Shaw, Alyra J. and Collins, Michael J. and Davis, Brett A. and Carney, Leo G. (2009) ***Eyelid pressure: inferences from corneal topographic changes.*** Cornea, 28(2).

Eyelid pressure: inferences from corneal topography changes

Alyra J. Shaw BAppSc(Optom), Michael J. Collins PhD, Brett A. Davis BAppSc, Leo G. Carney PhD

Corresponding author:

Alyra Shaw

Contact Lens and Visual Optics Laboratory, School of Optometry,

Queensland University of Technology,

Victoria Park Road, Kelvin Grove, Queensland, Australia, 4059

Phone: +61 7 3138 5715, Fax: +61 7 3138 5665, E-mail: aj.shaw@qut.edu.au

Financial interest of the authors: none

Figures: 5 Table: 1

Date of initial submission: 29/01/2008

Date of revised submission: 08/07/2008

Date accepted: 11/08/2008

ABSTRACT

Purpose: It is known that eyelid pressure can influence the corneal surface. However the distribution of eyelid pressure, the eyelid contact area and the biomechanics of the changes are unknown. While these factors are difficult to directly measure, analysis of eyelid-induced corneal topography changes and eyelid morphometry enable some inferences to be drawn. **Methods:** Eighteen subjects, aged between 19 and 29 years, with normal ocular health were recruited. Corneal topography changes were measured after four conditions consisting of two downward gaze angles (20° and 40°) and two types of visual tasks (reading and steady fixation). Digital photography recorded the width of Marx's line, the assumed region of primary eyelid contact with the cornea. **Results:** Significantly larger corneal changes were found after the 40° downward gaze conditions compared with 20° due to the upper eyelid contact ($p<0.001$). For the 40° downward gaze tasks, the lower eyelid changes were greater than those due to the upper eyelid ($p<0.01$). The upper eyelid Marx's line width was associated with the amplitude of corneal change ($R^2=0.32$, $p<0.05$). **Conclusion:** Analysis of the corneal topography changes gives insight into the pressure applied by the upper and lower eyelids in different situations. These include greater upper eyelid pressure with increasing downward gaze and larger lower eyelid pressure compared to the upper eyelid in 40° downward gaze. There was some evidence that supports Marx's line as the primary site of contact between the eyelid margins and the cornea.

Key words: corneal topography, eyelid pressure, near tasks, Marx's line

INTRODUCTION

The cornea is the principal refractive component of the eye. However, the corneal surface is not fixed and is known to be susceptible to eyelid pressure. Increased or altered eyelid pressure can occur from eyelids that are abnormal in structure. For example, induced astigmatism from eyelid chalazia and haemangiomas has been shown to be dependent on the size and location of the eyelid defect[1, 2]. Ptosis also causes changes in corneal astigmatism [3, 4], with surgery able to partially reverse the induced change [4-7].

Normal eyelids can also alter corneal topography. Eyelid retraction and narrowing of the palpebral aperture have been shown to alter corneal astigmatism [8-10]. Typically the mechanical effect of the eyelids on the cornea causes a change in 90/180 astigmatism [8, 11]. In primary gaze the vertical palpebral aperture is 9.7 mm, which decreases to 7.9 mm in 20° downward gaze and 6.4 mm in 40° downward gaze [12]. The altered position of normal eyelids on the cornea in downward gaze has been found to have a clear association with bands of corneal topography change which are parallel to the eyelid margin[13-15].

Marx's line extends along both the upper and lower eyelid margins and is thought to be the primary site of contact between the eyelid margin and the surfaces of the bulbar conjunctiva and cornea. It is a distinct line of squamous cells located just posterior to the Meibomian gland orifices and is visible when stained with lissamine green dye [16, 17]. Its anatomical features are consistent with tissue that is subject to mechanical trauma and is thought to stain with vital clinical dyes due to a lack of mucous coating. Doughty et al. [17] reported that Marx's line seems to be present in nearly all individuals and is an anatomical feature with no obvious age or gender-related differences.

Previous investigations considering eyelid-induced corneal changes have assessed the influence of downward gaze angle[18], eye movements[18] and different visual tasks including reading, microscopy and computer work [14]. An association between the magnitude of the corneal optical changes and anatomical features of the eyelid has also been examined. Both Buehren et al. [19] and Shaw et al. [20] found that narrower palpebral apertures during reading lead to increased higher order aberrations and increased spherical power changes respectively. Shaw et al. [20] have shown that eyelid curvature and tilt also influence the magnitude of corneal optical change. It was also noted that subjects with narrower palpebral apertures during reading did not necessarily have significantly narrow aperture sizes in primary gaze [19].

This study provides further detail of the corneal changes induced by the upper and lower eyelids. A localised topographical analysis method was developed to determine the magnitude, shape and width of the corneal changes. Analyzing the eyelid-induced corneal changes for a number of conditions allowed the relative eyelid pressure to be inferred. Digital photographs were taken of Marx's line to explore possible correlations with the corneal changes.

MATERIALS AND METHODS

Eighteen subjects, aged between 19 and 29 years, with an average age of 23 ± 3 years took part in the study. There were eight emmetropic (± 0.25 D) and ten myopic ($\leq$ -0.50 D) subjects and equal numbers of males and females. The average refractive error was -1.22 ± 0.66 D and ranged from +0.25 to -5.75 D with -0.75 D or less astigmatism. Inclusion criteria for subjects included corrected acuity of 0.0 log MAR or better and normal anterior ocular health. Conditions that excluded subject participation were blepharitis, conjunctivitis, Meibomian gland dysfunction and dry eye, as they have the potential to alter eyelid morphometry, ocular surface health and the staining of Marx's line [21-23]. A diagnosis of dry eye was made on the basis of dry eye symptoms (McMonnies score $\geq$ 14) and reduced tear film stability (NITBUT < 10 seconds) [24].

Subjects were excluded if they had a history of ocular surgery or rigid gas permeable contact lens wear, to minimise existing topographical alterations from eyelid pressure and contact lenses. All subjects were asked to avoid any substantial reading on the morning of the experiment [14, 25] and soft contact lenses wearers were requested to refrain from lens wear for at least 32 hours prior to testing [26-31]. Only the left eye was tested for each subject to avoid issues associated with enantiomorphism in eyelid morphometry and corneal topography [32, 33].

The protocol fulfilled the requirements of the university ethics committee and adhered to the tenets of the Declaration of Helsinki, including obtaining informed consent from all participants. Six baseline corneal topography measurements of the left eye were taken using the Medmont E300 Corneal Topographer (Medmont Pty. Ltd., Victoria, Australia). This videokeratoscope has high levels of accuracy and precision for both spherical and aspherical test surfaces [34] and high repeatability on human subjects [35]. Subjects were instructed to blink prior to topography measurements and the image was taken within a few seconds.

The protocol was designed to allow investigation of the effects of eyelid pressure in four downward gaze conditions. This involved combinations of two downward gaze angles, 20° and 40°, with two visual tasks, reading (eye movements) and steady fixation (no eye movements). The 20° downward gaze conditions most closely represents the vertical eye gaze angle usually adopted during reading (approximately 25°) [36], while the 40° conditions examine a more extreme downward gaze angle. Blinking occurred during both the reading and steady fixation conditions. While blink rate has been shown to vary for different tasks [37-39], variation in blink rate is unlikely to influence the corneal changes. A blink lasts approximately 0.26 seconds [40] and therefore with approximately 11.1 blinks per minute [41], less than 5% of the total time is spent blinking. So the four conditions studied were: 1) reading at 20° downward gaze; 2) steady fixation at 20° downward gaze; 3) reading at 40° downward gaze; and 4) steady fixation at 40° downward gaze.

For each of these tasks the subject was positioned in a head rest, to ensure consistency of eye and head position, and viewed a computer monitor with reading text at 40 centimetres distance from the eyes. For the 15-minute reading task, three lines of N12 text (standard novel font size) were visible at any one time through a cut-out window and a mouse or keyboard was used to scroll the text to allow continuous reading. This set-up ensured that the subject's eye movements were primarily in the horizontal plane. During the steady fixation tasks a fixation cross was visible in the centre of the cut-out window. Subjects were instructed to blink naturally during all four tasks, which were completed in random order.

Immediately following the near task, six topography measurements were captured. As the magnitude of lid-induced corneal distortions declines sharply immediately after a near task [42], these measurements were taken within two minutes.

A lissamine green impregnated strip, wetted with two drops of sterile saline, was applied to the superior and inferior bulbar conjunctiva of the left eye. To photograph Marx's line the upper eyelid was everted and the lower eyelid was rotated away from the eye globe. Images of Marx's line were captured using a high resolution digital camera and macro lens with a fluorescent ring light.

Following data collection, height data were exported from the videokeratoscope and analysed using custom written software. Elevation topography maps were chosen for analysis as these most closely represent the actual physical corneal change. An average of 6 maps were exported and averaged according to the method of Buehren et al. for each condition [25], Elevation difference maps (post-task minus pre-task) were then calculated to examine eyelid-induced corneal changes after each visual task.

Within the band of topography change, the corneal valley (depression) was used as the reference. User-defined points were chosen along the valley and fit with a 4th order polynomial function (Figure 1). Cross-sections of data were taken perpendicular to the polynomial function, extending 1 mm either side, with a spacing of 0.05 mm. The limits of these cross-sections define the localised area under consideration (refer to open circles and first and last cross-sections in Figure 1). Across each 2 mm cross-section, 16 points were interpolated with a spacing of 0.13 mm, replicating the Medmont topographer's normal radial spacing of data points. Each cross-section was fit with a 9th order polynomial, which was the lowest order found to minimise the fit error while also closely representing the original data. The maxima and minima (peaks and valleys) were determined by locating when the first derivative of the fit was equal to zero.

As a measure of the magnitude of the eyelid-induced corneal change, peak-to-valley amplitudes of change were calculated from the difference topography maps [42]. Peak-to-valley amplitudes were determined from the valley towards the centre of the cornea (central peak-to-valley) and from the valley towards the edge of the cornea (peripheral peak-to-valley) (Figure 2). The distance from the central peak to the peripheral peak was used as a measure of the width of corneal change. The amplitudes and widths for each subject and condition were saved in an output file along with the original x, y and z coordinates of the valley and the corresponding cross-section number. Three corneal regions were defined relative to the videokeratoscope centre: nasal (-2.5 to -1.5 mm), central (-0.5 to 0.5 mm) and temporal (1.5 to 2.5 mm) (Figure 1). Approximately 20 cross-sections within each of these areas were averaged to obtain mean values for each region.

Some subjects had narrow palpebral apertures and couldn't open their eyes wide enough, so the eyelash shadows often inferred with the image captured by the corneal topographer. For these subjects the eyelid-induced changes were often at the edge of the topography map. Data was only analysed for subjects with distinct eyelid-induced corneal changes that were not in close proximity to the edge of the topography map. This ensured the integrity of the polynomial fit to the elevation topography data. The number of maps analysed for the upper eyelid-induced corneal change for each condition was 9 (20° reading), 10 (20° steady fixation), 13 (40° reading) and 17 (40° steady fixation). For the lower eyelid there were no eyelid-induced corneal changes within the area captured by the videokeratoscope for the 20° tasks. While for both the 40° reading and 40° steady fixation conditions, 11 maps had complete eyelid-induced changes and were analysed.

The central and peripheral peak-to-valley amplitudes were compared using mixed linear analysis and their relationship examined by a Pearson's product moment correlation. The ideal method to analyse the effect of the downward gaze angle, type of visual task, corneal region and central peak-to-valley amplitude versus peripheral peak-to-valley amplitude, would be to apply a repeated measures MANOVA. However there was a high correlation between central and peripheral peak-to-valley amplitudes and few subjects had data for every condition and corneal region. So a mixed linear model was used which took into account the differing amount of data per subject by including subject identity as a random factor. Using this method, the effects of downward gaze angle, visual task and corneal region were investigated for the central peak-to-valley amplitudes for both upper and lower eyelids. A comparison of upper and lower eyelid-induced corneal changes was examined using Pearson's correlation. Associations between the amplitude of corneal change and the corneal topography simK values (mean K, flat K, steep K and astigmatism) were also investigated with Pearson's correlations.

Mixed linear analysis was also applied to the width of corneal change (central peak to peripheral peak width) for both the upper and lower eyelid-induced corneal changes. Correlations were investigated between the peak-to-peak width of the 20° and 40° tasks and between the widths after the reading and steady fixation tasks.

Custom-written software was used to measure the width of Marx's line of the upper and lower eyelids in the nasal, central and temporal regions using the digital photographs (Figure 3). Five measurements of width were made in each of the three regions and the averages calculated for both the upper and lower eyelids. For both eyelids the average standard deviation between repeated measures of Marx's line width was approximately 20% of the mean (about 0.02 mm). There were small variations in the width of Marx's line between nasal, central and temporal locations. However the error associated with estimating Marx's line width was of similar magnitude to the regional variations, so only the central Marx's line width was used in subsequent analyses. Associations between the central Marx's line width and the corneal topography peak-to-peak widths and peak-to-valley amplitudes were investigated with Pearson's correlations.

RESULTS

Peak-to-valley amplitudes of corneal change

The mean peak-to-valley amplitudes were calculated for all conditions, corneal regions and for both eyelids. In the central corneal region the mean upper eyelid-induced central peak-to-valley amplitudes were 1.4 ± 0.6 μm (20° reading, n=9), 1.4 ± 0.5 μm (20° steady fixation, n=10), 1.9 ± 0.7 μm (40° reading, n=13) and 1.5 ± 0.5 μm (40° steady fixation, n=17) (Figure 4). The corresponding peripheral peak-to-valley amplitudes were larger than those for the central cornea for each condition: 1.6 ± 0.8 μm (n=5), 1.6 ± 0.3 μm (n=5), 2.5 ± 1.4 μm (n=9) and 1.7 ± 0.8 μm (n=14) respectively (Figure 4). For the lower eyelid there were no corneal changes within the area captured by the videokeratoscope for the 20° tasks. For the 40° reading and 40° steady fixation tasks, the mean lower eyelid-induced central peak-to-valley amplitudes were 2.8 ± 1.5 μm (n=11) and 2.6 ± 1.1 μm (n=11) and the peripheral peak-to-valley amplitudes were 2.2 ± 1.4 μm (n=2) and 2.5 ± 0.8 μm (n=4) respectively (Figure 5).

For the upper eyelid region there was a highly significant difference between the central and peripheral peak-to-valley amplitudes (mixed linear analysis, p<0.001), with the mean peripheral peak-to-valley amplitudes being larger than the central peak-to-valley amplitudes (Figure 4). For the lower eyelid-induced corneal changes there was no statistical difference between the central and peripheral peak-to-valley amplitudes (Figure 5). The central and peripheral peak-to-valley amplitudes were highly correlated for both the upper and lower eyelid-induced changes ($R^2=0.69$, $p<0.001$). Due to this strong correlation, further analyses were conducted only using the central peak-to-valley amplitudes.

All the within-subject factors (downward gaze angle, type of task and corneal region) were found to have a significant influence on the central peak-to-valley amplitudes for the upper eyelid. The corneal changes after 40° downward gaze were larger than after 20°, changes after reading were larger than those following steady fixation and nasal corneal changes were larger than the central and temporal regional changes (Figure 4, Table 1). However this was not the case for the region affected by the lower eyelid. Analysis of the 40° tasks showed that neither the type of visual task nor the corneal region (nasal, central or temporal) were statistically significant factors in the elevation change (Figure 5, Table 1). As there was a consistent amplitude of change across the cornea (nasal, central and temporal regions), only data from the central region data is presented in Figures 4 and 5.

For the 40° tasks, there were statistically significant differences in peak-to-valley amplitudes between the upper and lower eyelids, with the lower eyelid causing greater elevation change ($p<0.01$). There was also some weak evidence of an association between the magnitude of corneal changes induced by the upper and lower eyelids for an individual, with a positive correlation coefficient ($R^2=0.27$, $p<0.1$). There were no significant associations between corneal curvature (mean K, flat K, steep K or astigmatism) and the magnitude of the eyelid-induced corneal change for any of the task conditions ($p > 0.05$).

Peak-to-peak width of corneal change

The mean distances from the central peak to the peripheral peaks due to the upper eyelid were 1.3 ± 0.2 mm (for the 20° reading, n=5 and 20° steady fixation conditions, n=5) and 1.4 ± 0.2 mm (for the 40° reading, n=9 and 40° steady fixation conditions, n=14). The lower eyelid peak-to-peak widths were 1.4 ± 0.3 mm (n=2) and 1.2 ± 0.1 mm (n=4) for the 40° reading and 40° steady fixation tasks respectively. The mixed linear analysis showed that the downward gaze angle was the only significant factor ($p<0.01$) affecting the upper eyelid-induced peak-to-peak width, with the width of change after the 20° tasks being smaller than after the 40° downward gaze conditions. There were no statistically significant differences related to the type of visual task or the corneal region (nasal, central or temporal) analysed for either upper or lower eyelid. The upper eyelid peak-to-peak width for the 20° steady fixation task was significantly correlated with the peak-to-peak width for the 40° steady fixation task ($R^2=0.60$, $p<0.01$). While there were no significant correlations between the widths after the 20° and 40° reading tasks or between reading and steady fixation conditions.

Marx's line width

The average width of Marx's line centrally for the upper eyelid was 0.11 ± 0.05 mm and 0.13 ± 0.10 mm for the lower eyelid. There were no statistically significant correlations between the widths of the upper and lower eyelid central Marx's line, or between the Marx's line width and the peak-to-peak width of corneal change for either eyelid for each individual. There was however, some evidence of an association between the upper eyelid Marx's line width and the peak-to-valley amplitudes. A positive correlation for the 40° steady fixation task ($R^2=0.32$, $p<0.05$) indicated that a wider Marx's line was associated with a deeper corneal change. There was also a positive correlation for the 20° steady fixation condition peak-to-valley amplitudes and Marx's line width ($R^2 = 0.14$) though it did not reach statistical significance. So there was evidence of an association between Marx's line and eyelid-induced corneal changes.

DISCUSSION

We have used a localised topographical analysis approach to investigate eyelid-induced corneal changes after downward gaze tasks. As previously reported, the presence of the eyelids on the corneal surface in downward gaze causes wave-like corneal distortions [13, 14, 18, 25, 42, 43]. The average elevation central peak-to-valley amplitudes ranged from 1.4 to 2.8 μm. As longer reading periods have been shown to cause larger corneal changes [42], this result for 15-minute tasks is comparable to the 4 μm average recorded for one hour reading sessions [25].

The magnitude of the downward gaze angle has a significant impact on the induced corneal change. For the upper eyelid, elevation peak-to-valley amplitudes were 25% larger for the 40° conditions compared with those at 20°. Centrally, the upper eyelid was 0.6 mm closer to the videokeratoscope centre for the 40° tasks than the 20° tasks. It is doubtful whether the corneal biomechanical properties would alter enough over this small distance to make the corneal tissue more susceptible to lid pressure and account for the 25% increase in corneal change. It is more likely that at the increased downward angle, the upper eyelid exerts higher pressure on the ocular surface. This increased pressure may be due to the eyelid resting closer to the centre of the cornea on a region of 'higher cornea' nearer to the apex. As Collins et al. have previously discussed, this would only be valid if there was no change in the antero-posterior position of the eye with downward gaze [18]. It is well known that the eye globe retracts on blinking with the contraction of the orbicularis oculi [40, 44]. In contrast, a downward gaze lid saccade is achieved almost exclusively by the passive elastic forces of the ocular tissues and the relaxation of the levator palpebrae superioris muscle with no involvement of the orbicularis oculi [45]. As these eyelid movements have different mechanisms it is unlikely that the globe would retract with a downward eyelid saccade. There is a possibility that the extraocular muscles may influence the corneal shape at large downward gaze angles. However this seems unlikely, as previous studies have failed to conclusively show a change in corneal shape with convergence [46-48]. Therefore it seems that eyelid pressure on the cornea is greater when the lid is closer to the corneal centre in larger downward gaze angles.

In contrast, despite the lower eyelid changes being further from the videokeratoscope centre (2.7 mm compared with 1.5 mm for the upper eyelid), the corneal changes associated with the lower eyelid were deeper than those associated with the upper eyelid. The lower eyelid has previously been shown to produce larger corneal changes than the upper eyelid following a 45° downward gaze task [18], although the position of the eyelids on the cornea was not considered. These findings suggest that at large downward gaze angles the lower eyelid pressure on the corneal surface is greater than that of the upper eyelid.

Previous studies have only been concerned with the central peak-to-valley amplitude of the wave-like change [14], however in this study both central and peripheral peak-to-valley amplitudes were analysed. There was a high correlation between the central and peripheral peak-to-valley amplitudes. For the upper eyelid, corneal changes were greater peripherally compared with centrally. There is little known about the exact area of contact between the eyelid margins and the cornea. The upper eyelid margin has been described as a `lid-wiper' [21], aiding tear film distribution during blinking. Mathematical modelling of the upper eyelid's blinking action suggests that the margin needs to change angle during opening and closing to effectively distribute tear fluid [49]. The shape or angle of the upper eyelid margin as it contacts the cornea could result in unequal tangential forces and asymmetrical tissue distribution. In contrast, the lower eyelid induced symmetrical peak-to-valley profiles with equal peaks either side of the valley and its movement during blinking is primarily in the horizontal direction [40].

For the lower eyelid, movements associated with reading did not produce statistically significant differences in corneal changes compared to the steady fixation conditions. However for the more mobile upper eyelid, reading-associated movements increased the peak-to-valley amplitudes by 3% and 25%, for the 20° and 40° downward gaze tasks respectively. Similar increases of between 17% and 35% have been recorded for 1 Hz eye movements compared with a steady fixation control for 15 minute visual tasks [18]. The increased amplitude of change may be due to increased frictional force between the upper eyelid and the ocular surface. There was evidence that eye movements during reading produced more random spatial corneal changes since the upper eyelid peak-to-peak widths of the 20° and 40° steady fixation conditions were correlated, while there were no significant correlations between the widths for the reading tasks. This conclusion was also supported by the larger standard deviations of corneal change associated with the reading conditions compared with the steady fixation tasks.

While the pressure of the eyelids is a major factor in the induced corneal change, corneal factors may also be involved. There was a moderate positive correlation between the upper and lower eyelid peak-to-valley amplitudes at 40° downward gaze. Subjects with a large upper eyelid-induced change were more likely to have a large lower eyelid-induced change. This indicates that certain individuals may be more susceptible to the pressure from the upper and lower eyelids due to either the cornea's mechanical properties or from common anatomical features of the eyelids.

Due to its anatomical structure, it is thought that Marx's line is the natural site of frictional contact between the eyelid margin and the surfaces of the bulbar conjunctiva and cornea. The average width of the upper eyelid Marx's line in this group of subjects was 0.11 ± 0.05 mm, which is a similar to the previous report of 0.10 ± 0.09 mm [16]. There does not appear to be any previous published values reporting the width of the lower eyelid Marx's line. The measured width of 0.13 ± 0.10 mm in this study suggests that it has similar dimensions to the upper eyelid.

While there was no association evident between Marx's line width and the width of the corneal change, there was some evidence of a positive association with the amplitude of corneal change. This relationship was significant for the 40° steady fixation condition when eyelid pressure was stable on the corneal surface, but was not significant for the 40° reading condition when eye movements resulted in more random spatial corneal changes. This indicated that a wider Marx's line was associated with a greater amplitude of corneal change. While the same force distributed over a wider area would result in less pressure, this finding suggests that subjects with greater eyelid pressure on the globe have a wider Marx's line and deeper corneal changes. The association between the width of Marx's line and the amplitude of corneal change that was observed suggests that it is likely to be the point of frictional contact between the cornea and eyelids. This is consistent with the hypothesis that the region of the eyelid surrounding Marx's line is the "eyelid wiper" in contact with the cornea [21, 50].

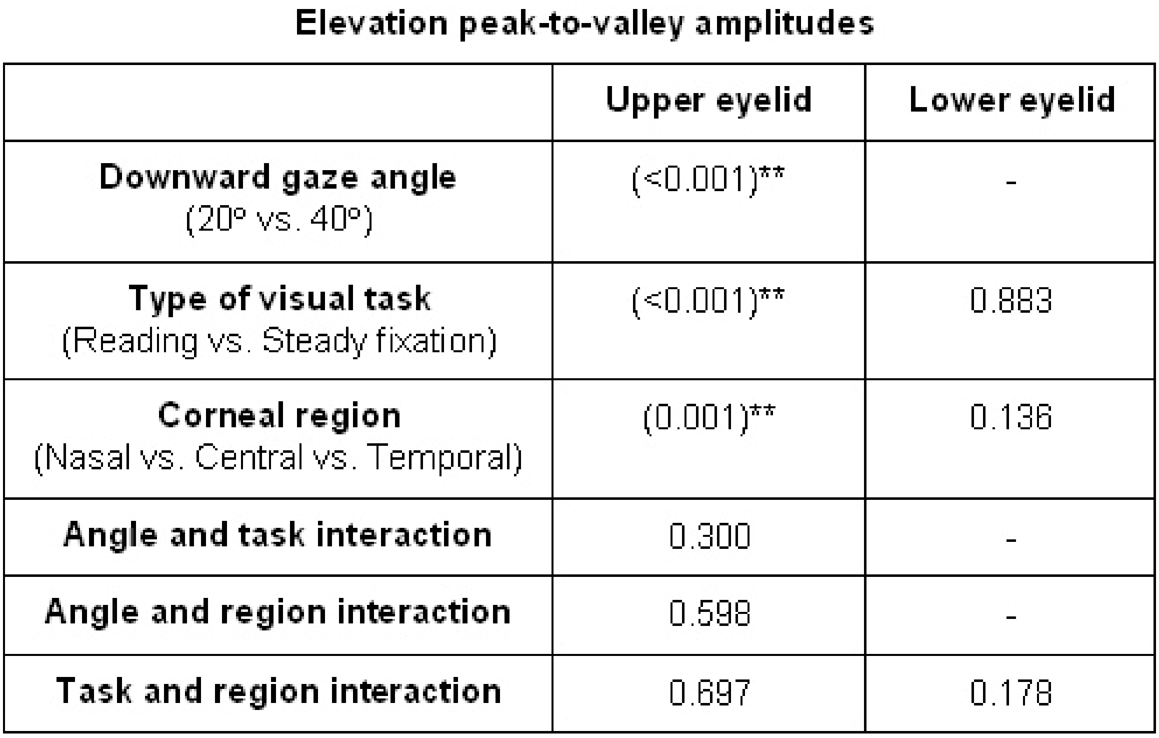
It is possible that the cellular mechanism associated with orthokeratology corneal changes may also be responsible for eyelid-induced corneal changes. Initial changes due to orthokeratology contact lenses occur after only 10 minutes of lens wear [51] and seem to be due to central epithelial thinning and mid-peripheral stromal thickening [30, 52, 53]. It seems likely that eyelid pressure also alters the epithelium as corneal changes occur in a short timeframe (after only 15 minutes) and increased changes are observed with reading-associated eye movements, presumably due to increased friction. Although the cellular mechanism behind the change with orthokeratology lenses is unknown, possibilities include epithelial cell redistribution, increased cell mitosis, cell compression and stromal remodelling [54]. It is unlikely that eyelid-induced corneal changes would be due to the redistribution of entire epithelial cells as surface epithelial cells have an individual thickness of about 4 µm [55] and the elevation changes in this study were between 0.4 to 5.3 µm. Recent work using a cat model suggests that epithelial cell compression and deformation are important features of corneal changes associated with short term orthokeratology contact lens wear (less than 8 hours) [56].

Various anatomical factors might contribute to the magnitude of corneal changes that occur due to eyelid pressure. Certain individuals may experience greater eyelid-induced corneal changes due to corneas that are more susceptible to deformation. Future studies using new instruments such as the Ocular Response Analyser (Reichart Inc, Depew, NY) to measure corneal hysteresis may shed light on this topic [57, 58]. The potential influence of corneal curvature was also considered in this study, but there was no association between either corneal curvature or corneal astigmatism with the magnitude of the eyelid-induced change. Another factor that has been previously investigated is the antero-posterior position of the eyes, though no relationship was found between the exophthalmus data and the degree of topographic change [18].

Several inferences about the pressure of the eyelids on the cornea can be drawn from the analysis of the corneal topography changes in this study. A difference in the tissue redistribution due to the upper and lower eyelids indicates that the upper eyelid may be angled when in contact with the cornea. It also appears that the degree of downward gaze alters the upper eyelid pressure on the cornea. Although the lower eyelid is further from the corneal centre in large angles of downward gaze [12, 20], its effect on the cornea is greater than that of the upper eyelid. Clearly the ability to directly measure eyelid pressure for both the upper and lower eyelids, in various angles of downward gaze, would enable confirmation of these inferences and lead to better understanding of the mechanism of these corneal changes.

ACKNOWLEDGEMENTS

The authors would like to thank Dr Diana Battistutta for advice on the statistical analysis used in this study.



Elevation peak-to-valley amplitudes

	Upper eyelid	Lower eyelid
Downward gaze angle (20° vs. 40°)	(<0.001)**	-
Type of visual task (Reading vs. Steady fixation)	(<0.001)**	0.883
Corneal region (Nasal vs. Central vs. Temporal)	(0.001)**	0.136
Angle and task interaction	0.300	-
Angle and region interaction	0.598	-
Task and region interaction	0.697	0.178

Table 1: Results of mixed linear analysis for the upper and lower eyelid-induced elevation peak-to-valley amplitudes. P value of the F statistic is shown and * = significant at $p<0.05$ and ** = highly significant at $p<0.001$. Factors incorporating downward gaze angle for the lower eyelid are blank as there was only data for one condition, 40° downward gaze.

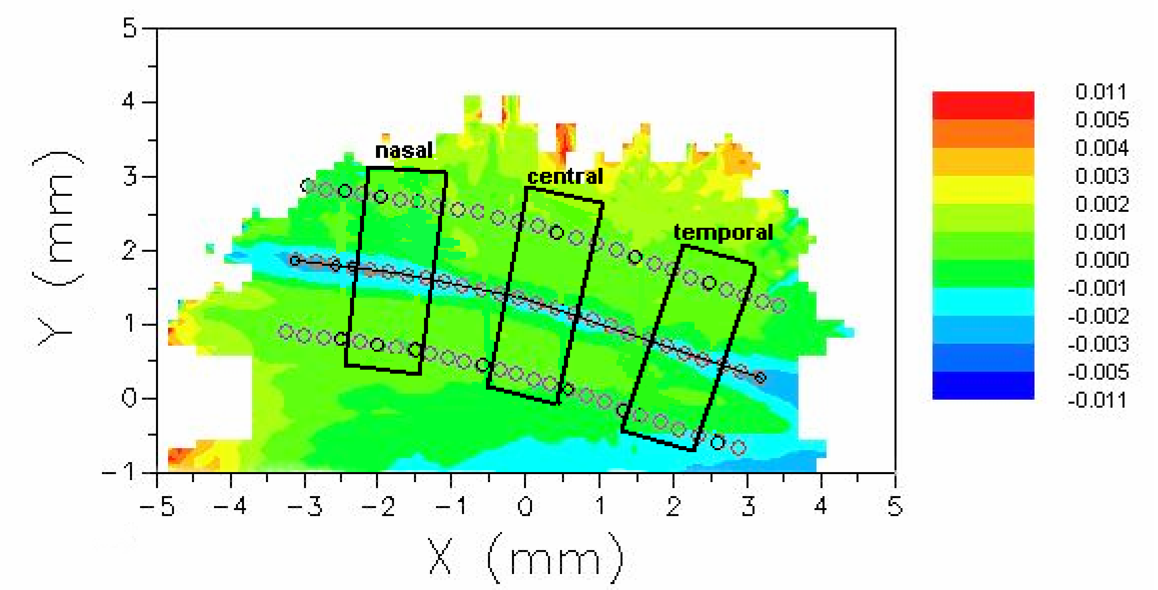


Figure 1: Elevation difference map. Valley (depression) fit with a 4th order polynomial. Open circles define the limits of the local area under consideration showing the first and last cross-sections and the beginning and end of each cross-section. Data was averaged in three corneal regions of 1 mm width: nasal, central and temporal.

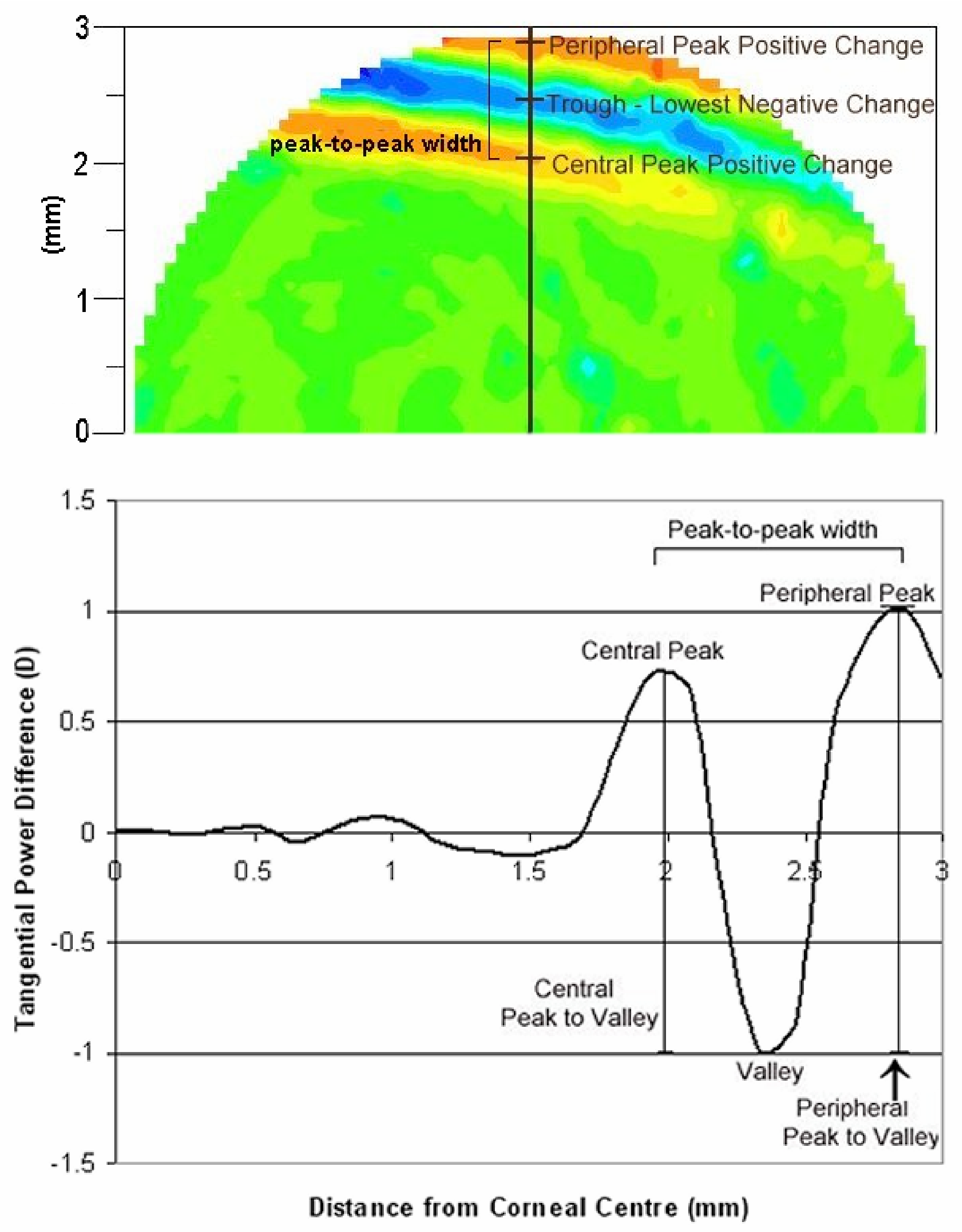


Figure 2: Tangential power difference map (average of a subject's post-task maps minus the average of the pre-task maps) with peaks and valley indicated. The 90° meridian cross section shows the central and peripheral peak-to-valley amplitudes and the peak-to-peak width.

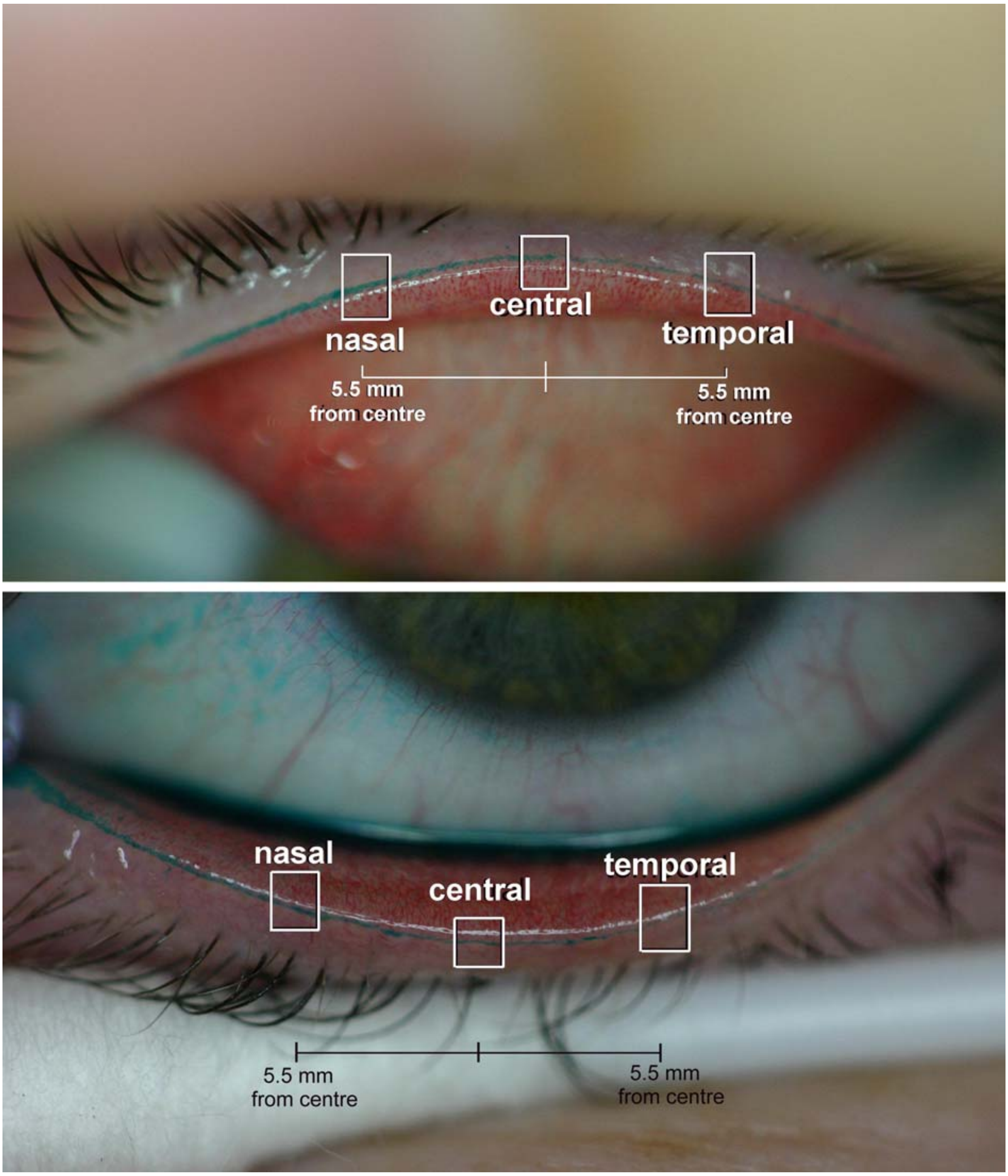


Figure 3: Marx’s line stained with lissamine green for the upper eyelid (top panel) and lower eyelid (bottom panel), with the nasal, central and temporal regions indicated.

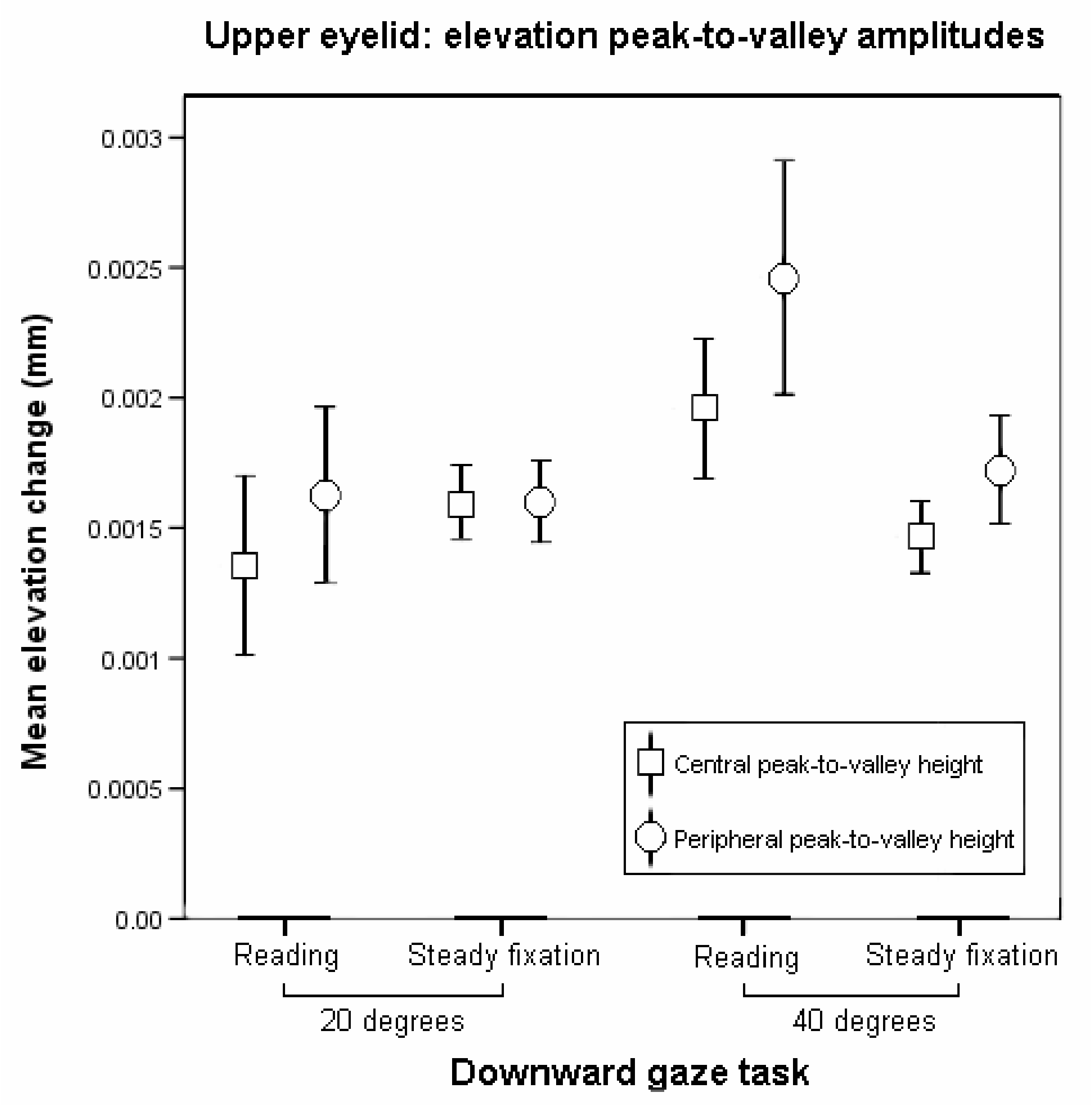


Figure 4: Group mean elevation peak-to-valley amplitudes due to the upper eyelid in the central corneal region. Error bars ± 1 SE.

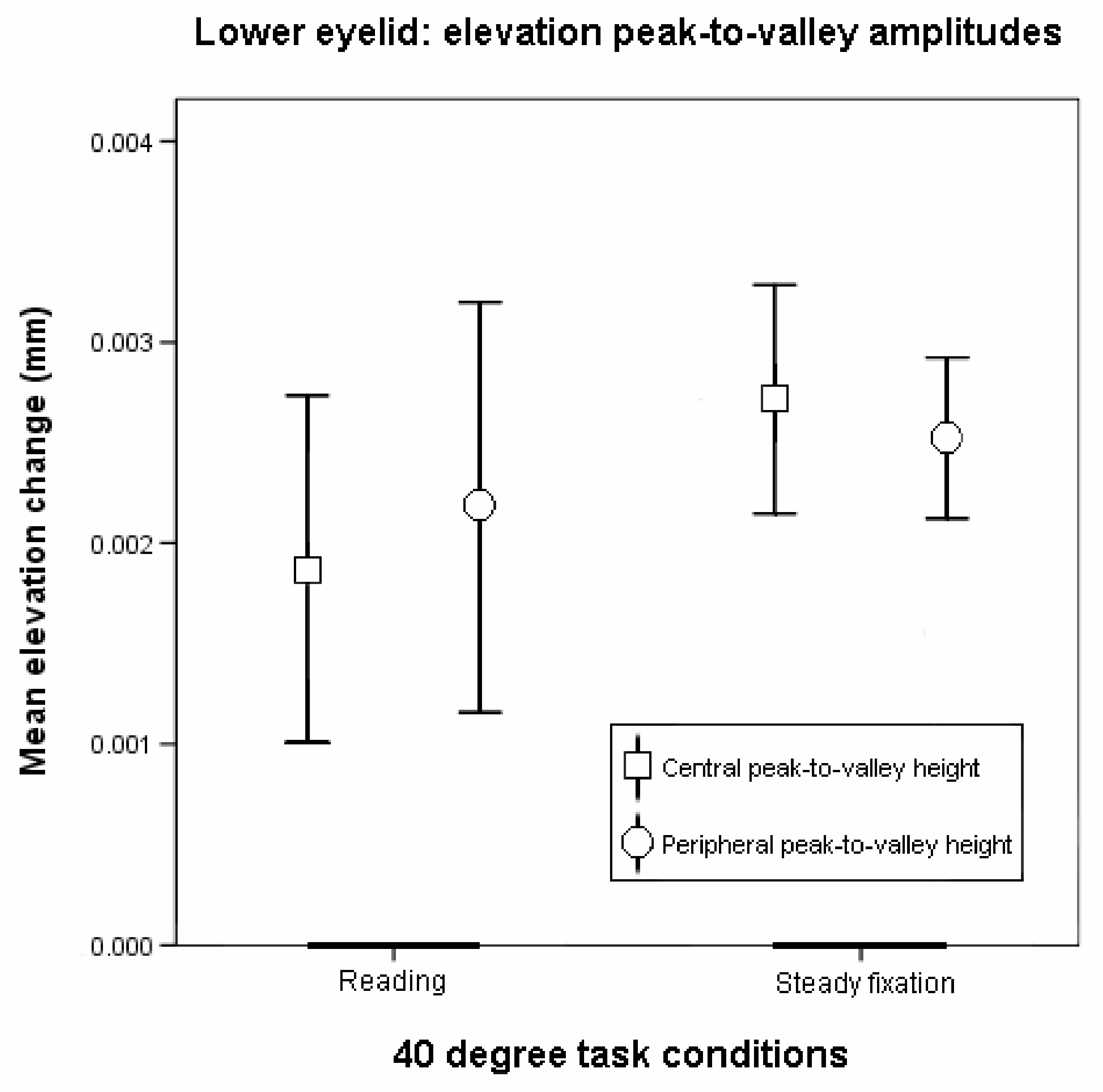


Figure 5: Group mean elevation peak-to-valley amplitudes due to the lower eyelid in the central corneal region. Error bars ± 1 SE.

REFERENCES

1. Nisted M and Hofstetter HW. Effect of chalazion on astigmatism. *Am J Optom Physiol Opt.* 1974; 51(8):579-582.

2. Robb RM. Refractive errors associated with hemangiomas of the eyelids and orbit in infancy. *Am J Ophthalmol.* 1977; 83(1):52-58.

3. Beckingsale PS, Sullivan TJ, Wong VA*, et al.* Blepharophimosis: a recommendation for early surgery in patients with severe ptosis. *Clin Experiment Ophthalmol.* 2003; 31(2):138-142.

4. Cadera W, Orton RB, and Hakim O. Changes in astigmatism after surgery for congenital ptosis. *J Pediatr Ophthalmol Strabismus.* 1992; 29(2):85-88.

5. Anderson RL and Baumgartner SA. Amblyopia in ptosis. *Arch Ophthalmol.* 1980; 98(6):1068-1069.

6. Brown MS, Siegel IM, and Lisman RD. Prospective analysis of changes in corneal topography after upper eyelid surgery. *Ophthal Plast Reconstr Surg.* 1999; 15(6):378-383.

7. Holck DE, Dutton JJ, and Wehrly SR. Changes in astigmatism after ptosis surgery measured by corneal topography. *Ophthal Plast Reconstr Surg.* 1998; 14(3):151-158.

8. Grey C and Yap M. Influence of lid position on astigmatism. *Am J Optom Physiol Opt.* 1986; 63(12):966-969.

9. Lieberman DM and Grierson JW. The lids influence on corneal shape. *Cornea.* 2000; 19(3):336-342.

10. Wilson G, Bell C, and Chotai S. The effect of lifting the lids on corneal astigmatism.

Am J Optom Physiol Opt. 1982; 59(8):670-674.

11. Han W, Kwan W, Wang J*, et al.* Influence of eyelid position on wavefront aberrations*.* *Ophthalmic Physiol Opt.* 2007; 27(1):66-75.

12. Read SA, Collins MJ, Carney LG*, et al.* The morphology of the palpebral fissure in different directions of vertical gaze. *Optom Vis Sci.* 2006; 83(10):715-722.

13. Buehren T, Collins MJ, Iskander DR*, et al.* The stability of corneal topography in the post-blink interval. *Cornea.* 2001; 20(8):826-833.

14. Collins MJ, Buehren T, Bece A*, et al.* Corneal optics after reading, microscopy and computer work. *Acta Ophthalmol Scand.* 2006; 84(2):216-224.

15. Golnik KC and Eggenberger E. Symptomatic corneal topographic change induced by reading in downgaze. *J Neuroophthalmol.* 2001; 21(3):199-204.

16. Hughes C, Hamilton L, and Doughty MJ. A quantitative assessment of the location and width of Marx's line along the marginal zone of the human eyelid. *Optom Vis Sci.* 2003; 80(8):564-572.

17. Doughty MJ, Naase T, Donald C*, et al.* Visualisation of "Marx's line" along the marginal eyelid conjunctiva of human subjects with lissamine green dye. *Ophthalmic Physiol Opt.* 2004; 24(1):1-7.

18. Collins MJ, Buehren T, Trevor T*, et al.* Factors influencing lid pressure on the cornea. *Eye Contact Lens.* 2006; 32(4):168-173.

19. Buehren T, Collins MJ, and Carney LG. Near work induced wavefront aberrations in myopia. *Vision Res.* 2005; 45(10):1297-1312.

20. Shaw AJ, Collins MJ, Davis BA*, et al.* Corneal refractive changes due to short-term

eyelid pressure in downward gaze (in press). *J Cataract Refract Surg.* 2008.

21. Korb DR, Greiner JV, Herman JP*, et al.* Lid-wiper epitheliopathy and dry-eye symptoms in contact lens wearers. *CLAO J.* 2002; 28(4):211-216.

22. Korb DR, Herman JP, Greiner JV*, et al.* Lid wiper epitheliopathy and dry eye symptoms. *Eye Contact Lens.* 2005; 31(1):2-8.

23. Norn M. Meibomian orifices and Marx's line. Studied by triple vital staining. *Acta Ophthalmol (Copenh).* 1985; 63(6):698-700.

24. Mengher LS, Pandher KS, and Bron AJ. Non-invasive tear film break-up time: sensitivity and specificity. *Acta Ophthalmol (Copenh).* 1986; 64(4):441-444.

25. Buehren T, Collins MJ, and Carney L. Corneal aberrations and reading. *Optom Vis Sci.* 2003; 80(2):159-166.

26. Hartstein J. Corneal warping due to wearing of corneal contact lenses. A report of 12 cases. *Am J Ophthalmol.* 1965; 60(6):1103-1104.

27. Harris MG, Sarver MD, and Polse KA. Corneal curvature and refractive error changes associated with wearing hydrogel contact lenses. *Am J Optom Physiol Opt.* 1975; 52(5):313-319.

28. Holden BA, Sweeney DF, Vannas A*, et al.* Effects of long-term extended contact lens wear on the human cornea. *Invest Ophthalmol Vis Sci.* 1985; 26(11):1489-1501.

29. Wilson SE, Lin DT, Klyce SD*, et al.* Topographic changes in contact lens-induced corneal warpage. *Ophthalmology.* 1990; 97(6):734-744.

30. Swarbrick HA, Wong G, and O'Leary DJ. Corneal response to orthokeratology. *Optom Vis Sci.* 1998; 75(11):791-799.

31. Liu Z and Pflugfelder SC. The effects of long-term contact lens wear on corneal thickness, curvature, and surface regularity. *Ophthalmology.* 2000; 107(1):105-111.

32. Rabinowitz YS and Klyce SE, *A Color Atlas of Corneal Topography: Interpreting Videokeratography*. 1993, New York, Tokyo: Igaku-Shoin Medical Publishers Inc.

33. Lam BL, Lam S, and Walls RC. Prevalence of palpebral fissure asymmetry in white persons. *Am J Ophthalmol.* 1995; 120(4):518-522.

34. Tang W, Collins MJ, Carney L*, et al.* The accuracy and precision performance of four videokeratoscopes in measuring test surfaces. *Optom Vis Sci.* 2000; 77(9):483-491.

35. Cho P, Lam AKC, Mountford J*, et al.* The performance of four different corneal topographers on normal human corneas and its impact on orthokeratology lens fitting. *Optom Vis Sci.* 2002; 79(3):175-183.

36. Hill SE, Han H, and Thorn F. Visual Posture and Focus During Recreational and Study Reading*. Invest Ophthalmol Vis Sci (Suppl).* 2005; 46(E-Abstract):5598.

37. Cho P, Sheng C, Chan C*, et al.* Baseline blink rates and the effect of visual task difficulty and position of gaze. *Curr Eye Res.* 2000; 20(1):64-70.

38. Doughty MJ. Consideration of Three Types of Spontaneous Eyeblink Activity in Normal Humans: during Reading and Video Display Terminal Use, in Primary Gaze, and while in Conversation*. Optom Vis Sci.* 2001; 78(10):712-725.

39. Sheedy JE, Gowrisankaran S, and Hayes JR. Blink rate decreases with eyelid squint. *Optom Vis Sci.* 2005; 82(10):905-911.

40. Doane MG. Interaction of eyelids and tears in corneal wetting and the dynamics of the normal human eyeblink. *Am J Ophthalmol.* 1980; 89(4):507-516.

41. Doughty MJ and Naase T. Further analysis of the human spontaneous eye blink rate by a cluster analysis-based approach to categorize individuals with 'normal' versus 'frequent' eye blink activity. *Eye Contact Lens.* 2006; 32(6):294-299.

42. Collins MJ, Kloevekorn-Norgall K, Buehren T, *et al.* Regression of lid-induced corneal topography changes after reading. *Optom Vis Sci.* 2005; 82(9):843-849.

43. Read SA, Collins MJ, and Carney LG. The diurnal variation of corneal topography and aberrations. *Cornea.* 2005; 24(6):678-687.

44. Collins MJ, *et al*. The synkinesis between antero-posterior eye position and lid fissure width. *Clin Exp Optom.* 1992; Vol. 75(No.2):38-41.

45. Davson H, *The protective mechanisms.*, in *The Physiology of the Eye*, H. Davson, Editor. 1972, Churchill Livingstone: Edinburgh.

46. Fairmaid J. The constancy of corneal curvature; an examination of corneal response to changes in accommodation and convergence. *The British Journal Of Physiological Optics.* 1959; 16(1):2-23.

47. Löpping B and Weale RA. Changes in corneal curvature following ocular convergence. *Vision Res.* 1965; 5(3):207-215.

48. Mandell RB and Helen RS. Stability of the corneal contour. *Am J Optom Arch Am Acad Optom.* 1968; 45(12):797-806.

49. Jones MB, Fulford GR, Please CP, *et al.* Elastohydrodynamics of the eyelid wiper. *Bull Math Biol.* 2008; 70(2):323-343.

50. Varikooty J, Srinivasan S, and Jones L. Atypical manifestation of upper lid margin staining in silicone hydrogel wearers with symptoms of dry eye. *Cont Lens Anterior Eye.*

2008.

51. Sridharan R and Swarbrick H. Corneal response to short-term orthokeratology lens wear. *Optom Vis Sci.* 2003; 80(3):200-206.

52. Wang J, Fonn D, Simpson TL*, et al.* Topographical thickness of the epithelium and total cornea after overnight wear of reverse-geometry rigid contact lenses for myopia reduction. *Invest Ophthalmol Vis Sci.* 2003; 44(11):4742-4746.

53. Alharbi A and Swarbrick HA. The effects of overnight orthokeratology lens wear on corneal thickness. *Invest Ophthalmol Vis Sci.* 2003; 44(6):2518-2523.

54. Choo J, Caroline P, and Harlin D. How does the cornea change under corneal reshaping contact lenses? *Eye Contact Lens.* 2004; 30(4):211-213.

55. Bron AJ, Tripath RC, and Tripath BJ, *Wolff's Anatomy of the Eye and Orbit. Eighth edition.* 1997, New York: Oxford University Press Inc.

56. Choo J. Morphological changes in cat epithelium following continuous wear of orthokeratology lenses: a pilot study (in press)*. Cont Lens Anterior Eye.* 2007.

57. Kotecha A, Elsheikh A, Roberts CR*, et al.* Corneal thickness- and age-related biomechanical properties of the cornea measured with the ocular response analyzer. *Invest Ophthalmol Vis Sci.* 2006; 47(12):5337-5347.

58. Shah S, Laiquzzaman M, Cunliffe I*, et al.* The use of the Reichert ocular response analyser to establish the relationship between ocular hysteresis, corneal resistance factor and central corneal thickness in normal eyes. *Cont Lens Anterior Eye.* 2006; 29(5):257-262.