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Axial elongation associated with biomechanical factors during near work

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ABSTRACT

Purpose: To investigate the changes occurring in the axial length, choroidal thickness and anterior biometrics of the eye during a 10 minute near task performed in downward gaze.

Methods: Twenty young adult subjects (10 emmetropes and 10 myopes) participated in this study. To measure ocular biometrics in downward gaze, an optical biometer was inclined on a custom built, height and tilt adjustable table.

Baseline measures were collected after each subject performed a distance primary gaze control task for 10 mins, to provide wash-out period for prior visual tasks before each of three different accommodation/gaze conditions. These other three conditions included a near task (2.5 D) in primary gaze, and a near (2.5 D) and a far (0 D) accommodative task in downward gaze (25°), all for 10 mins duration. Immediately after, and then 5 and 10 mins from the commencement of each trial, measurements of ocular biometrics (e.g. anterior biometrics, axial length, choroidal thickness and retinal thickness) were obtained.

Results: Axial length increased with accommodation and was significantly greater for downward gaze with accommodation (mean change ± SD 23 ± 13 μm at 10 mins) compared to primary gaze with accommodation (mean change 8 ± 15 μm at 10 mins) ($p < 0.05$). A small amount of choroidal thinning was also found during accommodation that was statistically significant in downward gaze (13 ± 14 μm at 10 mins, $p < 0.05$). Accommodation in downward gaze also caused greater changes in anterior chamber depth and lens thickness compared to accommodation in primary gaze.

Conclusion: Axial length, choroidal thickness and anterior eye biometrics change significantly during accommodation in downward gaze as a function of time. These changes appear to be due to the combined influence of biomechanical factors (i.e. extraocular muscle forces, ciliary muscle contraction) associated with near tasks in downward gaze.

Keywords: near work, myopia, accommodation, axial length, downward gaze.

INTRODUCTION

Myopia is one of the major global causes of vision impairment and creates a substantial socio-economic burden worldwide.[1] Myopia is thought to have a multifactorial aetiology including both genetic and environmental factors. Near work has been considered as one of the environmental risk factors for myopia progression in children and young adults,[2-6] since educational performance, longer time spent reading and close working distances have all been found to be associated with myopia development and/or progression.[3, 7-10] Myopia progression occurring during adulthood has also been found to be associated with certain types of occupations that typically involve substantial periods of near work activities.[11, 12 13]

Understanding the ocular changes associated with near work is of particular interest given the association between myopia and near tasks[3, 4, 6, 14] and the increasing prevalence of myopia in many populations.[15-18] Accommodation and convergence have often been suspected to be involved in myopia progression associated with near work.[19, 20]

Myopia progression in younger populations is typically associated with progressive increases in vitreous chamber depth and the overall axial length of the eye over time.[21, 22] However small transient changes in axial length are also known to occur due to accommodation.[23-26] The axial elongation during accommodation is most likely related to the mechanical stretching or squeezing of the globe caused by ciliary muscle contraction.[27] There is evidence that the ciliary body dimensions are thicker in longer myopic eyes than shorter emmetropic eyes,[28, 29] which suggests the mechanical force transmitted by the ciliary body to the choroid and sclera during accommodation could be different between myopes and emmetropes.

The majority of previous studies of ocular changes associated with near work have examined the eyes in primary gaze. However, since many near tasks involve downward gaze and accommodation, it is important to investigate ocular biometry in downward gaze during accommodation in a way that attempts to simulate natural viewing conditions. It has been suggested that mechanical forces on the globe imposed by the contraction of the extraocular muscles can be substantially greater than that of the ciliary muscle.[30] Using optical low-coherence reflectometry to measure axial length, we have also recently found small changes in axial length associated with shifts in gaze, suggesting that extraocular muscle tension on the globe can result in changes in eye length in certain angles of gaze (e.g. downward gaze).[31]

Given that forces related to accommodation and the extraocular muscles appear to be independently capable of influencing axial length, it follows that accommodation combined with downward gaze could have a greater effect on axial length than accommodation or downward gaze alone. Therefore, in order to better understand the changes in the biometric properties of the eye during natural viewing conditions of a typical near task, we investigated the changes in anterior biometrics, axial length, retinal thickness and posterior choroidal thickness of the eye associated with accommodation during downward gaze over 10 minutes duration. This investigation was conducted for 25° downward gaze at two levels of accommodation (0 D and 2.5 D) using a modified optical biometer.

METHODS

Subjects

Twenty young adult subjects (10 emmetropes and 10 myopes) aged between 18 and 30 years (mean ± SD age, 24 ± 4 years) were recruited for this study. The mean spherical equivalent of the tested eye (i.e. OS) of the emmetropic subjects was – 0.14 ± 0.24 DS (mean ± *SD*) [range: + 0.20 D to – 0.50 D] and that of the myopic subjects was – 2.26 ± 1.42 DS [range: – 1.00 D to – 4.06 D]. None of the subjects had anisometropia greater than 1.00 DS or astigmatism greater than 1.50 DC. All subjects were free of any significant ocular diseases or history of eye surgery. Subjects recruited in the study had no apparent binocular vision anomalies and all had monocular amplitude (push-up test) of accommodation greater than 7 D. All subjects had best corrected visual acuity of logMAR 0.00 or better in both eyes. Any subjects who habitually wore soft contact lenses (n = 2) were asked to discontinue lens wear for 2 days prior to, and throughout their involvement in the study. Ethics approval was obtained from the University Human Research Ethics Committee prior to the commencement of the study, and subjects gave written informed consent and were treated in accordance with the declaration of Helsinki.

Experimental design

A non-contact optical biometer (Lenstar LS900, Haag-Streit international, Koeniz, Switzerland), was shifted to a custom built height and tilt adjustable table to measure ocular biometrics in downward gaze with accommodation (Figure 1). The subjects' head position was adjusted with a sliding bar mounted on the custom built headrest to maintain a consistent upright head position during both downward gaze (25° rotation of the eye) and primary gaze conditions. To verify head angle during downward gaze, digital images of the head position in profile were captured for both primary gaze and downward gaze conditions. The relative angle of a reference line (i.e. a straight line connecting the top of the ear to the bottom of the nose) in both the downward and primary gaze images were measured to confirm the true amount of head turn. A similar method was outlined in Ghosh et al.[31]

A free space accommodation target (a high contrast Maltese cross target displayed on a digital pocket device screen) was also mounted on the head rest and viewed via a front surface mirror by the fellow eye (i.e. right eye) (Figure 1). In dichoptic view, an image of the external target was visible with the right eye and an image of the biometer's fixation target was simultaneously seen from the left (tested) eye. Subjects were given their full distance refractive error correction (spherical equivalent in a trial lens mounted in the optical path of the fixation target) before the fellow eye (0 D) during each of the testing conditions. The fixation target was positioned to provide an accommodation demand of either 0 D (i.e. displayed on a TV at 6 m distance) or 2.5 D. Mutti et al.'s [32] thin lens formula, taking into account spectacle lens effectivity, was used to determine the target distance for myopic subjects, to ensure an equal accommodative stimulus between subjects.

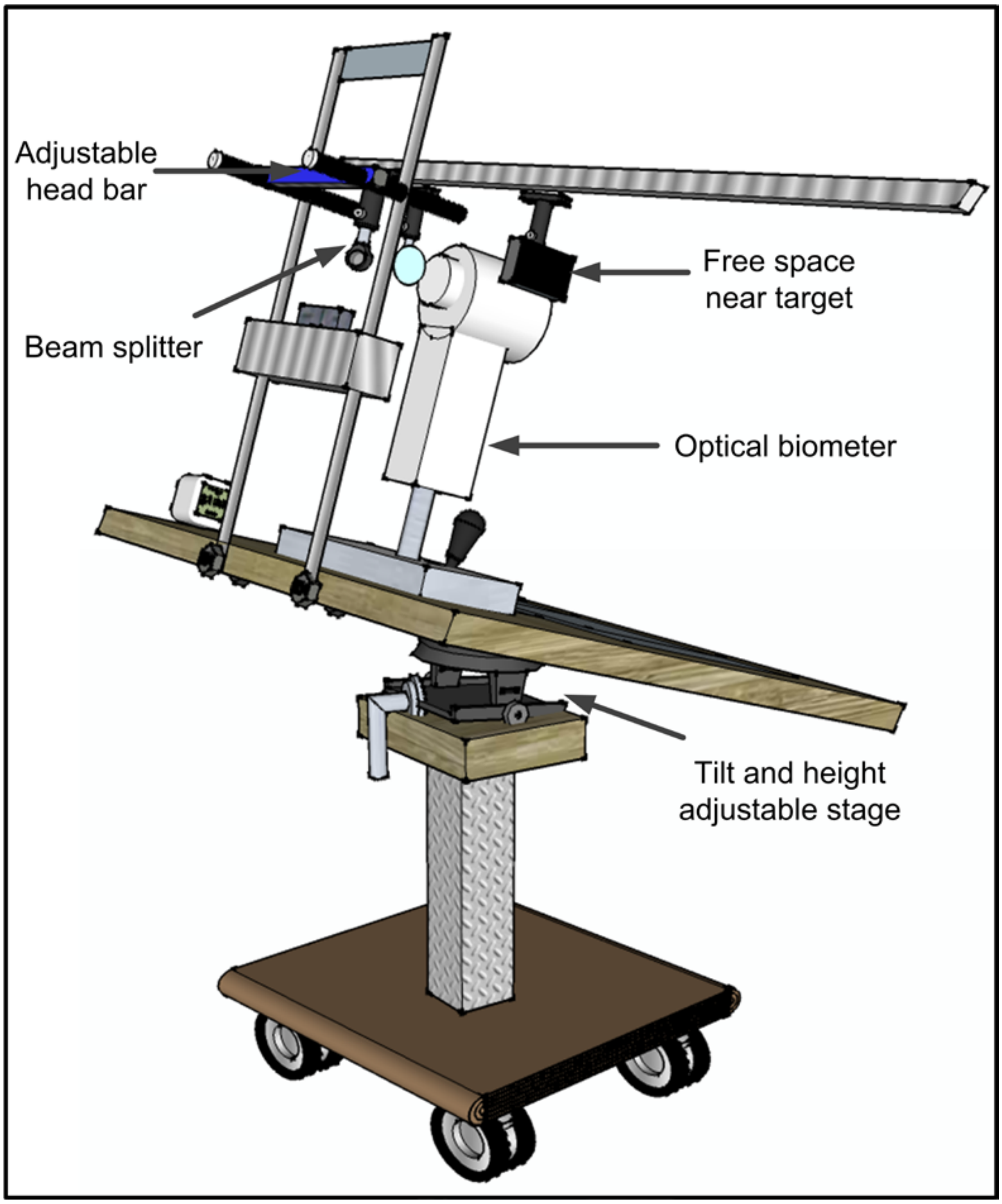

Figure1. A schematic diagram of the experimental setup that allows measurements of ocular biometrics of the eye with accommodation in downward gaze.

Data collection procedures

Measurements of the ocular biometrics were taken for four different testing conditions, i) baseline (far accommodation in primary gaze, following a 10 minute distance task in primary gaze) ii) far accommodation in downward gaze, iii) 2.5 D accommodation in primary gaze, and iv) 2.5 D accommodation in downward gaze. Five measurements were taken using the optical biometer at each time point and for each condition and the data were averaged. To reduce any systematic error, the order of the three test conditions was randomized between subjects.

Before each of the three test conditions, the subject performed a 10 minute wash-out task (subjects watched a video on TV) binocularly at a 6 m distance. Constant viewing of the distant target was used to try and standardize the state of the eye before measurements were taken, since prior factors such as accommodation have been shown to alter the level of ocular biometrics such as axial length.[23-25] We then measured ocular biometrics using the optical biometer in primary gaze at the end of the 10 minutes wash-out period. During the measurements, the subjects were instructed to fixate the Maltese cross (displayed on the TV screen) with 0.16 D far accommodation demand. These baseline measurements were taken prior to each of the three test conditions.

After the baseline measurements, the biometer was kept in primary gaze (0°) or tilted by 25° in downward gaze. The subject remained in the headrest throughout the testing session and watched a video through a front surface mirror with either a far accommodation demand or with an accommodation demand of 2.5 D. Biometric measurements were taken after 0 min (immediately after the start of the test condition), and then 5 minutes and 10 minutes from the starting time.

During measurements with the optical biometer, the fixation was controlled by pausing the video (since we did not want any movement to distract the subject's fixation) and the subject then fixated the centre of a high contrast Maltese cross target, displayed on the screen. The subjects then had a break for 5 minutes after the completion of each of the three test conditions and then completed the 10 minutes wash-out task of watching a TV at 6 m before baseline measurements were taken again. In pilot studies, we observed that any changes in optics or biometrics of the eye that occurred with accommodation and downward gaze had recovered within 2-3 minutes after shifting gaze from down gaze to primary gaze, and changing fixation from the near target to the distance target.

Data analysis

For each test condition, the mean of five biometric measures [central corneal thickness (CCT), anterior chamber depth (ACD), lens thickness (LT) and axial length (AxL)] were derived for each subject from the optical biometer's automatic data output. Axial length of the eye was defined as the distance from the anterior cornea to the retinal pigment epithelium. Foveal retinal thickness (RT) and subfoveal choroidal thickness (ChT) were also determined through a manual analysis of the instrument output. An independent, masked observer used a magnified A-scan to align the retinal cursors with the prominent retinal and choroidal peaks, in order to measure the distances between the 'P1' peak (i.e. anterior retinal peak) and the P3 peak [i.e. central retinal epithelium peak (RPE)] to determine retinal thickness and the 'P3' peak (i.e. RPE peak) and the 'P4' peak (i.e. corresponding to the choroid/scleral interface) to determine choroidal thickness. This approach for deriving retinal thickness and choroidal thickness from the Lenstar A-scan has been found to exhibit good repeatability and to be well correlated with an imaging method (i.e. optical coherence tomography) used to quantify choroidal thickness.[33] In order to avoid potential bias, the manual analysis of the retinal and choroidal thickness were carried out by an experienced observer who was masked to the subjects' demographic data and name of the testing condition for all biometric scans that were collected in this experiment.

An increase in lens thickness during downward gaze and accommodation will lead to an increase in the eye's average refractive index.[34] As the Lenstar biometer uses an average ocular refractive index to calculate axial length, these measurements collected with the instrument during downward gaze with accommodation will be overestimated. We therefore corrected the changes in axial length measured during downward gaze and accommodation based on the measured lens thickness for each subject.[35] These values were then used to calculate a corrected change in axial length for each test condition (far accommodation in downward gaze, 2.5 D accommodation in primary gaze and 2.5 D accommodation in downward gaze) for each subject.

Statistical analyses were performed using SPSS software (version 19). A repeated measure ANOVA was used to assess the significance of the ocular biometric component changes for the various within-subject factors including the effect of accommodation, gaze and measurement time (0, 5 minutes and 10 minutes). Pairwise comparisons (Bonferroni adjusted) were also performed to examine the level of significance of changes in biometric components at each time in all test conditions. The between subjects factor was refractive error group (myopes and emmetropes).

RESULTS

Changes in axial length

The mean baseline axial length for all subjects was 23.625 ± 0.869 mm, which was significantly greater ($p < 0.05$) in the myopes (mean 23.984 ± 1.001 mm) compared to the emmetropes (mean 23.265 ± 0.746 mm). The group mean changes in axial length in downward gaze from baseline with far accommodation over 10 minutes duration showed small but significant increases (gaze, $p < 0.05$) with 4 ± 9 µm at 0 min, 6 ± 11 µm at 5 minutes and 8 ± 13 at 10 minutes (Figure 2). The increase in axial length was significantly greater with 2.5 D accommodation in downward gaze [mean (±SD) changes from baseline 13 ± 13 µm at 0 min, 17 ± 9 µm at 5 minutes and 23 ± 13 at 10 minutes, $p < 0.05$] than with 2.5 D accommodation in primary gaze [mean (±SD) changes from baseline 7 ± 8 µm at 0 min, 9 ± 14 µm at 5 minutes and 8 ± 15 at 10 minutes] (gaze by accommodation interaction, $p < 0.05$) (Figure 2). Significant gaze by time ($p < 0.05$), and gaze by time by accommodation ($p < 0.05$) interactions were also found for the changes in axial length. There was no gaze by refractive error or accommodation by refractive error interactions for the changes in axial length ($p > 0.05$).

There were no significant differences ($p > 0.05$) in the baseline axial length measurements between any of the testing conditions (baseline measurements were obtained prior to each of the three testing conditions after 10 mins of viewing a far target in primary gaze). The maximum group mean difference for baseline axial length measurements was 3 microns.

Changes in retinal and choroidal thickness

We excluded retinal and choroidal thickness data for four subjects (2 emmetropes and 2 myopes) as choroidal and retinal peaks were not consistently observed in all measurements for these subjects by the masked observer. Therefore, the retinal and choroidal analysis represents data from 16 subjects. Choroidal thickness was found to change by a smaller magnitude and in the opposite direction to the axial length changes (Figure 2). ANOVA revealed a significant effect of gaze, and gaze by time interaction (both $p < 0.05$) for the changes in choroidal thickness during 2.5 D accommodation. On average the greatest choroidal thinning occurred during 2.5 D accommodation in 25° downward gaze [mean changes (±SD) from baseline 11 ± 13 µm at 0 min, 13 ± 13 µm at 5 minutes and 13 ± 14 µm at 10 minutes]. There were no gaze by refractive error, or refractive error by accommodation interactions for the changes in choroidal thickness ($p > 0.05$). There was no significant change in retinal thickness with downward gaze or accommodation ($p > 0.05$) [Figure 2].

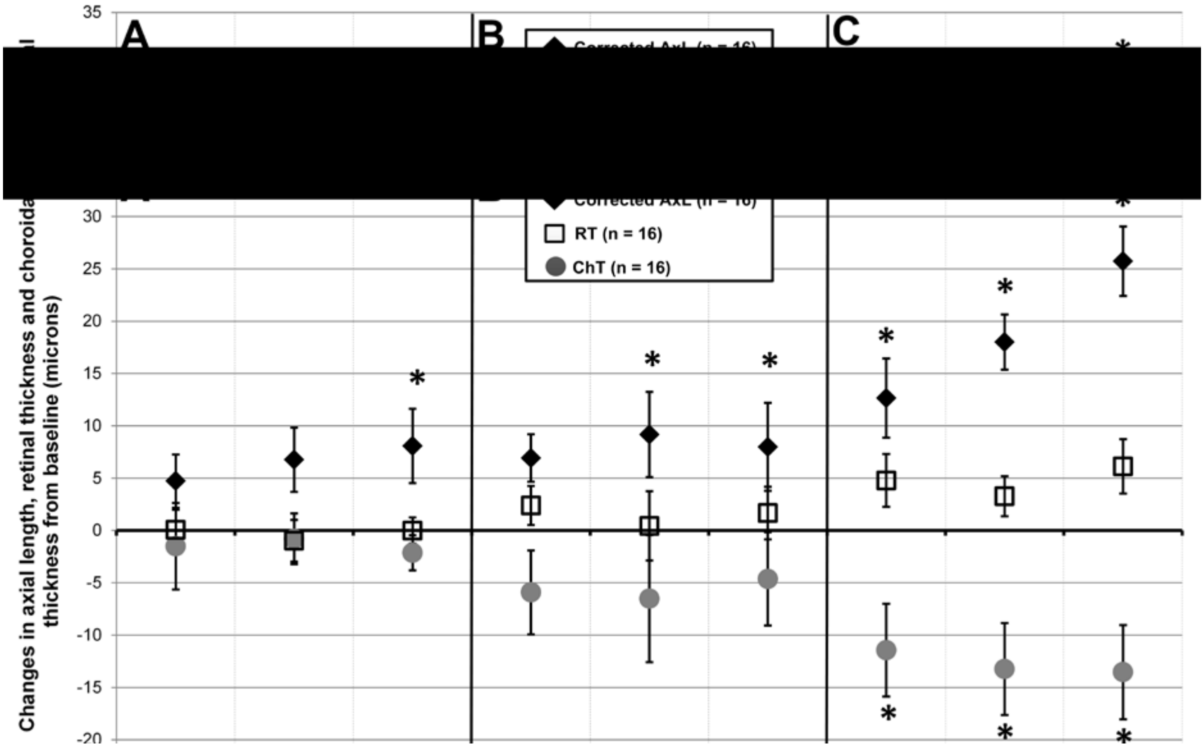

Figure 2. Group mean (± SE) changes in corrected axial length (AxL), retinal thickness (RT) and choroidal thickness (ChT) in downward gaze with far accommodation (A), primary gaze with 2.5 D accommodation (B) and downward gaze with 2.5 D accommodation (C), relative to baseline (i.e. primary gaze with far accommodation) over the 10 minutes task. Asterisks indicate the significant changes (p <0.05) in axial length and choroidal thickness from baseline with the effect of accommodation and/or downward gaze.

Changes in anterior eye biometrics

Accommodation and downward gaze had no significant influence on central corneal thickness (mean difference from baseline < 2 microns for all conditions, p > 0.05). There was a trend for the ACD to decrease in downward gaze with far accommodation, compared to primary gaze (mean changes from baseline: – 8 ± 9 µm at 0 min, pairwise comparison p > 0.05; – 7 ± 7 µm, at 5 minutes, p > 0.05 and – 11 ± 10 µm at 10 minutes, p < 0.05) [Figure 3]. These changes in anterior chamber depth with angle of gaze and gaze by time were not significant (ANOVA, gaze, p = 0.06 and gaze by time interaction, p = 0.09).

Accommodation caused a large decrease in ACD in both primary (mean change from baseline –114 ± 10 µm at 0 min, $p < 0.001$; –127 ± 12 µm at 5 min, $p < 0.001$ and –138 ± 12 µm at 10 min, $p < 0.001$) and downward gaze (mean change from baseline –121 ± 10 µm at 0 min, $p < 0.001$; –150 ± 12 µm at 5 min, $p < 0.001$ and –163 ± 12 µm at 10 min, $p < 0.001$), compared to the baseline condition of primary gaze with far accommodation (ANOVA, both $p < 0.001$). The decrease in ACD with accommodation was significantly greater in downward gaze compared to primary gaze after 5 minutes (mean difference 23 ± 11 µm, $p < 0.05$) and 10 minutes (mean difference 25 ± 13 µm, $p < 0.05$) of the tasks. There were no significant interactions between gaze and refractive error group, between time and refractive error group, or between accommodation and refractive error group for the changes in anterior chamber depth (all $p > 0.05$).

Downward gaze had no significant effect on lens thickness during the far accommodation task, compared to the baseline condition of primary gaze with far accommodation (mean change from baseline 2 ± 10 µm at 0 min, 3 ± 10 µm at 5 min and 4 ± 11 µm at 10 min) (gaze, $p > 0.05$) [Figure 3]. The 2.5 D accommodation stimulus caused a significant increase in LT for both primary (mean change 125 ± 14 µm at 0 min, $p < 0.001$; 127 ± 15µm at 5 min, $p < 0.001$ and 131 ± 15 µm at 10 min, $p < 0.001$) and downward gaze (mean change 150 ± 21 µm at 0 min, $p < 0.001$; 171 ± 17 µm at 5 min, $p < 0.001$ and 173 ± 17 µm at 10 min, $p < 0.001$). Pairwise comparisons revealed that the changes in lens thickness with accommodation were significantly greater in downward gaze than in primary gaze after 5 minutes (mean difference 44 ± 20 µm, $p < 0.05$) and 10 min (mean difference 42 ± 21 µm, $p < 0.05$) of the near task. There were no significant interactions between gaze and refractive error group, between time and refractive error group, or between accommodation and refractive error group for the changes in lens thickness (all $p > 0.05$).

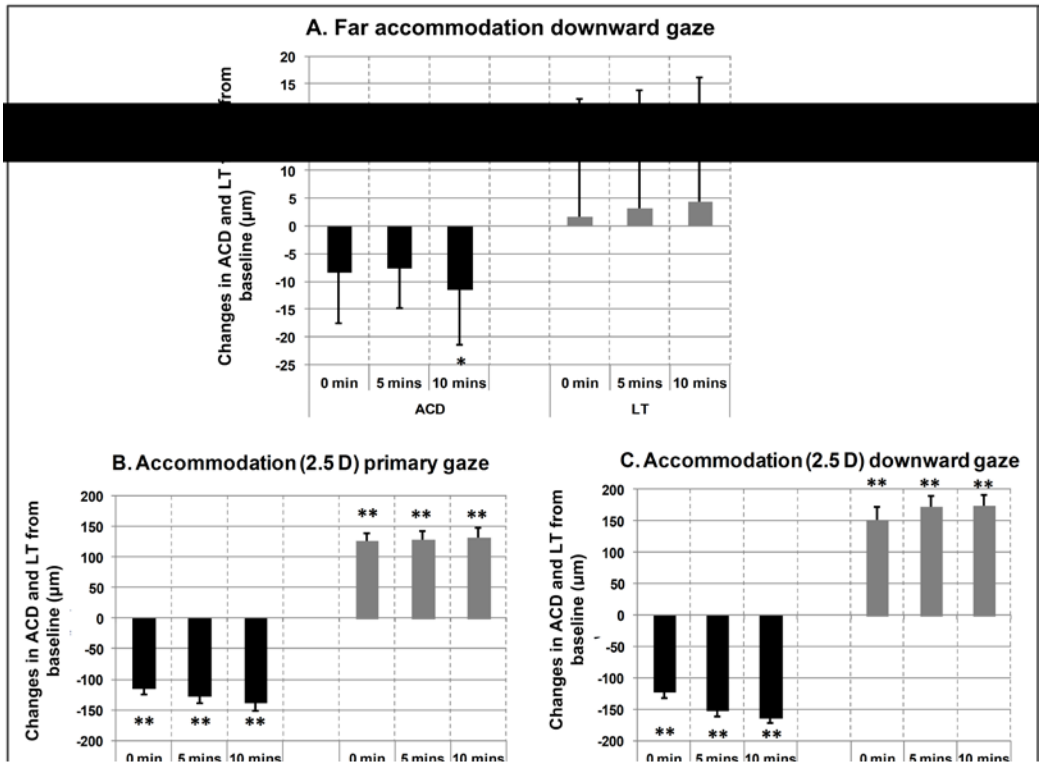

Figure 3. (A) Group mean changes in the anterior chamber depth (ACD) and lens thickness (LT) in downward gaze with respect to baseline with far accommodation over the 10 minutes task. (B) Group mean changes in anterior chamber depth and lens thickness in primary gaze with respect to baseline with 2.5 D accommodation over the 10 minutes task. (C) Group mean changes in the anterior chamber depth and lens thickness in downward gaze with respect to baseline with 2.5 D accommodation over the 10 minutes task. The baseline value was taken after 10 minutes viewing a 6 m target [i.e. far accommodation (0 D)] in primary gaze. Asterisks indicate the significant changes [single asterisk (*) corresponds to $p < 0.05$ and double asterisks (**) correspond to $p < 0.001$] in ocular biometrics (ACD and LT) from baseline with the effects of accommodation and/or downward gaze. Note that the scales for Y axes are different in far accommodation and 2.5 D accommodation conditions.

DISCUSSION

This is the first report of the interaction between downward gaze and accommodation on the axial length of the eye. We found a small but significant increase in axial length (about 8 microns after 10 minutes) in downward gaze with far accommodation. However we also found that axial elongation with accommodation is significantly greater in downward gaze over time (~23 microns after a 10 minutes task), compared to primary gaze. It appears that ciliary muscle contraction during accommodation, combined with changes in extraocular muscle tension in downward gaze, have additive effects on the magnitude of axial elongation in downward gaze. This may have implications for refractive error development, given the previous association between near work and myopia and the fact that many typical near tasks are performed in downward gaze. However, this biomechanical hypothesis makes the assumption that repeated small increases in axial length, or decreases in choroidal thickness, could lead to longer term eye growth.[30, 31]

There is consistent evidence that accommodation can cause a transient increase in axial length during near tasks.[23-26] It seems feasible that ciliary muscle contraction could exert biomechanical forces on the posterior tissues of the globe resulting in axial elongation during accommodation.[24, 25] A recent study has shown forward movement of the anterior retinal and choroidal tissues towards the ciliary muscle up to 6-7 mm beyond the region of the ora serrata during accommodation in the rhesus monkey's eye.[27]

In this study, the mean "corrected" change in axial length with accommodation in primary gaze (~ 6 microns for 2.5 D stimulus at 0 min), was of similar magnitude to that reported by Read et al. [26] (~ 5 microns for 3.0 D stimulus). We did not find any significant difference in axial elongation between myopes and emmetropes during accommodation for both primary and downward gaze. This finding is also consistent with the results of Read and colleagues of the effect of accommodation on axial length.[26] On the other hand, Mallen et al. [24] and Woodman et al.[23] reported a significantly greater eye elongation in myopic subjects compared with emmetropic subjects, but both these studies used higher accommodative demands during testing than in this study.

The changes in biomechanical forces acting on the globe may cause axial elongation in downward gaze. It has recently been reported that axial length increases in downward gaze over time with far accommodation, under the apparent influence of extraocular muscles.[31] It should also be noted that our findings of the axial length changes occurring with a moderate level of accommodation (i.e. 2.5 D) relate to a typical reading distance of 40 cm.[36] There is evidence that children may perform reading at close working distance (< 30 cm).[3]

We obtained axial length measurements during a relatively short duration of a near task. Recently, Woodman et al.[37] found a significant axial elongation (~ 13 microns) following the commencement of a 30 minutes task with 4 D accommodation demand in primary gaze. Given that many typical near tasks involve accommodation, downward gaze and convergence, it may be important to further investigate the influence of longer periods of near tasks, with higher levels of accommodative demands on the length of the eye in infero-nasal gaze (i.e. a combination of downward gaze and convergence) among different refractive error groups and in children. This may help us to better understand the potential importance of axial length changes associated with near tasks.

A component of the axial elongation we observed was choroidal thinning. The most obvious and statistically significant choroidal thinning took place during accommodation in downward gaze, with the highest magnitude of change in choroidal thickness observed after 10 minutes of task. The change in choroidal thickness accounted for about 50% of the total axial length change (i.e. distance from the anterior corneal surface to retinal pigment epithelium). Unlike the accommodation condition, the changes in the choroid were smaller, and not statistically significant for the far accommodation and downward gaze condition. Therefore, other factors such as scleral stretch or contraction are also likely to contribute to the axial elongation associated with biomechanical forces (i.e. extraocular muscle force) during a near task in downward gaze. Recently, Woodman et al.[37] also observed a significant decrease in choroidal thickness during accommodation (4 D) over time in young adults.

The exact mechanism underlying the changes in choroidal thickness during accommodation in downward gaze is not clear. The posterior part of the ciliary muscle inserts into the elastic fibre network of the anterior choroid,[38] which provides a potential mechanical link between ciliary muscle contraction and choroidal thickness change. In a previous experiment, we observed that negative spherical aberration with accommodation was significantly greater in downward gaze compared to primary gaze, and this leads to hyperopic defocus and image blur at the retina.[39] Given that optical defocus leads to changes in the choroidal thickness,[40-42] it is conceivable that changes in the optics of the eye associated with accommodation and downward gaze could contribute to the changes in the choroidal thickness during near tasks.

The retinal thickness did not exhibit significant change during downward gaze or accommodation. Small misalignments of the line of sight during biometric measurements could result in artefacts in the measurements of ocular biometrics in downward gaze,[43] however the lack of significant change in retinal thickness is good evidence that the changes we observed in axial length and choroidal thickness during downward gaze and accommodation were not due to off-axis measurements of the ocular biometrics, since the specific morphology of the foveal retina means that a small misalignment during biometry measures will cause large changes in retinal thickness. To examine the potential influence of a small axis-misalignment on the ocular biometrics, we measured retinal thickness (n =7) using the Lenstar optical biometer both on-axis and for off-axis measurement eccentricities up to 2° by increments of half a degree along the horizontal and vertical meridians. The retinal thickness increased linearly from the fovea (i.e. on-axis) to the peripheral retina, with the greatest change occurring at 2° eccentricity (mean change 42 ± 9 µm at temporal retina; 38 ± 12 µm at nasal retina; 42 ± 26 µm at superior retina and 47 ± 23 µm at inferior retina) [Figure 4]. In contrast to the changes in retinal thickness, any changes in axial length with these small misalignments were minimal (mean change –10 ± 11 µm at temporal retina; –5 ± 9 µm at nasal retina; –11 ± 9 µm at superior retina and –1 ± 6 µm at inferior retina). Since the results of our study showed only small changes in retinal thickness but larger changes of axial length in some conditions, we are confident that the changes we observed were not the result of subject misalignment during the measurements.

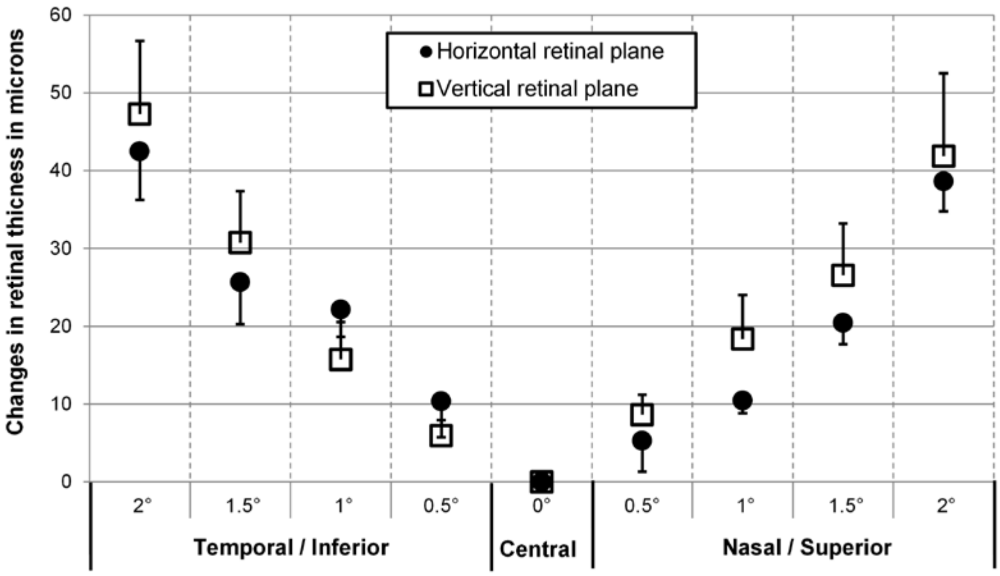

Figure 4. Mean (± SE) difference in retinal thickness (periphery minus fovea) with off-axis measurements at eccentricities up to 2° along the horizontal and vertical plane of the retina.

As expected, lens thickness increased and anterior chamber depth decreased with accommodation.[44-46] Interestingly, we found that changes in ACD and LT with accommodation were significantly greater in downward gaze over time, compared to primary gaze. This finding may explain the results of previous studies that have shown a greater amplitude of accommodation in downward gaze compared to primary gaze.[47-49] A recent study also reported that anterior chamber depth in the human eye may be altered due to lens movement under the action of gravity.[50]

CONCLUSIONS

We have demonstrated that the axial length of the eye increases significantly with accommodation in downward gaze as a function of time. Our study suggests that downward gaze and accommodation have a greater effect on axial elongation than accommodation alone. There was also small but significant choroidal thinning during accommodation in downward gaze over time. Anterior chamber depth and lens thickness exhibit greater changes in downward gaze with accommodation, compared with accommodation in primary gaze. These findings provide a better understanding of the dynamic characteristics of the biometric properties of the eye during near work in downward gaze.

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