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Clinical measurement of compensatory torsional eye movement during head tilt

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ABSTRACT.
Purpose: **To measure the degree of compensatory torsional eye movement during head tilt using a fundus photography method.**
Methods: **We enrolled 55 healthy subjects who were 20–66 years of age. Fundus photographs were obtained in the presumed baseline position and in stepwise head tilt positions to evaluate ocular torsion using a non-mydriatic fundus camera. Horizontal marks on the nose were photographed simultaneously to evaluate head tilt. Images were analysed using Photoshop to measure the degree of ocular torsion and head tilt.**
Results: **A consistent compensatory torsional eye movement was observed in all subjects during head tilt. The degree of compensatory torsional eye movement showed a positive correlation with the angle of head tilt. Ocular torsional disconjugacy was observed during head tilt, with larger excycloductional eye movement than incycloductional eye movement (4.88 ± 2.91° versus 4.50 ± 2.76°, $p < 0.001$). In multiple linear regression analysis, the degree of compensatory torsional eye movement was significantly associated with the degree of head tilt ($\beta = 0.191$, $p < 0.001$), and the direction of cycloduction ($\beta = -0.548$, $p < 0.001$).**
Conclusions: **The fundus photography method is a non-invasive, accurate and objective tool for measuring compensatory torsional eye movement. Considering the availability of fundus photography in clinical ophthalmology practice, the proposed method can be used as a clinical tool to measure compensatory torsional eye movement.**

Key words: eye movements – fundus photography – head tilt – oblique muscles – ocular torsion

Dr. Han Woong Lim had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. Han Woong Lim was involved in study concept and design. Ji Hong Kim and Han Woong Lim were involved in acquisition, analysis or interpretation of data. Han Woong Lim and Ji Hong Kim drafted the manuscript. Sei Yeul Oh was involved in intellectual content. Han Woong Lim and Seung Hun Park were involved in statistical analysis. Sei Yeul Oh obtained the funding. Han Woong Lim, Ji Hong Kim and Sei Yeul Oh were involved in administrative, technical or material support.

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Introduction

When the head is tilted about the naso-occipital axis, a partially compensatory torsional eye movement occurs in the opposite direction of the head tilt. This torsional vestibulo–ocular reflex serves to stabilize retinal images during lateral head tilt (Diamond & Markham 1983). The compensatory torsional eye movement is classified as either static or dynamic. Dynamic movement is mediated by the semicircular canal–ocular reflex that occurs in response to torsional angular acceleration during active head roll movements. Conversely, static movement is mediated by an otolith–ocular reflex that occurs in response to gravitational direction change (Collewijn et al. 1985). Static compensatory torsional eye movement is especially important from an ophthalmologic viewpoint because the otolith-driven reflex forms the basis of the Bielschowsky head-tilt test. This also explains the abnormal compensatory head tilt in patients with superior oblique muscle palsy (Hofmann & Bielschowsky 1900).

The compensatory torsional movement has been studied for nearly two centuries, and many different methods have been used to measure it (Simonsz 1985; Olsson et al. 2015). Recently, several reliable instruments such as the scleral search coil and video oculography have been used in measuring the degree of compensatory torsional movement (Collewijn et al. 1985; Cheung et al. 1992; Schworm et al. 2002; Goltz et al. 2009). However, there are still no standardized, clinically applicable tests for measuring compensatory torsional movement. Accurate measurement of compensatory torsional movement is of clinical importance when evaluating the function of the oblique eye muscles which give rise to torsional movements.

In this study, we developed a photographic technique using fundus photography. Fundus photography is widely used in a general ophthalmology practice, so this technique provides an inexpensive alternative for measurement of compensatory torsional movement. Here, we describe a new photographic technique used to measure the degree of compensatory torsional movement, and evaluate this method in healthy subjects.

Patients and Methods

Study design and participants

This prospective study included 55 healthy subjects (20–66 years of age; 29 males, 26 females). Exclusion criteria consisted of the presence of: strabismus, orbital disease, neurological disease, ocular motility dysfunction, diabetes, and previous ocular or periocular surgery, as well as a corrected visual acuity worse than 20/50 in each eye. The study protocol complied with the Declaration of Helsinki and was approved by the Institutional Review Board (IRB) of Hanyang University Guri Hospital. Informed consent was obtained from all participants prior to inclusion in the study.

Measurement device

Ocular torsion was recorded in different head-tilt positions using a fundus photographic technique. Fundus photographs were taken with a non-mydriatic fundus camera featuring three-dimensional optical coherence tomography 2000 (3D OCT-2000) (Topcon, Tokyo, Japan). The 3D OCT-2000, which includes a high-resolution (12.3 megapixel) fundus camera, was used to obtain fundus images. An internal-fixation target (matrix liquid crystal display) was used in all photographs, and the location of each scan on the retina was monitored using an infrared-sensitive video camera. Single 45° field fundus photographs were centred on the macula. Images were of 24-bit colour depth and were displayed at a resolution of 300 pixels per inch.

Measurement procedure

The optical coherence tomography (OCT) was set-up and a single observer (J.H.K.) examined subjects in a dark examination room. Before obtaining fundus photographs, fiducial marks with a horizontally black striped pattern with 1 mm intervals on a white plastic plate (10 mm × 20 mm) (Fig. 1) were placed on each subject's nose between the medial canthi. Fiducial marks are horizontal lines used to evaluate head tilt. The baseline head position was defined with an individual's head in the straight upright position (0° head roll tilt) without any head tilt or turn. The chin and forehead were firmly anchored to the device chin rest with a band fastened around the subject's head to minimize changes in head position during the examination (Fig 2A). Head position was confirmed at 0° by checking whether the centre of both pupils was parallel to the horizontal line. Care was taken to align pupils horizontally to avoid any significant head tilt and to ensure the gaze was straight ahead. While fundus photographs were obtained, subjects were instructed to fixate on an internal-fixation target, which was presented as a cross on a matrix liquid crystal display. The reference photographs of horizontal marks and both fundi were obtained using the OCT fundus camera (Fig 3A).

After reference photographs of the baseline head position were obtained, the examiner tilted the subject's head about the naso-occipital axis towards his or her right shoulder. Head position was controlled to avoid obvious horizontal and vertical movements with fixation of the subject's head still fastened against the chin rest (Fig 2B). In reference to the horizontal line of fiducial marks using real-time display of OCT, the subject's head was tilted by four stages with interval of 5–10° and with the maximal angle of approximately 40 degrees the right shoulder then returned to the upright position. The head was then tilted correspondingly to the left shoulder. At each head tilt position, photographs of the horizontal marks and both fundi were obtained with fixation of the subject's head using the chin rest (Fig 3B).

Image-processing procedures

Fundal images were processed using Photoshop® 6.0 (Adobe, San Jose, CA, USA). The reference image of the baseline head position was opened in Photoshop®. Images of each head tilt position were selected and copied to a clipboard, and the clipboard contents were pasted onto the baseline image to create a separate layer. The pasted layer was converted to a semitransparent image to overlap with the baseline image (Fig 3C) (Lim et al. 2014a,b). Using the free transform and rotate tool, the pasted layer was rotated to match the baseline image. The angle of rotation expressed in the Photoshop® menu bar was recorded to measure head tilt angle and ocular torsion angle.

Measurement of the degree of compensatory torsional movement

The degree of compensatory torsional movement was defined as the difference

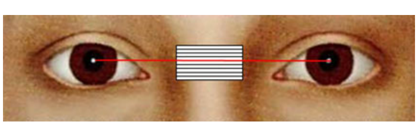

Fig. 1. Fiducial marks are horizontal lines placed on the nose between the medial canthi. The centre of both pupils and horizontal lines of fiducial mark lined up parallel. Fiducial marks are used to evaluate the degree of head tilt.

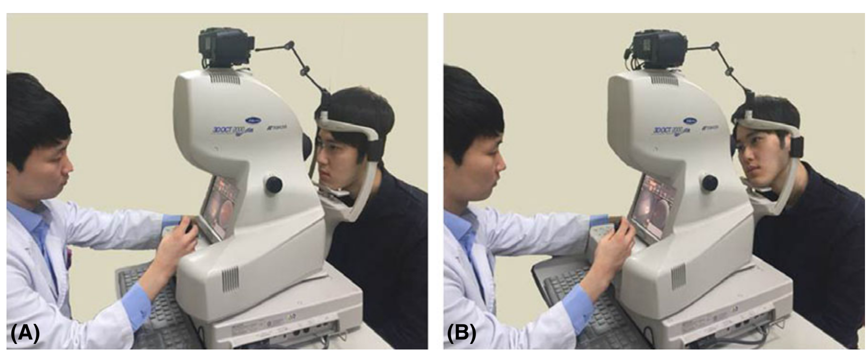

Fig. 2. The method of compensatory torsional movement measurement using fundus photograph. The chin and forehead were firmly anchored to the device with chin rest using a band wound around subject's head. A, The baseline head position (0°head roll tilt) in the straight upright position. B, The right head tilt position. The subject tilted his head about the naso-occipital axis towards his right shoulder.

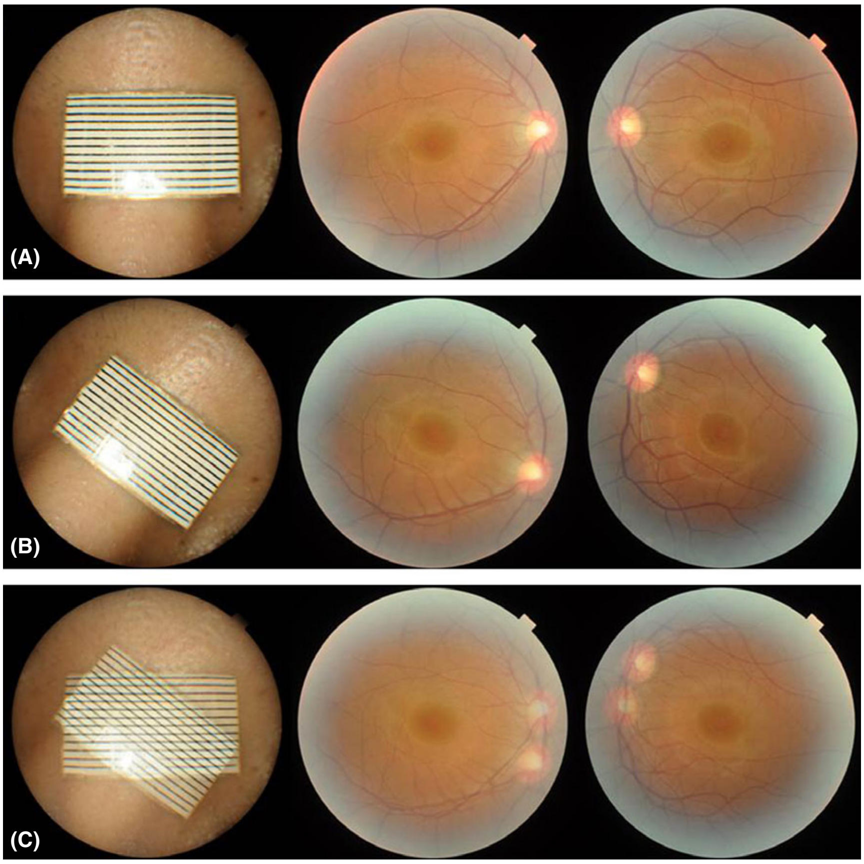

Fig. 3. Image processing by Photoshop for quantitative measurement of the degree of compensatory torsional movement during head tilt. A, Photograph of horizontal marks on the nose and fundus photographs of both eyes obtained in the presumed baseline position. B, Photographs of horizontal marks and both fundus at the left head tilt position. C, The image of the head tilt position was converted to a semitransparent image, and it overlapped with the baseline image.

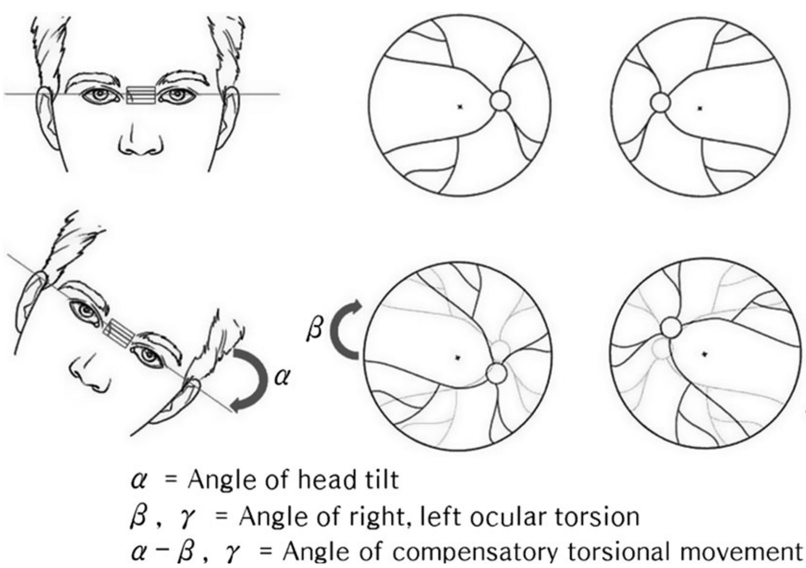

Fig. 4. Schematic of both ocular torsions according to head tilt. The degree of compensatory torsional movement is defined as the difference between the angle of head tilt (α) and the angle of an ocular torsion (β = angle of right ocular torsion, γ = angle of left ocular torsion).

between the head tilt angle and ocular torsion angle (Fig. 4). It was assessed by calculating the recorded angle of rotation with Photoshop. To determine interobserver reliability, two independent observers (H.W.L. and J.H.K.) measured the images using the above method.

Statistical analysis

Statistical analyses were performed using SPSS for Windows version 17.0 (SPSS, Inc, Chicago, IL, USA) and the MEDCALC statistical packages (V.12.7, MedCalc Statistical Software, Ostend, Belgium). The relationship between the degree of compensatory torsional movement and the angle of head tilt was evaluated using the Pearson's coefficient of correlation. The degree of compensatory torsional movement between the right eye and left eye, right head tilt and left head tilt, and the excycloductional eye and incycloductional eye was compared with the paired *t*-test. Multiple linear regression analysis with stepwise variable selection was used to determine the relationship between the degree of compensatory torsional movement and multiple variables (the angle of head tilt, the direction of head tilt, and the direction of cycloduction). Agreement between measurements was represented with Bland–Altman plots (Bland & Altman 1986). p-values <0.05 were considered statistically significant.

Results

Fifty-five subjects were included in this study: 29 males and 26 females (age range, 20–66; mean, 38.3 ± 14.9 years). All subjects showed consistent compensatory torsional eye movements corresponding to the amount of head tilt. The relationship between head tilt angle and the degree of compensatory torsional movement is shown in Fig. 5. In any direction of head tilt (right and left), the compensatory torsional movement was observed consistently in both eyes. When analysing the relationship between the angles of head tilt and the degrees of compensatory torsional movement, the degrees of compensatory torsional movement were positively correlated with the angle of head tilt (right head tilt; right eye $R = 0.744$, left eye $R = 0.678$; left head tilt; right eye $R = 0.743$, left eye $R = 702$; all $p < 0.001$).

There were no significant differences in the mean degree of compensatory torsional movement between right and left eyes (4.60 ± 2.83° versus

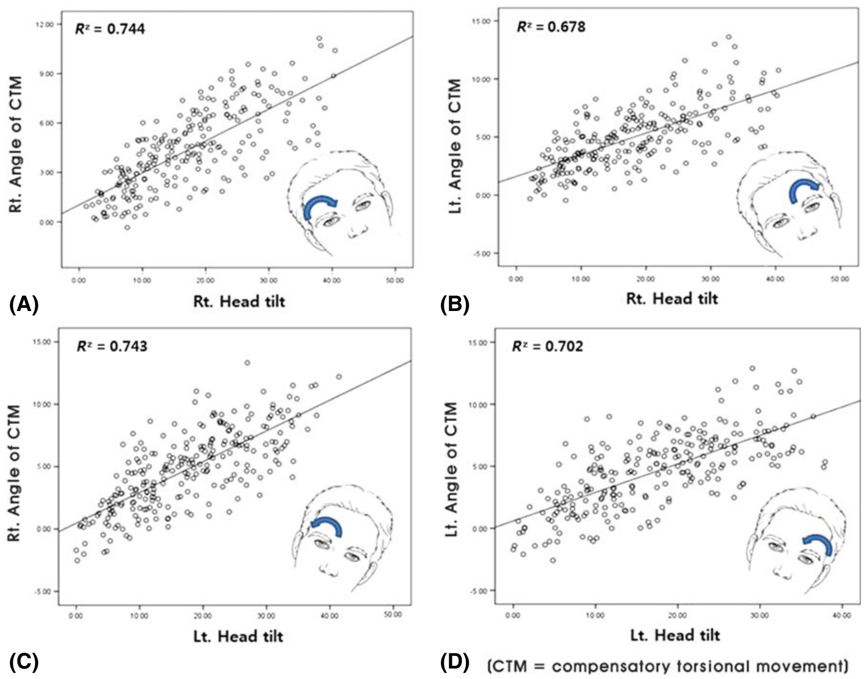

Fig. 5. Scatter plots showing the correlations between the angle of head-tilt and the degree of compensatory torsional movement. A, Scatter plots showing compensatory torsional movement of right eye when the head was tilted to the right. B, Scatter plots showing that of left eye when the head was tilted to the right. C, Scatter plots showing that of right eye when the head tilted to the left. D, Scatter plots showing that of left eye when the head was tilted to the left. All subjects exhibited a consistent compensatory torsional movement corresponding to the amount of head tilt.

Table 1. Mean degree of compensatory torsional movement during head tilt in both eyes, head tilt and cycloduction

	Compensatory torsional movement (°)	p-value
Right eye	4.60 ± 2.83	0.311
Left eye	4.78 ± 2.86	
Right head tilt	4.67 ± 2.57	0.829
Left head tilt	4.71 ± 3.08	
Excycloduction	4.88 ± 2.91	<0.001
Incycloduction	4.50 ± 2.76	

Table 2. Multiple linear regression analysis for the association between the degree of compensatory torsional movement, amplitude of head tilt and direction of cycloduction

	R^2	$\beta \pm$ SE	p value
The degree of head tilt (°)	0.423	0.190 ± 0.007	<0.001
The direction of cycloduction	0.432	−0.535 ± 0.1.38	<0.001

SE = standard errors.
Overall R^2 = 0.431.

4.78 ± 2.86°, p = 0.311) or between right head tilt and left head tilt (4.67 ± 2.57° versus 4.71 ± 3.08°, p = 0.829). However, the mean degree of compensatory excycloduction (compensatory torsional movement of the left eye in right tilt and the right eye in left tilt) was significantly larger than the compensatory incycloduction (compensatory torsional movement of the right eye in right tilt and the left eye in left tilt) (4.88 ± 2.91° versus 4.50 ± 2.76°, p < 0.001) (Table 1).

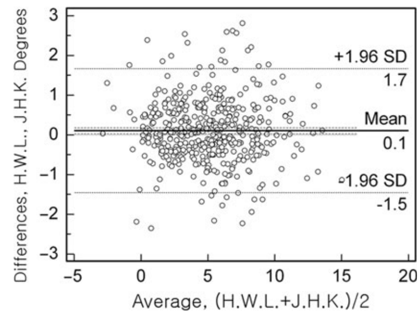

Fig. 6. Interobserver reproducibility for measurement of the compensatory torsional movement by two observers (H.W.L. and M.L.), assessed using the strategy of Bland and Altman. Upper and lower dotted lines: 95% limits of agreement with 95% confidence intervals. SD = standard deviation.

We used multivariate analysis to identify the factors that directly influenced the degree of compensatory torsional movement. The results of multiple linear regression analysis showed that the angle of head tilt and the direction of cycloduction were significant predictors of the degree of compensatory torsional movement, and the angle of head tilt was the most relevant variable (p < 0.001; standard regression coefficient = 0.243). Table 2 summarizes the multiple linear regression analysis, which shows the individual relationships between the angle of head tilt, the direction of head tilt and the direction of cycloduction with the degree of compensatory torsional movement.

Interobserver variability was determined using the results of two independent examiners. The Bland–Altman strategy was applied to compare the differences between the two measurements with averages. The mean difference between observers was 0.1°, with 95% confidence limits of −1.5° and 1.7° (Fig. 6). The zero difference line lies within these confidence levels, confirming that mean interobserver difference is not significant.

Discussion

In this study, we presented a new fundus photographic method that measures compensatory torsional eye movement during head tilt with a fundus camera. This method may be used as a non-invasive, inexpensive and objective technique for measuring compensatory torsional movement. It requires fundus photography, which is widely used, and thus can be implemented in clinical practice more easily than eye-tracking methods such as scleral search coils or video oculography. This study demonstrated that a new fundus photographic method can objectively measure the degree of compensatory torsional movement during head tilt. The fact that our method requires only a fundus camera makes this technique more available and valuable in clinical practice.

Many different methods have been used to measure compensatory torsional movement during head tilt. In 1975, Kanzaki reported the compensatory torsional movement measurements of 14 normal adults performed with a funduscopic camera (Kanzaki 1975). He measured this using a tilting chair with a head frame and an ophthalmic funduscopic camera. Although this is similar to our method, our method is advantageous in that it does not require a large motor-driven tilting chair or mydriatics. In addition, our method allows objective photograph evaluation using Photoshop.

A scleral search coil has also been used to study compensatory torsional movement during head tilt. Collewijn et al. (1985) assessed the static and dynamic properties of compensatory torsional movement using a scleral search coil technique. They concluded that dynamic torsional movement reduces cyclorotational slip velocity on the retina, and static torsional movement is smaller than dynamic. However, the scleral search coil technique is invasive and can underestimate real torsion due to coil slippage. In addition, free eyeball movement might be restricted when a contact lens is pressed against the sclera or the lead wires of the contact lens contact the upper lid (Bergamin et al. 2004). More recently, compensatory torsional movement during head tilt has been measured using three-dimensional video oculography (3D-VOG). Three-dimensional video oculography (3D-VOG) is an infrared video-based system used to measure 3D eye movements (horizontal, vertical, and torsional). Infrared-illuminated video cameras simultaneously record eye images for both eyes, and torsional eye positions are determined from iris landmarks. This technique has been applied in several studies to objectively measure torsional movement (Jampel & Shi 2002; Schworm et al. 2002; Goltz et al. 2009). However, this method requires expensive equipment and sustained technical expertise to use and maintain and thus is not practical or applicable in common clinical settings.

The main strength of our method is that the results are based on the real torsion of the fundus, which is coincident with the visual axis. Most previous studies have evaluated eyeball positions based on an assumption that the corneal light reflex is the centre of torsional movement. Intrinsic errors are therefore inevitable, as the real centre of ocular cycloduction is not the corneal light reflex. Moreover, a slight amount of lateral and vertical head movement can cause significant shifts in the corneal light reflex. In addition, fundus photographs can obtain accurate data from the optic disc and retinal vessels in reference to its zero position, so markers of iris pattern do not affect measurements. Despite the use of miotics in the VOG method, lighting direction or pupillary movement can displace landmarks on the iris and limbus. Finally, this study employed an internal OCT fixation target, which gives the highest reproducibility of RNFL measurements (Schuman et al. 1996). This device provided constant target fixation regardless of head movement and prevented disparity convergence, which can reduce the angle of compensatory torsional movement (Kushner 2004).

In this study, the degree of compensatory torsional movement increased according to the amount of head tilt. There was consistent compensatory torsional movement in both eyes with head tilt in any direction. The degree of torsional movement correlated positively with the angle of head tilt ($R = 0.723$). The results are similar to those reported previously using an eye-tracking technique. Using VOG, Goltz et al. (2009) reported that compensatory ocular torsion is strongly dependent on the amount of head tilt. They showed a sigmoidal relationship between mean torsional eye movement and head tilt angle. Similarly, Schoworm et al. (2002) used VOG with a tiltable chin rest to measure compensatory torsional movement in 5 healthy individuals. They reported that all subjects had consistent torsional movement in both eyes that increased with head tilt. Cheung et al. (1992) reported that static compensatory torsional movement increased (2.0–4.5°) in response to head tilt when measured with a scleral search coil.

We found significant disconjugate torsional movement. The mean degree of the compensatory excycloduction (contralateral to the direction of head tilt) was larger than that of incycloduction. These results agree with the findings reported by Pansell and colleagues, a study which showed a consistent excyclovergence (compensatory excycloduction >incycloduction) in 20 healthy subjects (Pansell et al. 2003). Markham and Diamond (2001) also reported the static compensatory torsional disconjugacy in 10 healthy subjects using VOG. They suggested that the disconjugacies might arise from intrinsic asymmetries in the otolith organs on each side of the head. Further studies involving the otolith organs are warranted to determine the relationship between ocular torsional disconjugacy and the otolith organ.

In multivariate regression analysis, we found that the degree of compensatory torsional movement was significantly influenced by the angle of head tilt and the direction of cycloduction. The angle of head tilt showed the strongest effect on the degree of torsional movement. This suggests that the compensatory torsional movement during head tilt is influenced mainly by the degree of head tilt, but not at all by the direction of head tilt.

The present study has several limitations. First, because bite bars were not used, there was potential for head movement, particularly patients turning their head or moving their chin up or down. However, it is difficult to use bite bars in clinical setting, so we used fiducial marks for measuring the angle of head tilt, and the examiner tilted the subject's head about the naso-occipital axis with help of an assistant with a chinrest and a band around the head was used to fix the head at each head tilt position. Second, fundus photography can require a long period of time if the subject has small pupils and/or when the fundus is difficult to focus on. Thus, examinations were performed in a darkened room, and mydriatics were only used in two subjects because it was impossible to obtain sharp fundus photographs despite the dark environment.

In conclusion, we propose a new photographic method that can measure the angle of compensatory torsional movement during head tilt using fundus photography. The current study demonstrated that compensatory torsional movement increased in response to lateral head tilting and ocular torsional disconjugacy occurred during head tilt. This new technique allows a non-invasive, inexpensive way to measure compensatory torsional movement. Considering these advantages, the proposed method can be used as a clinical tool to measure the compensatory torsional movement induced by head tilt.

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