Axial length and choroidal thickness changes accompanying prolonged accommodation in myopes and emmetropes

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Abstract

The time course of elongation and recovery of axial length associated with a 30 minute accommodative task was studied using optical low coherence reflectometry in a population of young adult myopic (*n* = 37) and emmetropic (*n* = 22) subjects. Ten of the 59 subjects were excluded from analysis either due to inconsistent accommodative response, or incomplete anterior biometry data. Those subjects with valid data (*n* = 49) were found to exhibit a significant axial elongation immediately following the commencement of a 30 minute, 4 D accommodation task, which was sustained for the duration of the task, and was evident to a lesser extent immediately following task cessation. During the accommodation task, on average, the myopic subjects exhibited 22 ± 34 μm, and the emmetropic subjects 6 ± 22 μm of axial elongation, however the differences in axial elongation between the myopic and emmetropic subjects were not statistically significant ($p = 0.136$). Immediately following the completion of the task, the myopic subjects still exhibited an axial elongation (mean magnitude 12 ± 28 μm), that was significantly greater ($p < 0.05$) than the changes in axial length observed in the emmetropic subjects (mean change -3 ± 16 μm). Axial length had returned to baseline levels 10 minutes after completion of the accommodation task. The time for recovery from accommodation-induced axial elongation was greater in myopes, which may reflect differences in the biomechanical properties of the globe associated with refractive error. Changes in subfoveal choroidal thickness were able to be measured in 37 of the 59 subjects, and a small amount of choroidal thinning was observed during the accommodation task that was statistically significant in the myopic subjects ($p < 0.05$). These subfoveal choroidal changes could account for some but not all of the increased axial length during accommodation.

Keywords

Myopia
Accommodation
Axial elongation
Choroid

1. Introduction

Since myopia often presents and progresses throughout the school years, it has been hypothesised that high levels of near work may contribute to its development (Curtin, 1985). A number of studies have reported significant associations between near work and myopia development (Curtin, 1985; Fulk, Cyert, & Parker, 2002; Jacobsen, Jensen, & Goldschmidt, 2008; Lin et al., 1996; McBrien & Adams, 1997; Onal et al., 2007; Saw et al., 2002; Tan et al., 2000), but there are other studies where the association between these factors is not as clear (Ip et al., 2008; Mutti et al., 2002; Saw et al., 2007). The documented associations between near work and myopia, and the fact that myopia typically develops as a result of an axial elongation of the eye (Grosvenor & Scott, 1991; Grosvenor & Scott, 1993; Jiang & Woessner, 1996) has prompted a number of investigations into whether changes in axial length accompany accommodation. Studies utilising partial coherence interferometry (PCI) for the measurement of axial length have demonstrated that a small axial elongation of the eye occurs with accommodation, although varying magnitudes have been reported (Drexler et al., 1998; Mallen, Kashyap, & Hampson, 2006; Read et al., 2010a; Suzuki et al., 2003; Woodman et al., 2010). However, the increase in optical path length of the eye associated with crystalline lens thickness changes during accommodation can result in an overestimation of axial length with PCI techniques in an accommodating eye (Atchison & Smith, 2004). Recent studies have endeavoured to overcome this potential error induced when measuring axial length during accommodation, by either measuring axial length immediately following accommodation (where lens thickness changes are expected to be minimal) (Woodman et al., 2010) or by measuring axial length during accommodation with an instrument that also provides measurements of lens thickness (this allows an estimate of the likely measurement error in axial length) (Read et al., 2010a). Both of these recent studies, that are unlikely to be substantially influenced by measurement errors associated with the PCI technique during accommodation, have also found a significant increase in axial length with accommodation.

Although studies have consistently noted small increases in axial length during accommodation, the exact cause of this axial elongation is unknown. It has been suggested that it may arise from a mechanical stretching of the globe from inward forces imposed by the ciliary muscle on the globe equator during accommodation (Drexler et al., 1998; Mallen, Kashyap, & Hampson, 2006; Woodman et al., 2010). As these previous studies define axial length as the distance from the cornea to the retinal pigment epithelium (RPE), it is also possible that changes in the thickness of the choroid with accommodation could contribute to the observed axial length changes. However, the presence of choroidal thickness changes during accommodation has not previously been investigated.

Reports of differences in the magnitude of accommodation induced axial elongation between refractive error groups have varied, with initial studies reporting a larger increase in axial length in emmetropes compared to myopes (Drexler et al., 1998), while later studies using the IOLMaster have found larger axial length changes in myopic subjects (Mallen, Kashyap, & Hampson, 2006; Woodman et al., 2010). Recently, Read et al. (2010a) reported no significant difference between a population of emmetropic and low myopic subjects in terms of magnitude of axial elongation during a brief period of accommodation, while Woodman et al. (2010) reported that progressing myopes exhibit a greater change in axial length after a prolonged accommodation task.

The majority of previous studies investigating axial length and accommodation have only used brief periods of accommodation, with measurements typically only collected at a single time point during accommodation (Drexler et al., 1998; Mallen, Kashyap, & Hampson, 2006; Read et al., 2010a; Suzuki et al., 2003). The exact time spent accommodating in these previous studies has either been very brief (i.e. 20 seconds (Mallen, Kashyap, & Hampson, 2006; Read et al., 2010a)) or has not been reported (Drexler et al., 1998; Suzuki et al., 2003). Woodman et al. (2010) investigated the influence of a longer period of accommodation (30 minutes) however measurements were only taken before and immediately after the near task, with no measurements during the 30 minute period of accommodation. Some of the differences between previous studies in terms of magnitude of change in axial length and differences between refractive error groups could therefore potentially relate to the length of time spent performing the accommodation task. An improved understanding of the time course of change and recovery of axial length with accommodation may help to clarify some of these previous inconsistencies.

In this experiment we aimed to investigate the time course of change and recovery in axial length during an extended period of accommodation, and to examine the potential role of the choroid in these changes. We have used optical low coherence reflectometry (a technique analogous to PCI) which allows measurement of a range of ocular biometrics including axial length, crystalline lens thickness and choroidal thickness, before during and after a 30 minute accommodation task in a population of young adult myopic and emmetropic subjects.

2. Methods

2.1 Subjects

Fifty-nine young, healthy adult participants (females *n* = 39, males *n* = 20) aged between 18 and 30 (mean age 21.83 ± 2.98 years, emmetropes 21.68 ± 2.97 years, myopes 21.92 ± 3.03 years) were recruited for the study, primarily from the students of the QUT School of Optometry and Vision Science. None of the subjects had any significant history of ocular or systemic disease, injury or surgery. Participants underwent a brief eye examination to ascertain their current refractive status, monocular amplitudes of accommodation and to ensure normal ocular health. Participants who routinely used soft contact lenses were asked to refrain from wear for 24 hours prior to testing (*n* = 31). To calculate myopic progression rates, a questionnaire was completed by each subject detailing their refractive history over the past five years, and if necessary the subjects' primary eye care practitioner was contacted to obtain previous prescription information. Approval from the university human research ethics committee was obtained before commencement of the study and subjects gave written informed consent to participate. All subjects were treated in accordance with the declaration of Helsinki.

The subjects were classified based upon their subjective spherical equivalent refraction (SER) as either emmetropes (*n* = 22, SER +0.50 to -0.25 DS, with no more than -0.50 DC), or myopes (*n* = 37, SER ≥ -0.75 DS, with no more than -1.00 DC). The mean SER ± SD for the right eye was +0.16 ± 0.28 DS for the emmetropes and -2.90 ± 1.57 DS for the myopes. The mean cylindrical refraction of the emmetropes right eye was -0.13 ± 0.24 DC and myopes -0.39 ± 0.39 DC. All subjects exhibited a best-corrected visual acuity of 0.00 logMAR or better. Monocular amplitude of accommodation measured with the push up method found all subjects' to have ≥ 8 D of accommodation in their right eye (mean = 11.25 ± 1.74 D, emmetropes = 11.18 ± 1.63 D, myopes = 11.38 ± 1.96 D). The emmetropic refractive group consisted of 14 females (64%) and 8 males, and the myopic group 25 females (68%) and 12 males. The population consisted of 39 subjects of Caucasian (66%), 13 of East Asian (22%), and 7 (12%) subjects of either Indian (6) or Middle eastern (1) ethnic origin.

2.2 Procedure

Following the screening and classification of participants, each subject had ocular biometry performed on their right eye before, during and after a 30 minute accommodation task. Ocular biometry measurements were obtained with the Lenstar LS900 (Haag-Streit AG, Koeniz, Switzerland) optical biometer, which measures a range of ocular biometric

parameters including central corneal thickness (CCT), anterior chamber depth (ACD), crystalline lens thickness (LT), axial length (AL, the distance from the anterior corneal surface to the retinal pigment epithelium), retinal thickness (RT, the distance from the inner limiting membrane to the retinal pigment epithelium) and choroidal thickness (ChT, the distance from the retinal pigment epithelium to the choroid/sclera interface). The Lenstar instrument is based upon the principles of optical low coherence reflectometry, and has been found to provide highly precise ocular biometric measurements that compare closely to previously validated instruments like the IOLMaster (Buckhurst et al., 2009; Cruysberg et al., 2009; Holzer, Mamusa, & Auffarth, 2009; Rohrer et al., 2009).

To reduce the likelihood that the measurements were confounded by the effects of previous visual tasks, prior to any ocular measurements participants were required to perform a distance viewing task for 20 minutes (watching television from a distance of 6 m wearing their full distance refractive correction). Participants were then required to view a fixation target imaged at infinity with their right eye through a Badal optometer via a beam splitter positioned in front of the Lenstar biometer (Figure 1). The fellow eye was occluded throughout the experiment to ensure reliable fixation of the tested eye and eliminate the need for convergence while viewing the target. Pilot studies performed with and without the beam splitter on a model eye and on the right eye of 5 subjects showed that the presence of the beam splitter had no significant effect ($p < 0.05$) on the ocular dimensions measured. The pellicle beam splitter used in this experiment had a transmittance of 72% and reflectance of 28% for the Lenstar's 820 nm beam wavelength (Edmund Optics, Singapore). Five measures were then taken to determine baseline ocular dimensions with relaxed accommodation. The fixation target in the Badal optometer consisted of a single spaced passage of size 12-point text, (each letter subtended 0.024° at the cornea). This target was retro-illuminated by an LED light source (luminance of 237 cd/m^2) and was positioned to correct for each subject's spherical equivalent distance refractive error. Before measurements commenced, the beam splitter was adjusted so that the Lenstar's measurement beam coincided with one of the letters in the fixation target's text. Subjects were instructed to maintain clear focus on the passage of text throughout the experiment and to focus on the letter closest to the measurement beam during all measurements. Following the baseline (0 D accommodation stimulus) measures, the fixation target was moved to provide a 4 D stimulus to accommodation and the subjects' were instructed to maintain clear focus on the passage of text for a 30 minute period. During this time, measurements were taken every 5 minutes. After 30 minutes of accommodation, the target was rapidly moved back to a 0 D accommodation demand and measurements were immediately captured to measure any post-task changes in ocular dimensions. Ocular

biometric measures were then monitored over a 10 minute period (with measures every 5 minutes), as subjects continued to view the target at a 0 D accommodation demand. The protocol therefore involved 1 baseline measure with relaxed accommodation (0 D), 6 measures during a 30 minute accommodation (4 D) task, and 3 measures after the task with relaxed accommodation (0 D) over a 10 minute period. At each measurement point during the protocol, 5 repeated measures were taken. The average time to collect the 5 measures at each session was 93 ± 13 seconds.

2.3 Analysis

The ocular biometric data for each subject were obtained and averaged at each of the 10 time intervals. CCT, ACD, LT, and AL are all automatically derived by the Lenstar software. Manual analysis of the Lenstar A-scan output was also performed to determine both RT and ChT as described in detail previously (Read, Collins, & Alonso-Caneiro, 2011). This was achieved by zooming on the posterior portion of the A-scan and adjusting the screen cursor of the Lenstar software to align with the A-scan peaks originating from the posterior eye. The distance between the anterior "P1" peak (which corresponds to the inner limiting membrane), and the central "P3" peak (which corresponds to the retinal pigment epithelium) was derived to determine RT. The distance from the central "P3" peak and the posterior P4 peak (which is assumed to originate from the choroidal/scleral interface) (Read, Collins, & Alonso-Caneiro, 2011; Read, Collins, & Sander, 2010b; Brown et al., 2009) was derived to provide an estimate of ChT (Figure 2). This approach for deriving retinal and choroidal thickness assumes that retinal and choroidal refractive indices are equal, which is consistent with previous interferometric methods used to quantify choroidal thickness (Schmid et al., 1996). One independent masked observer was used to manually determine the retinal and choroidal peaks to avoid potential measurement bias.

The Lenstar instrument is known to use an average ocular refractive index for calculating axial length. To account for any error induced in our axial length measures by increases in lens thickness during accommodation (Atchison & Smith, 2004) we 'corrected' each subject's axial length measures based upon their individual biometric measures. Using the optical parameters of the Gullstrand no. 1 (exact) shell lens model eye, the error (E) in the estimated axial length of the accommodating eye can be calculated using the equation $E = OPL_a/n_{ave} - L_u$, where OPL_a is the optical path length of the accommodating eye, n_{ave} is the average refractive index of the unaccommodated eye, and L_u is the geometrical length of the unaccommodated eye (Atchison & Smith, 2004). Atchison and Smith's formula assumes there is no change in axial length between accommodative and non-accommodative states, and calculates the amount of change (error) in axial length that would occur as a result of

changes in effective ocular refractive index with accommodation. Each subject's ocular dimensions provided by the Lenstar instrument were used to derive OPL_a and n_{ave} in order to calculate the potential error induced by the accommodation in the near task (E), and this error was subtracted from the measured axial length to provide the 'corrected axial length' for each individual subject. The average refractive index of the unaccommodated eye, n_{ave}, is calculated as the sum of the individual ocular components' refractive indices, weighted by the proportion that each component takes up of the eye's total geometric length (with these geometric lengths for the unaccommodated eye taken from the Lenstar data of each individual subject). The optical path length of the accommodating eye (OPL_a) is given by the sum of the optical path lengths of each of the ocular components in the accommodating eye. The refractive indices used in these calculations were taken from the Gullstrand no. 1 (exact) eye with shell lens. The proportion of the lens thickness taken up by the anterior, core and posterior lens shells was kept the same for all subjects, and consistent with the proportions in the Gullstrand no. 1 (exact) model unaccommodated eye. The exact refractive index used by the Lenstar LS900 for converting optical path lengths to geometric distances to calculate axial length is propriety information, and so only an estimate of the error can be made.

Following data collection, 4 subjects (1 myope, 3 emmetropes) were excluded from all analyses as they did not exhibit evidence of a consistent, significant accommodative response during the near task (i.e. they showed a 100 micron or less shallowing of the ACD and thickening of the crystalline lens during the accommodation task). Eleven subjects (7 myopes, 4 emmetropes) did not exhibit consistent peaks from the posterior crystalline lens surface in their A-scan data during all measurement sessions and one of these additional subjects was also missing ACD measurements at some time points, and was therefore excluded from ACD analysis. Of the 11 subjects with incomplete LT data, five had LT data in more than 50% of their measurements, and were able to have their lens thickness at those time points where they were missing data, estimated based on extrapolation of their average LT measures at the other time points, and were therefore included in the corrected AL analysis. We analysed the data from the remaining subjects with complete LT data for all time points, to estimate the likely reliability of the extrapolated data. A similar extrapolation for LT at one time point during accommodation was performed, which allows a comparison to be made between the extrapolated and the actual LT. For those subjects with complete data, the average difference between an extrapolated LT and the actual LT was 2 μm. Potential errors of this magnitude are unlikely to have a substantial influence on the corrected AL values (a 2 μm change in LT would result in a 0.1 μm change in AL).

To examine the ocular changes over time during the experiment and to investigate for any significant differences between refractive error groups, a multivariate repeated measures analysis of variance (MANOVA) was performed for each of the ocular parameters (CCT, ACD, LT, AL, RT, and ChT), with one within subject factor (time) and the between subject factors of refractive error group. This MANOVA analysis was performed firstly to examine the ocular changes from baseline (pre-task) occurring during the accommodation task, and then to examine the changes during the post-task (disaccommodation) phase of the experiment. Ocular parameters showing significant main effects in the MANOVA were further examined using Bonferroni adjusted planned comparisons to examine the significance of the change from the pre-task measures at each time point. Analysis of covariance was also carried out to examine for associations between the changes in each of the measured ocular parameters over time, using the methods of Bland and Altman for the analysis of repeated measures (Bland & Altman, 1995).

3. Results

Baseline AL was highly significantly different ($p < 0.001$) between the two refractive groups, with the average AL being 24.73 ± 1.04 mm ($n = 33$) for the myopes and 23.37 ± 0.81 mm ($n = 16$) for the emmetropes. The average of all subjects was 24.29 ± 1.16 mm ($n = 49$). For the accommodation task, MANOVA revealed a significant effect of time on the corrected AL measures ($p < 0.05$). Immediately following task commencement (0 min) corrected AL increased by 20 ± 31 μm ($p < 0.001$), and remained elongated by a similar magnitude compared to baseline ($p < 0.05$) at all time points during accommodation (except for the 25 minutes measurement $p = 0.072$). There was no significant time by refraction interaction found for corrected AL values during accommodation ($p = 0.554$) and no significant refractive error effect for the change in AL during accommodation ($p = 0.136$), indicating that the magnitude of axial elongation for the myopic subjects (mean elongation across all time points during the accommodation task 22 ± 34 μm) was not statistically significantly different to that observed in the emmetropes (mean elongation 6 ± 22 μm) (Figure 3).

When considering the disaccommodation task, a significant effect of time was not observed for the corrected AL values. There was however a significant ($p < 0.05$) time by refractive error interaction. Immediately following task cessation (time 30 min) axial elongation for the myopes was significantly longer than baseline (13 ± 28 μm) and myopes showed a significantly greater change in corrected AL from baseline compared to the emmetropes ($p < 0.05$) at both 30 and 35 minutes (Figure 3). None of the changes in AL in the emmetropic group post-task were significantly different from baseline ($p > 0.05$).

When the myopic group was classified in terms of refractive error progression there was no clear evidence of a difference between the stable (*n* = 20) and progressing (*n* = 12) subjects in terms of the axial elongation observed during (stable 26 ± 42 μm versus progressing 20 ± 25 μm at time 0 min) or after the accommodation task (stable 14 ± 30 μm versus progressing 11 ± 26 μm at time 30 min, immediately post-task). Pearson's correlation also revealed no significant correlation between the subjects' baseline AL or myopic progression rate and axial elongation at any time point.

The mean baseline ACD ± SD for all subjects (*n* = 54) was 3.27 ± 0.34 mm, and the myopes exhibited a significantly deeper ACD (*n* = 36) than the emmetropes (*n* = 18) (3.37 ± 0.24 mm versus 3.09 ± 0.42 mm) ($p < 0.05$). Baseline LT was thinner on average in the myopes (*n* = 29) than the emmetropes (*n* = 15), although this difference did not reach significance. MANOVA revealed the reduction in ACD and increase in LT during the accommodative task to be highly significant, but there was no significant time by refractive group interaction or refractive group effect for the changes in either dimension. Each of the time points during accommodation was highly significantly different from baseline for both parameters. During the disaccommodation period only ACD showed a significant time effect, with highly significant ACD shallowing from baseline observed at all times post-task (average change of -0.04 ± 0.02 mm during accommodation measures).

The independent masked observer could detect consistent choroidal peaks in all measurements in the Lenstar data for 37 of the 59 subjects, comprised of 25 myopes and 12 emmetropes. Throughout the time course of the task, ChT was observed to change by a smaller magnitude and in the opposite direction to the AL changes observed (the mean thinning of the choroid during accommodation was 38% of the mean axial elongation). MANOVA revealed the effect of time to approach significance during accommodation ($p = 0.064$) and disaccommodation ($p = 0.071$). A significant time by refractive error interaction was noted during accommodation ($p < 0.05$), with myopes showing evidence of statistically significant ($p < 0.05$) thinning of ChT from baseline at 5 and 10 minutes into the accommodative task (Figure 3). There was no time by refractive error interaction found during disaccommodation ($p = 0.165$). On average the choroid of the myopic subjects became thinner by 9 ± 18 μm during accommodation, and the emmetropes by 7 ± 22 μm. Figure 4 graphically illustrates the mean change in ChT with time in the myopes and emmetropes for both accommodation and disaccommodation, and the mean changes in corrected AL during the accommodation and disaccommodation tasks for the subjects who had both valid choroidal and axial length data at all time points (*n* = 27). Analysis of

covariance revealed a highly significant but weak negative association between the changes in AL and ChT ($p < 0.001$, $r^2 = 0.077$, slope $\beta = -0.321$).

Retinal thickness could be estimated in 41 of the 59 subjects (22 myopes, 19 emmetropes). MANOVA showed no significant effect of time, refraction, or time by refraction interaction during accommodation or disaccommodation.

4. Discussion

Using optical low coherence reflectometry and adjusting for potential errors in axial length due to changes in lens thickness, our cohort of young adult subjects demonstrated a significant axial elongation immediately following the commencement of an accommodation task. This was sustained for the duration of the task, and was also evident to a lesser extent immediately following task cessation. Axial length had returned to baseline levels 10 minutes after the accommodation task. The changes in axial length during and following prolonged accommodation were typically of larger magnitude in the myopic subjects compared to the emmetropic subjects, with statistically significant differences between the myopic and emmetropic populations primarily observed during disaccommodation. A small magnitude thinning of the choroid was also observed during the near task that was statistically significant in the myopic subjects, suggesting that these choroidal changes could potentially account for a portion of the increased axial length during accommodation.

The increase in axial length which accompanies accommodation has been well documented, (Drexler et al., 1998; Mallen, Kashyap, & Hampson, 2006; Read et al., 2010a; Suzuki et al., 2003; Woodman et al., 2010) however the time course of change in axial length with accommodation or the effect of disaccommodation after a prolonged near task has not been investigated in detail. Although the axial elongation observed during the accommodation task was of slightly higher magnitude in the myopic subjects, the corrected axial length data indicates that differences in elongation during the task between refractive groups were not statistically significant. However significant differences associated with refractive error were observed in the post-task measures. During this time, the myopic subjects still exhibited a small degree of axial elongation, but the axial length of the emmetropic subjects was not significantly different to the baseline measures. This suggests that the time for recovery from accommodation induced axial elongation is greater in myopes, and this could reflect differences in the biomechanical properties of the globe associated with refractive error. Our findings of differences in axial elongation between myopes and emmetropes following the completion of the near task is consistent with our previous work (Woodman et al., 2010)

using the IOLMaster that also found a tendency for myopes to exhibit greater axial elongation than emmetropes following a prolonged near task.

It is possible that an increase in the effective refractive index of the lens could account for some of the reported changes in axial length which accompany accommodation. However, there is some debate in the literature surrounding the nature of the changes in the crystalline lens' refractive index with accommodation. While earlier reports suggest a small increase in refractive index with accommodation (Dubbelman, Van der Heijde, & Weeber, 2005), later studies which measured the accommodation response and controlled for a lag of accommodation found no change (Hermans et al, 2008) and others report a small decrease in refractive index of the central lens with accommodation (Jones, Atchison, & Pope, 2007). Because the nature of the changes in lens refractive index with accommodation is not completely understood, in our analysis we used an approach that kept the effective refractive index of the crystalline lens constant for both states (i.e. the proportion contribution to the overall lens thickness of the lens shells was kept constant for the unaccommodated and accommodated cases). However, to examine the potential influence of an increase in effective lens refractive index with accommodation, we performed additional analysis using a model that assumes an increase in effective refractive index of the crystalline lens of 0.13% (similar to the increase for the gradient index model of Atchison and Smith (2004)) which reduced the magnitude of elongation, but still resulted in an average significant ($p = 0.02$) increase in axial length with accommodation of 11 ± 31 μm (myopes 17 ± 35 μm, emmetropes 0 ± 18 μm).

The axial elongation seen in the myopic group immediately after task cessation could account for low levels of near-work induced transient myopia (NITM), however the 12 μm difference from baseline immediately following the accommodative task in the myopic subjects would only equate to an 0.04 D myopic shift. This would only account for a small proportion of the typical magnitude of NITM previously reported (Rosenfield & Ciuffreda, 1994; Ciuffreda & Wallis, 1998; Ciuffreda & Lee, 2002). Our results show a transient axial elongation following the near task in the myopic but not emmetropic subjects and this is consistent with previous studies that have found myopes to show significant effects of NITM, while emmetropes show full decay to baseline levels by task completion (Vasudevan & Ciuffreda, 2008; Ciuffreda & Wallis, 1998; Ciuffreda & Lee, 2002).

Both Drexler et al. (1998) and Mallen, Kashyap, & Hampson (2006) hypothesized that ocular elongation accompanying accommodation was due to the force of ciliary muscle contraction decreasing the circumference of the sclera at the equator of the globe, and resulting in axial

elongation of the globe. Another possible anatomical change which could potentiate an apparent increase in axial length would be a thinning of the choroid, rather than a stretching of the globe. In this study we found some evidence of a decrease in choroidal thickness during accommodation, and these choroidal changes exhibited a significant negative correlation with the changes in axial length. The most prominent and statistically significant reductions in choroidal thickness were observed in the myopic subjects during accommodation, with the highest magnitude of change in choroidal thickness observed 10 minutes after beginning the accommodation task. Although the emmetropic subjects on average also exhibited a reduction in choroidal thickness during accommodation, these changes did not reach statistical significance. The magnitude of change in choroidal thickness compared to axial length (38%), and the relatively weak correlation between the two measures suggests that although choroidal thickness changes appear to contribute to the changes in axial length, other factors such as scleral stretch are also highly likely to play a role in the axial elongation during accommodation.

It is unlikely that the choroidal thickness measures derived from the Lenstar will be influenced by the same accommodation induced artefact as the axial length measurements (Atchison & Smith, 2004), because the optical path length measured through the choroid should not be affected by alterations in lens thickness. However, it is possible that magnification effects associated with an increase in the eye's refractive power could potentially influence the choroidal thickness estimates. To investigate the potential influence of magnification factors upon the measurement of intraocular distances with the Lenstar optical biometer, we performed additional measurements with a model eye. Measurements of ocular distances of the model eye were unchanged whether the model eye was measured on its own (23.91 mm) or whether it was measured with a +4 D lens placed in front of it. This suggests that magnification effects associated with 4 D of accommodation are unlikely to have a substantial influence upon our measures of choroidal thickness with the Lenstar instrument. There are however limitations to the measurements obtained by the Lenstar of choroidal thickness. Prominent choroidal peaks are not observed in all subjects, and the method of identifying the P4 peak associated with the choroid requires subjective judgement. The Lenstar measurements also represent the choroidal thickness from a single subfoveal location. It is possible that the changes in choroidal thickness may increase anteriorly, closer to the ciliary body. Future research utilising alternative measurement techniques capable of more reliable choroidal imaging at the fovea and across the posterior pole, such as optical coherence tomography will be useful to more comprehensively understand the choroidal response with accommodation.

Whilst the results from this study indicate that a thinning of the choroid accompanies accommodation, the mechanism underlying this change is less clear. Although there is an overall small amount of thinning in the choroid and an axial elongation with accommodation, the axial length and choroidal data do not always show the same trends in magnitude and time course. Given that tendons from the ciliary muscle have been found to insert into regions of the anterior choroid (Tamm et al., 1991), it is possible that forces from contraction of the ciliary muscle could be transmitted to the choroid, and hence influence choroidal thickness mechanically. However, if choroidal thickness changes were linked to forces from the ciliary muscle, then a correlation should be seen in the dynamic changes in lens thickness during accommodation and recovery. However, there was no association evident between these parameters as the lens thickness returned to baseline values immediately following task cessation. It is therefore unlikely that changes to the subfoveal choroidal thickness that we have observed during accommodation are mechanically linked. The changes observed in choroidal thickness could also potentially involve alterations in blood flow or changes in the tone of non-vascular smooth muscle within the choroid. Given that choroidal blood vessels and non-vascular smooth muscle (NVSM) cells both receive autonomic innervation, it is conceivable that neural signals associated with accommodation could also influence these choroidal structures (Lutjen-Drecoll, 2006; Nickla & Wallman, 2010; Poukens, Glasgow, & Demer, 1998). In our experiment, during accommodation the choroid was observed to thin, returning to baseline levels after accommodation subsided. One possible explanation for this is an increase in parasympathetic input to the NVSM cells during accommodation, leading to a contraction of these cells and thinning of the choroid.

It is also possible that optical factors associated with accommodation could lead to changes in the choroid. It is well known from animal research, (Nickla & Wallman, 2010) and it has recently been found in human subjects (Read, Collins, & Sander, 2010b), that optical stimuli that blur the retinal image can lead to changes in the thickness of the choroid, which result in alterations in the axial length of the eye. These choroidal changes in response to defocus have been shown to occur rapidly (Read, Collins, & Sander, 2010b). It is therefore conceivable that changes in the optical characteristics of the eye during accommodation (e.g. increased lag of accommodation or increased levels of higher order aberrations), could also influence choroidal thickness and hence contribute to the axial length changes associated with near work. Future research utilising simultaneous measurements of ocular optics (e.g. measures of ocular aberrations) and ocular biometrics during near tasks, to examine the relationship between the optical and axial length changes associated with accommodation will help to clarify whether accommodative changes in choroidal thickness are mechanically or optically driven.

There were differences observed between the myopic and emmetropic subjects' choroidal response to accommodation and disaccommodation, with a more prominent choroidal thinning observed in myopes, which suggests a possible difference in choroidal structure or innervation between the two refractive error groups. A thinning of the choroid with accommodation could therefore potentially be an important factor in refractive error development, given that animal research has demonstrated that a choroidal thinning can occur during the development of myopia, and can precede changes in overall scleral growth (Hung, Wallman, & Smith, 2000; Wallman et al., 1995; Wildsoet & Wallman, 1995). However, given that the changes we have observed are short term and transient, further research is required to better understand the implications of accommodation induced choroidal thinning for human myopia development.

As expected, significant changes were also found in anterior chamber depth and lens thickness with accommodation. The magnitude of change in these anterior eye parameters is consistent with previous studies and indicates an accommodative response close to the 4 D stimulus from the myopic and emmetropic populations (Ostrin et al., 2006).

5. Conclusions

In summary, this study confirms previous findings demonstrating a significant axial elongation associated with accommodation. This elongation persists for a short time following task cessation in myopic subjects before returning to baseline levels. We have also shown for the first time, that accommodation is accompanied by a thinning of the choroid, that accounts for some but not all of the changes in axial length that are apparent during accommodation.

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Figure Captions

Figure 1. Illustration of the experimental setup. The retro-illuminated target was viewed through a 12 D Badal lens and beam splitter (BS), and ocular biometrics of the subjects' right eye were measured with the Lenstar (LS). The target was either imaged at infinity (0 D), or to give a 4 D stimulus to accommodation, accounting for each subject's spherical equivalent refractive error. The subjects' left eye was occluded for the duration of the experiment.

Figure 2. A typical A-scan from the posterior eye, the peaks are thought to correspond to posterior eye anatomical landmarks; with the anterior peak (P1) originating from the inner limiting membrane (ILM), the prominent central peak (P3) from the retinal pigment epithelium (RPE), and the most posterior peak (P4) thought to originate from the choroidal/sclera interface (Ch/Scl). Manually adjusting the screen cursor of the Lenstar software allows the determination of retinal thickness (RT) and choroidal thickness (ChT).

Figure 3. Plot of change in corrected axial length (AL) from baseline (BL) and change in choroidal thickness (ChT) from baseline versus time in myopes and emmetropes. All mean ± SEM values are presented in microns (μm). Baseline measurements were taken before the near task was commenced.

Figure 4. Plot of change in corrected axial length (AL) from baseline (BL) and change in choroidal thickness (ChT) from baseline versus time for all subjects. All mean ± SEM values are presented in microns (μm). These results were taken from the subjects who had both valid choroidal and axial length data at all time points (n = 27). Baseline measurements were taken before the near task was commenced.