover, they were not compared with fundus photography.[27–29]

The proposed alternative methods for measuring OCR have generally been implemented in a static posture, rather than in a dynamic posture, and have not used multiple fixation distances. OCR measurements might be performed under dynamic postures and various fixation distances by photographing the iris pattern via slit-lamp biomicroscopy with a half-silvered mirror. This study investigated manual OCR measurement by means of slit-lamp biomicroscopy with a half-silvered mirror under binocular fixation and head tilt, then compared the results with those of fundus photography.

Materials and methods

Participants

Participants were college students with no histories of vestibular or ophthalmic diseases, as well as no histories of strabismus or ocular surgery (especially involving the cornea and iris). Lateral and vertical phoria were measured using the Maddox rod test; cyclophoria was measured using the double Maddox rod test. This study was conducted from March 2019 to July 2019 at the Department of Optometry, Kangwon National University

(Samcheok, Korea). This study protocol complied with the Declaration of Helsinki and was approved by the Institutional Review Board of Kangwon National University (IRB approval number: KWNUIRB-2018-12-006-002). Written informed consent was obtained from each participant.

Measurement procedures

Iris images were taken with a slit-lamp biomicroscope (SL-D701; Topcon, Tokyo, Japan) with an ophthalmic camera (DC-4; Topcon) and a half-silvered mirror to enable forward near binocular fixation (Figure 1). Fundus images were collected using a non-mydriatic retinal camera (TRC-NW8; Topcon). Iris images and fundus images (FIs) were taken at intervals of 5 minutes. The location of the target was 40 cm in front of each participant. To measure the head tilt angle, a stick was attached to the center of the participant's forehead using a head band; the angle was confirmed by matching with the angle previously indicated on the forehead and chin rest of the slit-lamp biomicroscope and fundus camera. Head tilt angle was verified using the Smart Protractor app (version 1.5.4; Smart Tools Co.; http://smarttools.me). The sharpest images were selected by capturing the iris images and FIs three times in seven conditions (head tilt angle: 0 degrees; 10, 20, and 30 degrees right; and 10, 20, and 30 degrees left). The selected images were analyzed using ImageJ software[30] to determine the OCR by measuring the angle difference between 0-degree head tilt and the other head tilt conditions (10, 20, and 30 degrees) (Figure 2).

Iris images were taken at 16× magnification; three images were acquired and analyzed to identify a reliable method. The three images were acquired as follows for each of the methods. The pupil center was determined using a drawn image with a total diameter of approximately 4.5 mm and center circle of approximately 1 mm. The drawn image and iris image were overlapped; the pupil center was determined based on the center circle. The first image (crossed pupil center, CPC) spanned from the iris crypts above the pupil, across the pupil center, connected the crypts below the pupil, and was completed with a horizontal line to measure the angle (Figure 3a). The second image (pupil center, PC) spanned from the iris crypts above the

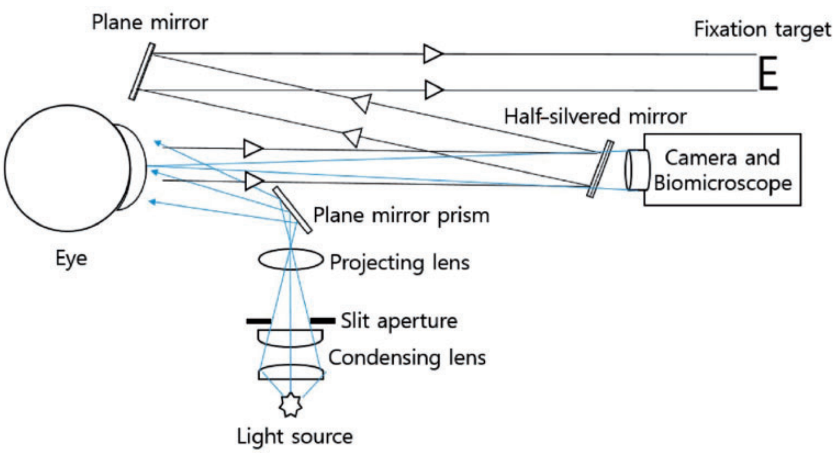

Figure 1. Schematic of a slit-lamp biomicroscope using a half-silvered mirror.

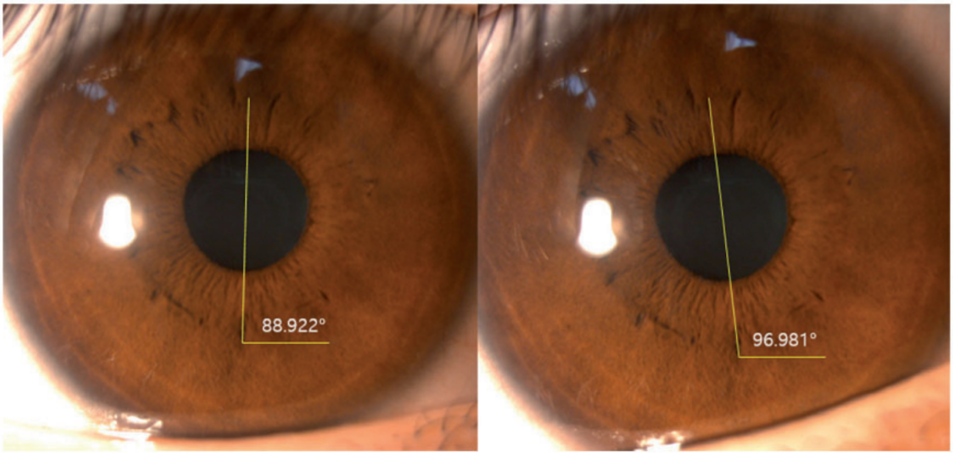

Figure 2. OCR calculated with ImageJ software for the right eye. Head tilt 0° (left image) and 10° rightward (right image). At a head tilt of 10° rightward, the expected angle is 96.981° from 88.922° + 10°; therefore, the OCR expressed by the actual angle is 1.941° from 98.922° to 96.981.
OCR, ocular counter-roll.

pupil, connected the pupil center, and was completed with a horizontal line to measure the angle (Figure 3b). The third image (pupil periphery, PP) spanned from the iris crypts above the pupil periphery, did not cross the pupil center, connected the crypts below the pupil periphery, and was completed with a horizontal line to measure the angle (Figure 3c). The FI OCR was measured by drawing a horizontal line after connecting the blood vessel crossing points around the optic disk and fovea (Figure 3d). Mydriatic drugs were not used in this study; only measurements from the dominant eye were recorded under strong and stable fixation conditions. The OCR was measured three times using each image, after which the mean value was compared.

Statistical analysis

IBM SPSS Statistics for Windows, version 19.0 (IBM Corp., Armonk, NY, USA) was used for data analysis. Two-way analysis of variance, repeated-measures analysis of variance, the Mann–Whitney U test, and Pearson's correlation analysis were to compare the mean OCR among images. In addition, Bland–Altman analysis was performed using MedCalc software, version 10.4 (MedCalc Software, Ltd., Ostend, Belgium) to determine the methodological reliability. A p-value < 0.05 was considered statistically significant; post hoc tests with Bonferroni correction were used to determine the level of significance.

Results

Participant characteristics

Participants ranged in age from 20 to 27 years; the mean age (± standard deviation) was 22.02 ± 1.99 years. In total, 53 participants (32 men and 21 women) were enrolled in this study. A corrected distance visual acuity of 20/25 (0.8) or better was confirmed by subjective refraction; 43 participants (81%) wore glasses. The mean spherical equivalent refractive power was -3.89 ± 2.97 diopters; 39 participants had a dominant right eye, while 14 had a dominant left eye. The mean lateral phoria was

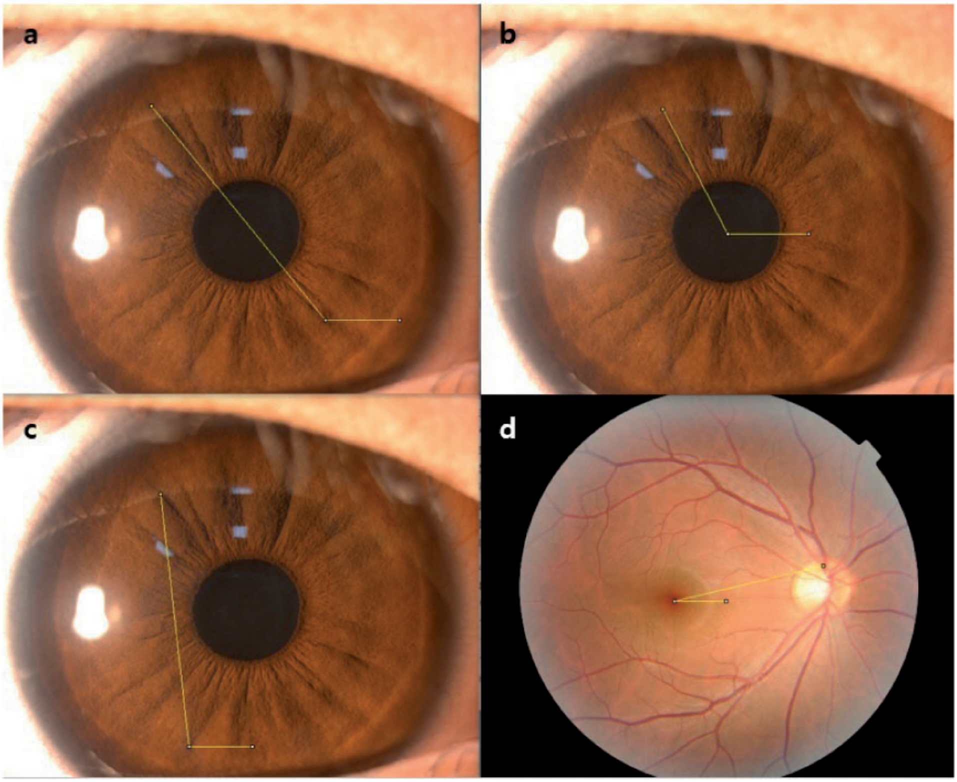

Figure 3. All image conditions of OCR measurements using ImageJ software in this study. (a) crossed pupil center; (b) pupil center; (c) pupil periphery; (d) fundus image. OCR, ocular counter-roll.

2.42 ± 3.98 △ (prism diopter) exo (exophoria) for distance vision and 5.57 ± 7.22 △ exo for near vision; the vertical phoria was 0.17 ± 1.07 △ hyperphoria (standard for right eye) for both distance and near vision. Cyclophoria was not present in any participants.

OCR as a function of head tilt

The mean OCR results among the 53 participants as a function of head tilt, measured with the three iris images and with the FI, are shown in Figure 4. As expected, two-way analysis of variance showed a significant main effect of head tilt, such that OCR increased with increasing leftward and rightward head tilts ($F = 159.296$, $p < 0.001$). Additionally, there was a significant main effect of measurement method ($F = 4.083$, $p = 0.007$; post hoc comparisons: $p = 0.039$ for CPC and PP, $p = 0.038$ for FI and PP), but no significant interaction between head tilt condition and measurement method ($F = 0.178$). In the rightward head tilt conditions, repeated-measures analysis of variance between methods showed significant differences at 10 and 30 degrees ($F = 3.697$, $p = 0.018$ for 10°; $F = 3.609$, $p = 0.019$ for 30°). Among the leftward head tilt conditions, there was a significant difference only at 30 degrees ($F = 4.325$, $p = 0.009$). Post hoc comparisons with Bonferroni correction showed

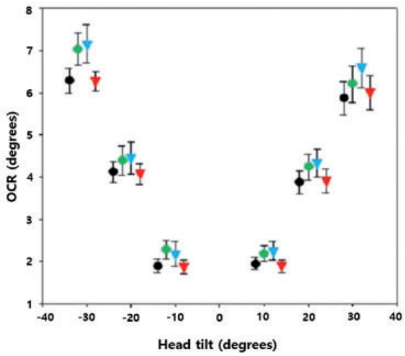

Figure 4. Mean OCR values of the three iris images and a fundus image under conditions of head tilt. Leftward tilt is indicated by a minus sign and error bars reflect standard deviations. Black circles indicate CPC method, green circles indicate PC method, blue triangles indicate PP method, and red triangles indicate FI method.
CPC, crossed pupil center; FI, fundus image; OCR, ocular counter-roll; PC, pupil center; PP, pupil periphery.

that measurements performed using the PC method overestimated the OCR, compared with measurements performed using the FI method in the 10° rightward head tilt condition ($p = 0.027$). Measurements performed using the PC method overestimated the OCR, compared with measurements performed using the CPC and FI methods ($p = 0.007$ and $p = 0.011$, respectively).

Ratios and ranges of OCR relative to head tilt

The ratios of OCR to rightward and leftward head tilt, and the corresponding mean OCR values, are shown in Table 1. Pearson's correlation analysis (Table 2) showed a strong positive correlation between CPC and FI (range of r: 0.938–0.989) and a moderate positive correlation between PP and FI (range of r: 0.506–0.813). Analyses based on dominant eyes (right eye, $n = 39$; left eye, $n = 14$) showed no significant differences between right and left dominant eyes in any condition.

Table 1. Ratios and ranges of OCR relative to head tilt

	Ratio (%)				
Head tilt	CPC	PC	PP	FI	Range (°)
Right 10°	19.5	22.0	22.5	18.7	1.87–2.25°
Right 20°	19.4	21.1	21.7	19.5	3.87–4.34°
Right 30°	19.6	20.7	21.9	20.0	5.87–6.58°
Left 10°	19.0	22.7	21.7	18.6	1.85–2.27°
Left 20°	20.6	22.0	22.3	20.3	4.07–4.46°
Left 30°	21.0	23.4	23.9	20.9	6.28–7.16°

CPC, crossed pupil center; FI, fundus image; OCR, ocular counter-roll; PC, pupil center; PP, pupil periphery.

Correlation and reliability analyses

Comparisons of mean differences and Pearson's correlation analyses among the four methods revealed that the CPC and FI methods showed robust relative reliability. Furthermore, the agreement between OCR values measured by the CPC and FI methods was evaluated via Bland–Altman analysis, as shown in Figure 5. The mean difference between the two methods in the 10 degrees rightward head tilt was 0.08°; the limit of agreement with a 95% confidence interval was 1.47°. At 20 degrees rightward head tilt, the mean difference and limit of agreement with 95% confidence intervals were 0.04° and 1.31°, respectively; these values were 0.13° and 1.69° at 30 degrees rightward head tilt. The corresponding leftward head tilt values were 0.03° and 1.12° at 10 degrees, 0.05° and 1.69° at 20 degrees, and 0.01° and 1.72° at 30 degrees. All images and data underlying the results presented in this study are available at the Zenodo repository (http://doi.org/10.5281/zenodo.4381080).

Discussion

In contrast to traditional fundus photography, the iris image method in this study could measure OCR values in binocular fixation. Although only the near fixation

Table 2. Comparison of mean OCR measured using four images according to head tilt condition

Head tilt	r (p)					
	CPC vs. PC	CPC vs. PP	CPC vs. FI	PC vs. PP	PC vs. FI	PP vs. FI
Right 10°	0.830 ($p < 0.001$)	0.667 ($p < 0.001$)	0.938 ($p < 0.001$)	0.597 ($p < 0.001$)	0.796 ($p = 0.002$)	0.635 ($p < 0.001$)
Right 20°	0.835 ($p < 0.001$)	0.764 ($p < 0.001$)	0.986 ($p < 0.001$)	0.766 ($p < 0.001$)	0.833 ($p < 0.001$)	0.771 ($p < 0.001$)
Right 30°	0.901 ($p < 0.001$)	0.815 ($p < 0.001$)	0.989 ($p < 0.001$)	0.846 ($p < 0.001$)	0.893 ($p < 0.001$)	0.813 ($p < 0.001$)
Left 10°	0.685 ($p < 0.001$)	0.538 ($p < 0.001$)	0.971 ($p < 0.001$)	0.754 ($p < 0.001$)	0.645 ($p < 0.001$)	0.506 ($p < 0.001$)
Left 20°	0.783 ($p < 0.001$)	0.725 ($p < 0.001$)	0.972 ($p < 0.001$)	0.845 ($p < 0.001$)	0.746 ($p < 0.001$)	0.678 ($p < 0.001$)
Left 30°	0.820 ($p < 0.001$)	0.684 ($p < 0.001$)	0.984 ($p < 0.001$)	0.736 ($p < 0.001$)	0.796 ($p < 0.001$)	0.670 ($p < 0.001$)

Analysis performed using Pearson's correlation coefficient.
CPC, crossed pupil center; FI, fundus image; OCR, ocular counter-roll; PC, pupil center; PP, pupil periphery.

distance condition was measured in this study, a half-silvered mirror can measure OCR values at various fixation distances. In addition, the iris image method does not require drug administration or dark adaptation for dilated pupils; it can measure OCR values without affecting patients' ocular media opacity. Moreover, OCR measurements using the iris image method are relatively simple and economical, compared with those performed via fundus photography.[25]

OCR measurements using iris images were divided into three conditions in this study (CPC, PC, and PP), then compared with measurements performed using FI. The CPC method exhibited the greatest reliability. The CPC and FI methods showed lower mean OCR values according to the head tilt (10°, 20°, and 30° right and left, respectively), compared with the PC and PP methods. The CPC method had the lowest mean difference in OCR values, compared with the FI method. The mean difference was greatest at 30 degrees of head tilt. Because the iris always demonstrates fine fluid movement and the pupil size is not fixed, the CPC results show a smaller mean difference from the FI results, compared with the PC and PP results. In this study, the mean ratios of OCR values to rightward and leftward head tilts were 20.6% and 21.4%, respectively. Previous studies concerning OCR values[31,32] reported that the maximum change in OCR according to head tilt was 11°. The OCR measured by the subjective and objective methods at 45 degrees of head tilt were 9.37° and 10.04°, respectively; these corresponded to approximately 21% and 22% for head tilt.[11] In addition, the ranges of OCR values measured by the two methods were 1° to 21° and 2° to 18°, respectively; wide ranges were reported based on differences among individual participants. In a synthesized study that investigated the amount of OCR that compensated for

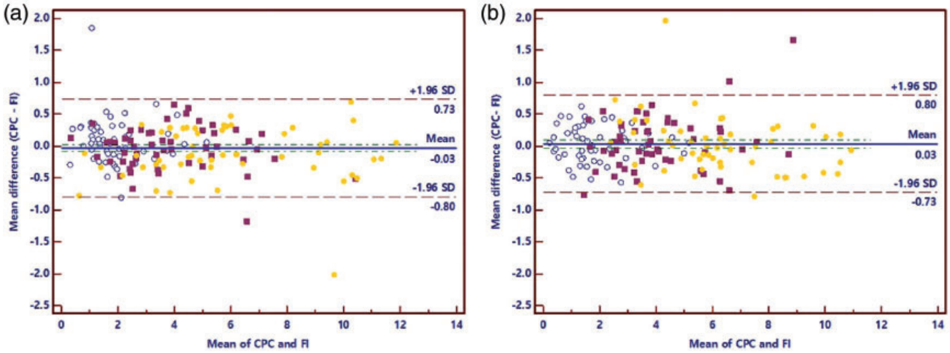

Figure 5. Comparison of mean OCR values measured using CPC and FI methods during head tilt. Red dashed lines represent mean CPC and FI values, with upper and lower 95% limits of agreement (mean difference $\pm$ 1.96 $\times$ standard deviation of the differences). Blue solid line represents the mean of the differences. Green dotted/broken lines indicate 95% confidence interval for mean differences (CPA – FI). (a) Rightward head tilt. (b) Leftward head tilt. Open circles indicate 10° head tilt, red squares indicate 20° head tilt, and yellow circles indicate 30° head tilt.
CPC, crossed pupil center; FI, fundus image; OCR, ocular counter-roll; SD, standard deviation.

head tilt, it was reported that OCR corresponded to approximately 20% of head tilt.[33] In addition, OCR decreased with increasing head tilt. For example, OCR at 20 degrees of head tilt was 20% of head tilt, while it was 10% at 80 degrees of head tilt.[33] The OCR values measured by our method were similar to the results of a previous study using a similar head tilt range.[25] Thus, our findings indicate that iris images are suitable for use in measuring OCR values.

In a previous study concerning the correlation between iris images and FIs in patients with torsional strabismus, the correlation coefficient was 0.988 ($p < 0.001$).[25] In addition, during measurement of OCR values, iris images reportedly could replace FIs. Previous studies that measured OCR values using iris images[25,34] reported that OCR measurement did not significantly differ between iris images and FIs; a strong correlation was observed between the two methods. Unlike previously described methods that lacked investigations of binocular fixation, our method used binocular fixation and a correlation analysis among the mean OCR values measured by the four methods (CPC, PC, PP, and FI); our findings showed positive correlations in all head tilt conditions. The greatest correlation coefficient (0.938–0.989) was observed between the CPC and FI results; this was similar to the value of 0.988 found in a previous study.[25] Therefore, when OCR is measured using iris images instead of FIs, measurement using the CPC method is recommended, because these results showed the greatest positive correlation with those of the FI method.

In our study, the CPC method showed the greatest correlation and lowest mean difference in OCR with the FI method, compared with the other iris imaging methods. Bland–Altman analysis of the CPC and FI results revealed that the mean differences in OCR were generally small (range of mean difference: −0.13 to 0.08) and the 95% limits of agreement were narrow (−0.53–0.59 to −0.85–0.87). The best agreement was observed between the CPC and FI results; therefore, the CPC method can be used as a replacement for fundus photography, which is widely used for OCR measurement.

Fundus photography has several disadvantages. In particular, it is difficult to perform in dynamic conditions (i.e., changes in fixation distance). Thus, it is of limited usefulness as a gold standard for the measurement of OCR and ocular torsion. The OCR measurement method used in this study can be adjusted for target fixation distance to facilitate measurement of OCR or ocular torsion under dynamic conditions. In a previous study concerning ocular torsion measurement in the context of dynamic fixation,[35] ocular torsion increased in excyclotorsion during convergence or when looking upward, but decreased under opposite conditions. Therefore, OCR is presumably affected in dynamic fixation conditions, so the iris image method may be more useful than fundus photography for OCR measurement under such conditions. In addition, the OCR measurement method involving iris images can be easily implemented by clinicians with minimal knowledge of programming or computers.

The method used in this study has some limitations. The half-silvered mirror requires the patient to fixate on an artificial target, rather than a natural target; moreover, the clarity of the target is low because of light reflection. In addition, this method cannot be employed to measure OCR continuously or in real time because considerable manual effort is needed to measure the OCR on each iris image of the patient performing the fixation. The method of measuring OCR using iris images is difficult to carry out in the presence of an iris-related disease or trauma (e.g., aniridia, post-iris adhesion, or pre-iris adhesion) because the iris must retain its crypts for this method to be used successfully.[25] Furthermore, in the presence of pupil eccentricity, the OCR measurement may be inaccurate. Despite these limitations, our results suggest that iris images can replace FIs in the measurement of OCR. Further studies are warranted concerning OCR measurement in the context of various dynamic fixating conditions, such as different target positions.

Conclusions

The use of a slit-lamp biomicroscope with an ophthalmic camera and a half-silvered mirror is useful for OCR measurements in dynamic conditions, which can compensate for the disadvantages of fundus photography. In addition, our findings clearly indicate a small mean difference and strong positive correlation between mean OCR values measured from iris images (especially CPC) and FIs. Thus, iris images can replace FIs in the measurement of OCR. Although OCR measurements using iris images have some limitations because of low target clarity, iris diseases, or pupil eccentricity, they may be more useful than fundus photography under conditions such as changes in fixation distance or dynamic conditions. Therefore, we propose the use of iris images as an alternative in the context of constrained fundus photography for measurement of OCR, or when measurements are required under dynamic fixating conditions.

Declaration of conflicting interest

The authors declare that there is no conflict of interest.

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References

1. Schworm HD, Ygge J, Pansell T, et al. Assessment of ocular counterroll during

head tilt using binocular video oculography. *Invest Ophthalmol Vis Sci* 2002; 43: 662–667.
2. Fetter M. Vestibulo-ocular reflex. *Dev Ophthalmol* 2007; 40: 35–51.
3. De Graaf B, Bos JE and Groen E. Saccular impact on ocular torsion. *Brain Res Bull* 1996; 40: 321–326.
4. Skalicky SE. *Ocular and visual physiology: clinical application*. Sydney: Springer Verlag, 2016, pp.231–249.
5. Liebermann L, Leske DA, Hatt SR, et al. Test-retest variability of cyclodeviations measured using the double Maddox rod test. *J AAPOS* 2018; 22: 146–148.
6. Hwang JM and Guyton DL. The Lancaster red-green test before and after occlusion in the evaluation of incomitant strabismus. *J AAPOS* 1999; 3: 151–156.
7. Madigan WP Jr and Katz NN. Ocular torsion-direct measurement with indirect ophthalmoscope and protractor. *J Pediatr Ophthalmol Strabismus* 1992; 29: 171–174.
8. Morton GV, Lucchese N and Kushner BJ. The role of funduscopy and fundus photography in strabismus diagnosis. *Ophthalmology* 1983; 90: 1186–1191.
9. Bos JE and De Graaf B. Ocular torsion quantification with video images. *IEEE Trans Biomed Eng* 1994; 41: 351–357.
10. Kushner BJ, Kraft SE and Vrabec M. Ocular torsional movements in humans with normal and abnormal ocular motility—Part 1: Objective measurements. *J Pediatr Ophthalmol Strabismus* 1984; 21: 172–177.
11. Fluur E. A comparison between subjective and objective recording of ocular counter rolling as a result of tilting. *Acta Otolaryngol* 1975; 79: 111–114.
12. Rosenbaum AL and Santiago AP. *Clinical strabismus management*. 1st ed. Philadelphia: Saunders, 1999, pp.55–59.
13. Jethani J, Seethapathy G, Purohit J, et al. Measuring normal ocular torsion and its variation by fundus photography in children between 5-15 years of age. *Indian J Ophthalmol* 2010; 58: 417–419.
14. Williams TD and Wilkinson JM. Position of the fovea centralis with respect to the optic nerve head. *Optom Vis Sci* 1992; 69: 369–377.
15. Kothari MT, Venkatesan G, Shah JP, et al. Can ocular torsion be measured using the slitlamp biomicroscope? *Indian J Ophthalmol* 2005; 53: 43–47.
16. Sim JH and Lee SY. The effect of inferior oblique weakening procedures on the correction of ocular torsion. *J Korean Ophthalmol Soc* 2005; 45: 1020–1026.
17. Lee D, Kim WJ and Kim MM. Changes in ocular excyclotorsion according to graded inferior oblique recession. *J Korean Ophthalmol Soc* 2016; 57: 1268–1273.
18. Choi DYD, Lee SM, Park KA, et al. Does decreased static ocular counter rolling account for Bielschowsky head tilt test in unilateral superior oblique palsy? *Invest Ophthalmol Vis Sci* 2017; 58: 4268–4273.
19. Ko BY, Choi JS, Kim KS, et al. Age and gender specific reference value of ocular torsion by using funduscope in Korean. *Res Vestib Sci* 2011; 10: 30–33.
20. Peli E and Schwartz B. Enhancement of fundus photographs taken through cataracts. *Ophthalmology* 1987; 94: 10–13.
21. Yu H, Agurto C, Barriga S, et al. Automated image quality evaluation of retinal fundus photographs in diabetic retinopathy screening. *2012 IEEE Southwest Symposium on Image Analysis and Interpretation* 2012; 1: 125–128. doi: 10.1109/SSIAI.2012.6202469
22. Vilela MA, Valenca FM, Barreto PK, et al. Agreement between retinal images obtained via smartphones and images obtained with retinal cameras or fundoscopic exams – systematic review and meta-analysis. *Clin Ophthalmol* 2018; 12: 2581–2589.
23. Pujari A, Mukhija R, Chawla R, et al. Smartphone-based evaluation of the optic nerve head. *Indian J Ophthalmol* 2018; 66: 1617–1618.
24. Seo J, Kim K, Kim J, et al. Measurement of ocular torsion using digital fundus image. *Conf Proc IEEE Eng Med Biol Soc* 2004; 3: 1711–1713.
25. Felius J, Locke KG, Hussein MA, et al. Photographic assessment of changes in torsional strabismus. *J AAPOS* 2009; 13: 593–595.
26. Hussein M and Coats D. Use of iris pattern recognition to evaluate ocular torsional

changes associated with head tilt. *Ther Adv Ophthalmol* 2018; 10: 1–5.
27. Zhu D, Moore ST and Raphan T. Robust and real-time torsional eye position calculation using a template-matching technique. *Comput Methods Programs Biomed* 2004; 74: 201–209.
28. Groen E, Bos JE, Nacken PF, et al. Determination of ocular torsion by means of automatic pattern recognition. *IEEE Trans Biomed Eng* 1996; 43: 471–479.
29. Hatamian M and Anderson DJ. Design considerations for a real-time ocular counterroll instrument. *IEEE Trans Biomed Eng* 1983; 30: 278–288.
30. Rasband, WS. *ImageJ*. Bethesda: U.S. National Institutes of Health, Bethesda, 2018. https://imagej.nih.gov/ij/ (accessed 29 January 2019).
31. Miller EF. Counterrolling of the human eyes produced by head tilt with respect to gravity. *Acta Otolaryngol* 1962; 54: 479–501.
32. Linwong M and Herman SJ. Cycloduction of the eyes with head tilt. *Arch Ophthalmol* 1971; 85: 570–573.
33. Nagel WA. Über kompensatorische raddrehungen der augen. *Z Physiol Phychol Sinnesorg* 1896; 12: 331–354.
34. Ong JK and Haslwanter T. Measuring torsional eye movements by tracking stable iris features. *J Neurosci Methods* 2010; 192: 261–267.
35. Allen MJ. The dependence of cyclophoria on convergence, elevation and the system of axes. *Am J Optom Arch Am Acad Optom* 1954; 31: 297–307.