Bifocal Lens Control of Myopia Progression in Children

Desmond Cheng
Dip(Opt), OD, MSc, FAAO

School of Optometry
Institute of Health and Biomedical Innovation
Queensland University of Technology
Brisbane, Australia

A thesis in fulfillment of the requirements for the degree of
Doctor of Philosophy
2008
Abstract

This research investigated underlying issues that were critical to the success of the bifocal trial and comprised of three studies. The first study evaluated if Chinese-Canadian children were suitable subjects for the bifocal trial. The high prevalence of myopia in Chinese children suggests that genetic input plays a role in myopia development, but the rapid increase in prevalence over the last few decades indicates environmental factors are also important. Since this bifocal trial was conducted in Canada, this work aimed to determine whether Chinese children who had migrated to Canada would still have high myopia prevalence and a high rate of myopia progression. The second study determined the optimal bifocal lens power for myopia treatment and the effect of incorporating base-in prism into the bifocal. In the majority of published myopia control studies, the power of the prescribed near addition was usually predetermined in the belief that the near addition would always help to improve the near focus. In fact, the effect of near addition on the accommodative error might be quite different even for individuals in which the same magnitude of accommodation lag had been measured. Therefore, this work was necessary to guide the selection of bifocal and prism powers most suitable for the subsequent bifocal trial. The third study, the ultimate goal of this research, was to conduct a longitudinal clinical trial to determine if bifocals and prismatic bifocals could control myopia progression in children. The following abstracts summarised the main findings in the published papers and submitted manuscript and were extracted from the journals of submission.

Study 1: Myopia Prevalence in Chinese-Canadian Children in an Optometric Practice

Background: The high prevalence of myopia in Chinese children living in urban East Asian countries such as Hong Kong, Taiwan and China has been well documented. However, it is not clear whether the prevalence of myopia would be similarly high for this group of children if they were living in a Western country. This study aims to determine the prevalence and progression of myopia in ethnic Chinese children living in Canada.

Methods: Right eye refraction data of Chinese-Canadian children aged 6-12 years were collated from the 2003 clinical records of an optometric practice in
Mississauga, Ontario, Canada. Myopia was defined as a spherical equivalent refraction (SER) equal or less than −0.50 D. The prevalence of myopia and refractive error distribution in children of different ages and the magnitude of refractive error shifts over the preceding 8 years were determined. Data were adjusted for potential biases in the clinic sample. A questionnaire was administered to 300 Chinese and 300 Caucasian children randomly selected from the clinic records to study lifestyle issues that may impact on myopia development.

**Results:** Optometric records of 1468 children were analyzed (729 boys and 739 girls). The clinic bias adjusted prevalence of myopia increased from 22.4% at age 6 to 64.1% at age 12 and concurrently the portion of the children that were emmetropic (refraction between −0.25 and +0.75 D) decreased (68.6% at 6 years to 27.2% at 12 years). The highest incidence of myopia for girls (~35%) and boys (~25%) occurred between 9 and 11 years. The average annual refractive shift for all children was −0.52±0.42 D and −0.90±0.40 D for just myopic children. The questionnaire revealed that these Chinese-Canadian children spent a greater amount of time performing near work and less time outdoors than did Caucasian-Canadian children.

**Conclusions:** Ethnic Chinese children living in Canada develop myopia comparable in prevalence and magnitude to those living in urban East Asian countries. Recent migration of the children and their families to Canada does not appear to lower their myopia risk.

**Study 2: The Effect of Positive-Lens Addition and Base-In Prism on Accommodation Accuracy and Near Horizontal Phoria in Chinese Myopic Children**

**Background:** The effect of positive-lens addition (0, +0.75, +1.50, +2.25, +3.00 D each eye) and base-in prism power (0, 1.5, 3 ∆ each eye) on both near focusing errors and latent horizontal deviations was evaluated in 29 Chinese myopic children (age: 10.3 ± 1.9 years, refractive error: −2.73 ± 1.31 D).

**Methods:** Accommodation response and phoria were measured by the Shin-Nippon auto-refractor (right eye) and Howell-Dwyer near phoria card at 33 cm with each of the 15 lens/prism combinations in random order.

**Results:** The initial accommodative error was −0.96 ± 0.67 D (lag) and near phoria was −0.8 ± 5.0 ∆ (exophoria). The positive-lens addition decreased the accommodative lag but increased the exophoria as the power increased (e.g. up to
−9.1 ± 4.1Δ with +3 D). A 6Δ base-in prism totally controlled the exophoria induced by a +1.50 D addition (−0.3 ± 4.3 Δ). In the graphical analysis of the data, a lens addition of +2.25 D combined with a 6Δ base-in prism minimized both the lag and lens induced exophoria to −0.33 D and −2.4 Δ respectively (regression analysis). This lens and prism combination decreased the lens induced exophoria by 4.5 Δ compared to that measured with +2.25 D alone (−2.4 Δ vs −6.9 Δ).

**Conclusions:** The results suggest that incorporating near base-in prism when prescribing bifocal lenses for young progressing myopes with exophoria could reduce the positive-lens induced oculomotor imbalance.

**Study 3: A Randomized Trial of Bifocal and Prismatic Bifocal Spectacles on Myopia Progression: Results After 24 Months**

**Objective:** To determine whether bifocal and prismatic bifocal spectacles compared with single vision spectacles could control myopia in children with high rates of myopia progression.

**Methods:** A randomized controlled clinical trial was conducted. 135 (73 female and 62 male) myopic Chinese-Canadian children (≥1.00D myopia) with myopia progression of at least 0.50D in the preceding year were randomly assigned to one of three treatments: (i) single vision lenses (SVL, n=41), (ii) +1.50D executive bifocal (BFL, n=48), or (iii) +1.50D executive bifocal with 3Δ base-in prism in the near segment of each lens (PBFL, n=46).

**Main Outcome Measures:** Myopia progression measured by an automated refractor under cycloplegia and increase in axial length (secondary) measured by ultrasonography at 6-monthly intervals for 24 months. Only the data of the right eye were used.

**Results:** Of the 135 children (age: 10.29±0.15yr, myopia: −3.08±0.10D), 131 (97%) completed the trial after 24 months. Myopia progression (mean±SE) averaged −1.55±0.12D for SVL, −0.96±0.09D for BFL and −0.70±0.10D for PBFL; axial length increased 0.62±0.04mm, 0.41±0.04mm, and 0.41±0.05mm respectively. The treatment effect of BFL (0.59D) and PBFL (0.85D) was significant (p<0.001) and both bifocal groups had less axial elongation (0.21mm) than the SVL group (p<0.001).

**Conclusions:** Both bifocals and prismatic bifocals could control myopia in children with high rates of myopia progression.
Applications to Clinical Practice: Bifocal spectacles are a justifiable myopia control treatment for myopic Chinese children with an annual myopia progression of at least 0.50D.

Trial Registration: clinicaltrials.gov  Identifier: NCT00787579

Key words: children, Chinese, myopia, prevalence, accommodation, bifocal, phoria
List of Publications and Manuscript

Study 1 (Chapter 2)

Study 2 (Chapter 3)

Study 3 (Chapter 4)

Ethical Clearance
*These studies were reviewed and approved by the Queensland University of Technology, Human Research Ethics Committee (Reference Number 3222H).*

Author and Co-authors

Desmond Cheng
*School of Optometry and Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, Qld, Australia*

Katrina L. Schmid
*School of Optometry and Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, Qld, Australia*

George C. Woo
*School of Optometry, The Hong Kong Polytechnic University, Hong Kong SAR, China*

Björn Drobe
*Essilor International, Research & Development Centre Singapore, Singapore*
Contents

Title page i
Abstract and key words ii
List of publications and manuscript vi
Table of contents vii
Signed statement of original authorship viii
Statement of contribution of co-authors for Chapter 2 ix
Statement of contribution of co-authors for Chapter 3 x
Statement of contribution of co-authors for Chapter 4 xi
Acknowledgements xii

Introduction 1

Chapter 1: Literature Review 6

1.1 Background 6
1.2 Accommodation and myopia 8
1.3 Convergence and myopia 14
1.4 Crosslink interaction of accommodation and convergence in myopigenesis 17
1.5 Bifocal control of myopia 22
1.6 Bifocal treatment and near oculomotor mechanism 36

Chapter 2: Myopia Prevalence in Chinese-Canadian Children in an Optometric Practice 54

Desmond Cheng, Katrina L. Schmid and George C. Woo
(Optom Vis Sci. 2007;84:21-32)

Chapter 3: The Effect of Positive-Lens Addition and Base-In Prism on Accommodation Accuracy and Near Horizontal Phoria in Chinese Myopic Children 79

Desmond Cheng, Katrina L. Schmid and George C. Woo

Chapter 4: A Randomized Trial of Bifocal and Prismatic Bifocal Spectacles on Myopia Progression: Results After 24 months 105

Desmond Cheng, Katrina L. Schmid, George C. Woo and Björn Drobe
(Submitted for publication)

Chapter 5: General Discussion 126
Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Desmond Cheng

Date:
Statement of Contribution of Co-authors for Chapter 2

The authors listed below have certified* that:

1. they meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;
2. they take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;
3. there are no other authors of the publication according to these criteria;
4. potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit,
5. and they agree to the use of the publication in the student’s thesis and its publication on the Australasian Digital Thesis database consistent with any limitations set by publisher requirements.

In the case of this chapter:


<table>
<thead>
<tr>
<th>Contributor</th>
<th>Statement of contribution*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desmond Cheng</td>
<td>wrote the manuscript, experimental design, conducted experiments, and data analysis</td>
</tr>
<tr>
<td>Sig:</td>
<td></td>
</tr>
<tr>
<td>Date:</td>
<td></td>
</tr>
<tr>
<td>Katrina L. Schmid*</td>
<td>aided experimental design, data analysis and writing the manuscript</td>
</tr>
<tr>
<td>George C. Woo*</td>
<td>reviewed the manuscript</td>
</tr>
</tbody>
</table>

Principal supervisor confirmation

I have sighted email or other correspondence from all co-authors confirming their certifying authorship.

Katrina L. Schmid
Name ___________________________ Signature ______________ Date __________
Statement of Contribution of Co-authors for Chapter 3

The authors listed below have certified* that:

1. they meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;
2. they take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;
3. there are no other authors of the publication according to these criteria;
4. potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit,
5. and they agree to the use of the publication in the student’s thesis and its publication on the Australasian Digital Thesis database consistent with any limitations set by publisher requirements.

In the case of this chapter:


<table>
<thead>
<tr>
<th>Contributor</th>
<th>Statement of contribution*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desmond Cheng</td>
<td>wrote the manuscript, experimental design, conducted experiments, and data analysis</td>
</tr>
<tr>
<td>Sig:</td>
<td></td>
</tr>
<tr>
<td>Date:</td>
<td></td>
</tr>
<tr>
<td>Katrina L. Schmid*</td>
<td>aided experimental design, data analysis and writing the manuscript</td>
</tr>
<tr>
<td>George C. Woo*</td>
<td>reviewed the manuscript</td>
</tr>
</tbody>
</table>

Principal supervisor confirmation

I have sighted email or other correspondence from all co-authors confirming their certifying authorship.

Katrina L. Schmid
Name ________________________ Signature ________________________ Date ________________________
Statement of Contribution of Co-authors for Chapter 4

The authors listed below have certified* that:

1. they meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;
2. they take public responsibility for their part of the publication, except for the responsible author who accepts overall responsibility for the publication;
3. there are no other authors of the publication according to these criteria;
4. potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit,
5. and they agree to the use of the publication in the student’s thesis and its publication on the Australasian Digital Thesis database consistent with any limitations set by publisher requirements.

In the case of this chapter:

“A Randomized Trial of Bifocal and Prismatic Bifocal Spectacles on Myopia Progression: Results After 24 Months” submitted for publication (February 2009)

<table>
<thead>
<tr>
<th>Contributor</th>
<th>Statement of contribution*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desmond Cheng</td>
<td>wrote the manuscript, experimental design, conducted experiments, and data analysis</td>
</tr>
<tr>
<td>Sig:</td>
<td></td>
</tr>
<tr>
<td>Date:</td>
<td></td>
</tr>
<tr>
<td>Katrina L. Schmid*</td>
<td>aided experimental design, data analysis and writing the manuscript</td>
</tr>
<tr>
<td>George C. Woo*</td>
<td>reviewed the manuscript</td>
</tr>
<tr>
<td>Björn Drobe*</td>
<td>aided experimental design and reviewed the manuscript</td>
</tr>
</tbody>
</table>

Principal supervisor confirmation

I have sighted email or other correspondence from all co-authors confirming their certifying authorship.

Katrina L. Schmid
Name Signature Date
Acknowledgements

I would like to thank my supervisor Associate Professor Katrina L. Schmid for her support and guidance. Her research experience and motivation were instrumental in helping me accomplish this study.

I am indebted to my associate supervisor Professor George C. Woo for his support and encouragement for doing my PhD at QUT. His advice and recommendations were invaluable throughout my career.

I would like to thank my committee members Professor Micheal J. Collins and Dr. Peter L. Hendicott for their comments and recommendations.

I would also like to acknowledge Essilor International for the support of this work and Dr. Björn Drobe for being the liaison.

Finally, I would like to thank my wife, Alice, and my children, Max and Erin, for their love, patience and understanding for my academic endeavours.
Introduction

Myopia is a refractive condition of the eye in which the images of distant objects are focused in front of the retina when accommodation is relaxed. Thus distance vision is blurred. In myopia the point conjugate with the retina, that is the far point of the eye, is located at some finite point in front of the eye (Millodot, 1993). Once myopia appears in childhood, it progresses steadily until about 16 years of age (Goss and Winkler, 1983). While myopia was previously thought of as little more than inconvenience and a source of unwanted expense to the affected individuals, it is now sufficiently prevalent to warrant national concerns (Edwards and Lam, 2004). The prevalence of myopia in children has increased substantially over recent years and is approaching to 10-20 % in non-Asian countries such as Europe (Goldschmidt, 1968), United States (Zadnik et al., 1994) and Australia (Junghans and Crewther, 2005) and to at least 50 to 60 % in urban South East Asian countries (Lam and Goh, 1991; Yap et al., 1994; Edwards, 1999; Lin et al., 2001). The financial cost of myopia in 1990 in the United States, with a population at that time of about 270 million and a myopia prevalence of about 30% (Sperduto et al., 1983) was estimated to be US$ 4.8 billion (Javitt and Chiang, 1994). In addition, myopia is associated with pathological conditions such as glaucoma and cataract, and is an important risk factor for retinal detachment. With an aging population, these myopia-related pathologies are also likely to increase in the coming decades.

Bifocal lenses have been used in myopic children as a treatment with the purpose of inhibiting myopia progression for many years, since the 1950s and perhaps earlier. The main premise underlying the use of bifocals as a therapeutic measure against the progression of myopia is that myopia is related to ocular accommodation. The early theory was that bifocals would control myopia by reducing the strength of the accommodative stimulus (Grosvenor et al., 1987; Hemminki and Parssinen, 1987; Jensen, 1991). The newer and currently more accepted theory is the defocus theory in which bifocals control myopia by reducing the lag of accommodation (retinal defocus) (Gwiazda et al., 2003). Unfortunately, bifocal lenses have not been proven to be very effective myopia control treatments in children (reviewed in Goss 1994, Hung and Ciuffreda 2000). The reported success varies greatly, as does the design of studies reporting their use (from the earlier retrospective analysis of records to later
prospective clinical trials). Collectively data of many studies support the suggestion that bifocal lenses inhibit myopia development in children, but only by a small amount and only in a subset of children with particular ocular characteristics. For example, those myopic children who are esophoric at near and have a lag of accommodation seem to benefit most (progressive addition lenses: Gwiazda et al., 2004). This lack of effectiveness for all children could relate to a lack of individualism in the treatment (for example a set lens addition power is usually given) or lack of accounting for the state of the convergence system. It is therefore the purpose of this work to investigate underlying issues that are critical to the success of the bifocal lens treatment. The aim of this body of work is to determine whether simultaneously reducing the demand of accommodation and convergence by means of positive-lens addition and base-in prism at near in a synchronized fashion can slow myopia progression. The ultimate goal of this research was to conduct a bifocal lens wearer trial to determine if bifocals and prismatic bifocals control myopia in children with high rates of myopia progression.

The first chapter of this thesis is a literature review to provide a clear understanding of how accommodation, convergence and the interaction of these two systems are linked to the development of myopia. The main emphasis of the review is to describe the link between the accommodation and convergence systems, how disruption to this linkage could cause myopia and how from this information a bifocal lens treatment could be devised to more effectively inhibit myopia. Critical analysis of previous myopia control studies using bifocal and multifocal lenses is also included.

The aim of the research described in the second chapter was to evaluate if Chinese-Canadian children are suitable subjects for a myopia control bifocal lens trial. The high prevalence of myopia in Chinese children suggests that genetic input plays a role in myopia development, but the rapid increase in prevalence over the last few decades indicates environmental factors are also important. Since the bifocal lens trial was to be conducted in Canada, this work aimed to determine whether Chinese children who have migrated to Canada will (like their Asian residing counterparts) also have high myopia prevalence and a high rate of myopia progression. This chapter entitled “Myopia Prevalence in Chinese-Canadian Children in an
The aim of the experiment described in the third chapter was to determine the bifocal lens power most suitable for myopia treatment and the accommodative and vergence effects of incorporating base-in prisms into the design of the bifocals. Various positive-lens addition and base-in prism powers were used to simultaneously modify the accommodation and convergence demands of myopic children in order to determine the lens and prism powers required to produce the least accommodation lag and lens-induced exophoria for near-work. This work was critical to guide the selection of the optimal bifocal and prism power combination for the bifocal lens trial. This chapter entitled “The Effect of Positive-Lens Addition and Base-In Prism on Accommodation Accuracy and Near Horizontal Phoria in Chinese Myopic Children” has been published as a journal paper in Ophthalmic and Physiological Optics (2008).

The fourth chapter describes the results after 24 months of a 3-year clinical trial of bifocals and prismatic bifocals on myopia progression children. The purpose of this study was to determine whether bifocal spectacles compared with single vision spectacles could control myopia in children with high rates of myopia progression (≥0.5D in the preceding year) and to investigate the effect of incorporating near base-in prisms along with the near-addition lenses (prismatic bifocal spectacles) on myopia progression. This manuscript entitled “A Randomized Trial of Bifocal and Prismatic Bifocal Spectacles on Myopia Progression: Results after 24 months” has been submitted for publication.

The last chapter is a general discussion of the findings of this work and implications for the clinical management of myopia. The clinical trial is ongoing and more publications will arise from the trial; these future data analyses are also discussed here.
References


Chapter 1: Literature Review

1.1 Background
The history of using bifocal lenses to control myopia in children is a long one, probably more than 50 years. Early reports regarding the efficacy of bifocal spectacles for reducing myopia progression were mainly clinical impressions or case studies. The basic principle underlying the use of bifocals to retard myopia progression is that myopia development is related to ocular accommodation. The early theory was that bifocals would control myopia by reducing the accommodative demand during near tasks (Grosvenor et al., 1987; Hemminki and Parssinen, 1987; Jensen, 1991). The recent and more accepted theory proposes that bifocals would control myopia by reducing the lag of accommodation; when the accommodation response is less than the demand a lag of accommodation occurs (Gwiazda et al., 2003). This type of accommodation error creates hyperopic retinal defocus and this has been shown to induce axial myopia in young animals (Schaeffel et al., 1988; Irving et al., 1991; Schmid and Wildsoet, 1996). However, experimental studies (reviewed in Hung and Ciuffreda, 2000; Saw at al., 2002) conducted to date have shown that bifocal lenses are not very effective in controlling myopia progression in children. Consequently, it appears that only reducing the accommodative stimulus and thus modifying the accommodative lag alone during near work is not an adequate measure to control myopia.

Excessive near work has been shown to be a risk factor for myopia development (reviewed in Rosenfield and Gilmartin, 1998), though it is a complex variable to examine and especially to quantify. The idea of an association between myopia and near work dates back to the observations of Ware (1813), Donders (1864) and Cohn (1867) (cited in Rosenfield and Gilmartin, 1998) that myopia has greater prevalence in more educated groups. Experimental and epidemiological lines of evidence have indicated that schooling, study, reading and other near work activities are associated with axial elongation and myopia (Hirsch, 1952; 1961; 1962; 1964; Baldwin, 1957; Morgan, 1960; Goldschmidt, 1968; Angle and Wissmann, 1978; Rosner and Belkin, 1987; Zylbermann et al., 1993). An unsolved question is why this association occurs, i.e. what aspect of the near task promotes myopia development. Accommodation and convergence are elements of the oculomotor near response mechanism (the near triad
includes accommodation, convergence and pupil constriction). They contribute to the production of a clear and single image at near under normal binocular viewing conditions. The closer the target the greater the accommodation and convergence demand. For that reason, it has been postulated that the increased amounts of accommodation and convergence that occur at near are linked to the development of myopia (Greene, 1980) but a definitive model for this linkage has not been established.

To date, most bifocal studies have been designed to control myopia by reducing only the accommodative demand in the near response, even though there is the suggestion (not currently well accepted though) that the act of convergence at near is related to myopia development (Greene, 1980; Bayramlar et al., 1999;). There have been very limited studies in the literature investigating the effect of reducing the convergence demand at near on myopia development. The one study that has been performed shows that reducing convergence and accommodation for near work can retard myopia (Rehm, 1975). However, it is not sure if the myopia control effect is related to reduction of the convergence or accommodative response. The lack of accounting for the state of the convergence system may be the reason why bifocal spectacles have not always been proven to be an effective myopia treatment method. It is therefore the aim of this body of work to determine whether simultaneously reducing the demand of accommodation and convergence at near in a synchronized fashion can slow myopia progression.

This review will cover how accommodation and convergence are associated with myopia and its development. Possible mechanical and intraocular pressure effects associated with the acts of accommodation and convergence are discussed. The main emphasis is the link between the accommodation and convergence systems, how disruption to this could cause myopia (including accommodation errors and nearwork induced transient myopia) and how bifocal treatment may be devised to inhibit myopia using this information. Also included in this review is the summary and evaluation of the literature of previous bifocal and multifocal studies. There are multiple other theories on how close work could cause myopia including increased negative spherical aberration (He et al., 2000; Cheng et al., 2003), altered Stiles Crawford functions (Blank et al., 1975; Choi et al., 2003), contrast adaptation
(Diether et al., 2001), visual deprivation due to the unchanging nature of text (Wallman and Winawer, 2004), peripheral retinal blur (Walker and Mutti 2002; Charman, 2005), lack of outdoor activity (Rose et al., 2008) that are outside the scope of this review.

1.2 Accommodation and myopia
Over the past 30 to 40 years, there have been two prevailing theories linking the actions of accommodation and the development of myopia. One early theory suggests that the act of accommodation mechanically stretches the sclera through an increase in intraocular pressure (Van Alphen, 1961; Coleman, 1970; Young, 1981a; 1981b). The other theory is the defocus theory in which the retinal image defocus created by accommodation errors provides feedback for refractive development (Gwiazda et al., 1993). The latter theory has gained more attention in recent years and the earlier theory is no longer supported.

1.2.1 Biomechanical effect of accommodation
The earliest theory put forth to link accommodation and myopia was formulated by Van Alphen (1961). He suggested that the act of accommodation created force on the sclera and a resultant increase in intraocular pressure (IOP). The higher pressure would then be poorly resisted by the sclera, resulting in scleral expansion, axial elongation and myopia. A similar idea was later proposed by Coleman (1970) and Young (1981a, 1981b). However, the act of accommodation has since been shown to lower the eye’s IOP (Armaly and Rubin, 1961; Armaly and Jepson, 1962; Mauger et al., 1984; Young and Leary, 1991) which would prevent myopia development not cause it.

Van Alphen (1961) also believed that the ability of the globe to resist scleral stretch from the forces of normal IOP was directly related to the tonus of the ciliary-choriod complex. A reduced ciliary tonicity (measured as a lower tonic accommodation) leads to a low choroidal tension making the sclera more vulnerable to stretching and therefore axial myopia. The importance of tonus of the ciliary-choriod complex is shown by investigations (McBrien and Millodot, 1987; Bullimore and Gilmartin, 1987; Rosenfield and Gilmartin, 1987a; McBrien and Millodot, 1988; Hung and Ciuffreda, 1991; Gwiazda et al., 1995a; Jiang, 1995; Woung et al., 1998; Zadnik et
al., 1999) that find myopes have lower tonic accommodation relative to hyperopes and emmetropes, but this relationship is not always able to be demonstrated (Fisher at al., 1987; Bullimore and Gilmartin, 1987; Rosenfield and Gilmartin, 1988a; Gilmartin and Bullimore, 1991; Morse and Smith, 1993; Woung et al., 1993; Strang et al., 1994). However, as the act of accommodation has been shown to create internally directed forces on the ciliary-choroid complex (leads to high choroidal tension) (Ostrin and Glasser, 2007), the act of accommodation should inhibit myopia development not cause it. Therefore, the role of the tonus of the ciliary-choriod complex on myopia inhibition and development has yet to be fully established.

Further to this, sustained accommodation is suggested to alter the tonic innervation of the ciliary muscle, making the muscle unable to relax accommodation fully when viewing distant targets after a period of close work (Young, 1981a; 1981b). This intermittent accommodation at distance, pseudomyopia, would transform into constant myopia if the tonus of the ciliary muscle was permanently shifted. This proposal has been supported by studies (Ciuffreda and Wallis, 1998; Vera-Diaz et al., 2002; Ciuffreda and Lee, 2002; Wolffsohn et al., 2003; Vasudevan and Ciuffreda, 2008) demonstrating that myopes are particularly susceptible to nearwork-induced transient myopia (NITM) but the evidence for a direct link between permanent myopia and NITM has been inconclusive (Vasudevan and Ciuffreda, 2008).

An alternative proposal is that the action of accommodation exerts stresses directly on the coats of eyes, resulting in retinal stretching. Accommodation has been shown to increase the axial length of the eye by at least a few microns as measured by partial coherence interferometry (Drexler et al., 1998; Mallen et al., 2006); although the ability of the technique to measure such small changes (microns) in eye length has been questioned (Atchison and Smith, 2004), as this instrument uses only one refractive index value for the entire eye and changes in lens thickness are not accounted for. According to this study, the increase in axial length is attributed to the accommodation-induced contraction of the ciliary muscle. The contraction of the ciliary muscles causes forward and inward pulling on the choroids at the equator, thus decreasing the circumference of the sclera equatorially, which causes the posterior pole to bulge outward eventually leading to permanent elongation of the axial length. The equatorial increased ciliary-choroidal tension has also been
proposed as a potential cause of both the elongated and distorted prolate ocular shapes observed in myopic eyes (Mutti et al., 2000b; Walker and Mutti, 2002).

1.2.2 Intraocular pressure and myopia
One proposal of the biomechanical theories is that during accommodation, the increased IOP exerts force on the coats of the eyes to expand the globe. Evidence for this proposal could take two forms, 1) myopes, in particular people with progressive myopia, have higher IOP than non-myopes, and 2) accommodation raises the IOP.

There is very little evidence to suggest that elevated IOP is a primary cause of myopia development in children. While it is true that many older myopes develop glaucoma than is predicted based on the relative prevalence of myopia (Mitchell et al., 1999; Casson et al., 2007), this is more likely due to structural changes that occur in the elongated eye rather than being IOP based. Slightly raised IOP only seems to occur after myopia has developed (Edwards and Brown, 1996), i.e. it is a consequence not a cause of myopia development. A higher IOP is found in myopic eyes compared to non-myopic eyes of young adults (Abdalla and Hamdi, 1970; Tomlison and Philips, 1970; Edwards and Brown, 1993; Edwards et al., 1993), but these studies only demonstrate a slightly elevated IOP (less than 3 mmHg difference) which is within the normal diurnal variation (Duke-Elder, 1952; Drance, 1960; Phelps et al., 1974). In addition, no difference is found between the IOP of emmetropic children who go on to develop myopia and those who do not (Lee, 2004). There was also no significant association between baseline IOP and baseline myopia or the degree of myopia progression in the COMET study (Manny et al., 2008).

There is also no evidence for the second proposal that accommodation raises the IOP and that this is why near work is linked to myopia development. Duke-Elder (1938) suggested that accommodation actually reduced IOP by causing constriction of the anterior ciliary arteries and dilation of the ciliary veins resulting in a widening of the anterior chamber angle to assist aqueous outflow. His idea was supported by investigations using Goldmann applanation tonometry (Armaly and Rubin, 1961; Armaly and Jepson, 1962; Mauger et al., 1984; Young and Leary, 1991) that reported IOP reduced as accommodation increased. A small but significant reduction in IOP
of 1-6 mmHg was demonstrated for increased accommodation demands of 0-4 D in these studies. Also, the ciliary muscle was found to exert a peak force of only 0.5-0.6 g (Van Alphen, 1961; Suzuki, 1973; Lograno and Reibaldi, 1986) on the choroid causing the vitreous chamber pressure to increase by less than 2 mm Hg; such a small increase is believed to have limited effect on the rigid sclera of the eye.

At the present time, there is little evidence to support the notion that the action of accommodation causes the axial length of the globe to increase via increased IOP. Perhaps axial myopia is the result of a structural weakness of the sclera in myopic eyes that allows them to stretch in response to the eye’s normal IOP or an increased inward equatorial stress during prolonged accommodation resulting in outward posterior pole stress. The lack of evidence for a role of IOP in myopia development explains why only small increases in IOP are measured in already myopic adults and no differences in the IOPs of emmetropes who go on to develop myopia compared to those who remain as emmetropic.

1.2.3 Effect of accommodative error (retinal defocus)
In addition to a biomechanical effect that might alter eye size, accommodation also provides a plausible means for determining the sign and magnitude of image defocus on the retina. Laboratory studies involving animal models clearly show that ocular growth is regulated by a vision driven process (Wiesel and Raviola, 1977; Wallman et al., 1978) and can be altered by manipulations to that visual experience, for example retinal defocus. While accommodation must be taken into account in this visual feedback system, how this is achieved is not known. It appears that an active accommodative motor output is not necessary for the regulation of eye growth and the development of myopia. Blocking accommodation in chicks by lesion of the Edinger-Westphal nucleus (Schaeffel et al., 1990; Troilo, 1990) or removal of the ciliary ganglion (Raviola and Wiesel, 1990; Wildsoet et al., 1993; Lin et al., 1996) does not prevent the development of deprivation myopia, the recovery from induced refractive errors, nor the compensation for spectacle lenses.

Studies on the effects of positive and negative spectacles across several vertebrate species including fish (Kroger and Wagner, 1996), chicks (Irving et al., 1991; Schaeffel et al., 1988; Schmid and Wildsoet, 1996), guinea pigs (McFadden and
Wallman, 1995), tree shrews (McBrien et al., 1999; Siegwart and Norton, 1993), and primates (Graham and Judge, 1999; Hung et al., 1995; Smith, 1998; Smith and Hung, 1999) strongly suggest that vision is used to guide the growth of the eye, since the eyes grow to compensate for the induced refractive errors. In young chicks errors between +15 D and -10 D can be rapidly and correctly compensated for (Irving et al., 1992; Wildsoet and Wallman, 1995; Schmid and Wildsoet, 1996). Also of relevance is the observation that chicks reared in cages designed with abnormally close ceilings develop local myopia in the lower retina (Miles and Wallman, 1990). This result is consistent with the report that chicks can respond to focusing errors imposed locally using lenses (Wallman et al., 1987). In addition, when both myopic and hyperopic defocuses are present, the myopic defocus transiently dominates the latter as a determinant of ocular growth (Diether and Wildsoet, 2005)

Mammals do not show such a large and consistent compensatory ability to lens-induced refractive errors as chicks. In cats, Nathan et al. (1984) found no refractive changes with imposed optical defocus but Ni and Smith (1989) found that myopia developed in cats regardless of the sign of lens used. A study of optical defocus in the tree shrew has reported that positive lenses, especially of high powers (>+6 D), do not elicit hyperopia and result in myopia instead (Siegwart and Norton, 1993). It has been suggested that tree shrews may have a limited capacity to compensate for myopic defocus (Siegwart et al., 2003). A later study found that tree shrew can only compensate for lens power ranged from 0 to +4 D (Metlapally and McBrien, 2008). Guinea pigs were also found to compensate for defocus in a narrower range (McFadden and Wallman, 1995) between 0 and 8 D of hyperopic defocus, beyond which the compensation was reduced (Howlett and McFadden, 2009). In primates, eyes of marmosets can compensate for lenses of +3 to <+4 D lenses (Graham and Judge, 1999) but the magnitude of refractive compensation was very limited in infant rhesus monkeys (Hung et al., 1995). This was attributed to a small range of effective emmetropization mechanism (Smith and Hung, 1999). Using a sequential lens rearing strategy with a small, constant, continual increase in defocus, rhesus monkey was able to compensate for lenses ranged from −3 to +3 D (Smith and Hung, 1999). The lack of consistent results among mammalian species may be due in part to methodological differences in experimental design, but species differences in eye growth control cannot be ruled out.
Most individuals do not accommodate adequately to bring the target into complete focus on the retina at near viewing distances. This under-accommodation creates a hyperopic defocus with the near target’s best image being localized slightly behind the retina (Gwiazda et al., 1993). If this hyperopic defocus is prolonged and sustained, as may be the case for extended near work, it is thought to contribute to the progression of myopia and axial elongation of the eye (Gwiazda et al., 1993). This proposal is consistent with the observation that hyperopic defocus (induced using negative lenses) stimulates posterior segment elongation in a wide range of neonatal animals (Irving et al., 1991; Wildsoet and Wallman, 1995; Schmid and Wildsoet, 1996). The near hyperopic focal error is quantified by the dioptric difference between the accommodative demand and response, and is also referred to as a lag of accommodation (Grosvenor, 1982). The accommodation stimulus response curve typically shows small leads of accommodation for zero and low accommodation demands and lags of accommodation at high accommodation demands, i.e. accommodation errors (McBrien and Millodot, 1986). For high accommodative demands (e.g. > 3 D), larger lags of accommodation have been measured in myopic children (McBrien and Millodot, 1986; Gwiazda et al., 1993; Gwiazda et al., 1995b) and in young myopic adults (McBrien and Millodot, 1986; Rosenfield and Gilmartin, 1988a; Abbott et al., 1998) compared to emmetropic individuals. These refractive error group differences in the magnitude of the accommodation errors are accentuated when the accommodation demand is induced using negative lenses (Gwiazda et al., 1993; Abbott et al., 1998) and when accommodative response is measured under monocular viewing conditions (Ibi, 1997; Rosenfield et al., 2002; Seidel et al., 2005). Under binocular conditions, the relationship between accommodative response and myopia becomes less significant (Rosenfield et al., 2002; Weizhong et al., 2008).

Although the higher lags of accommodation in myopic individuals may be a consequence of ocular changes from being myopic rather than the cause of the myopia, it is generally believed that accommodation errors are important in myopia development (McBrien and Millodot, 1986; Bullimore et al., 1992; Gwiazda et al., 1993; Gwiazda et al., 1995b; Abbott et al., 1998). Evidence for this link includes the fact that emmetropes who become myopes have reduced near-point accommodative amplitude (Drobe and de Saint-Andre, 1995) and reduced positive relative...
accommodation (Goss, 1991; Drobe and de Saint-Andre, 1995) and myopic eyes have reduced accommodative facility at distance (Pandian et al., 2006) and that young adults whose myopia is progressing have greater accommodation lags at near than those whose myopia is stable (Abbott et al., 1998). In school-aged children, the link between accommodative error and myopia has also been investigated at different stages of myopia development. A reduced blur driven accommodative response is found to occur before (Gwiazda et al., 2005), concurrent with (Gwiazda et al., 1995b; Gwiazda et al., 2005) and after the onset of myopia (The CLEERE Study Group, Mutti et al., 2006).

In addition, retinal defocus (blur) is also observed at far immediately after performing sustained near focus tasks as a result of the process of accommodative adaptation to reduce accommodative error at near over time. The transient increase in accommodation (near work induced transient myopia, NITM) is typically about 0.2 D (Ehrlich, 1987; Rosenfield et al., 1992), but shifts exceeding 1.00 D have also been reported (Ong and Ciuffreda, 1995; 1997). This shift in accommodation could result in pseudomyopia, which might be a transitional stage in the development of permanent myopia. It is not sure which of the two defocus errors (i.e. lag of accommodation or pseudomyopia) is more likely to contribute to permanent myopia. If the sign of defocus is critical, then this would support the proposal that the defocus present during the course of sustained near task is most relevant. However, such directionally guided change in axial length of the globe to reduce the induced defocus error has not always been correct even in primates (Smith et al. 1994, Hung and Smith 1996). Ong and Ciuffreda (1997) speculated that the very small amount of retinal defocus associated with the subtle accommodative dysfunctions found in many myopic eyes may not be sufficient to provide directional information, and would therefore always produce axial elongation.

1.3 Convergence and myopia
Convergence is another element of the near response mechanism with close association with myopia development. Similar to accommodation, it has been suggested that convergence causes axial myopia by contributing directly to stress on the globe or via an increase in IOP. In addition, the vergence bias at near (i.e. near
latent horizontal deviation) could affect ocular growth by changing the degree of retinal defocus experienced through its crosslink interaction with accommodation.

1.3.1 Biomechanical effect of convergence

The convergence hypothesis proposes that the mechanical action of the extraocular muscles during convergence is the basis for lengthening of the antero-posterior dimension of the eye. Donders (1864) (cited in Ong and Ciuffreda, 1997) attributed near vision as the primary cause of myopia, with the extraocular muscle contraction required to achieve convergence directly applying pressure to the equatorial aspect of the globe and this pressure causing the eye to elongate. Von Arlt (1876) (cited in Ong and Ciuffreda, 1997) proposed that during convergence the pressure from the extraocular muscles hindered the outflow of blood from the eye, resulting in congestion and increased intraocular pressure. Several other investigators (Von Graefe, 1854; Cohn, 1883; Stillig, 1891; Muller, 1926) (cited in Ong and Ciuffreda, 1997) express similar opinions regarding the role of extraocular muscles in the development of myopia.

Work by Greene (1980) indicated that the physical changes producing axial elongation generally only occurred in the posterior portion of the globe, with the myopic eye becoming a prolate spheroid with a thinner posterior sclera. Greene (1980) suggested that these changes might either be due to a mechanically weaker posterior half of the globe or greater deforming forces concentrated in this area. This mechanical stress imposed on the posterior sclera caused it to yield, stretch and lead to myopia. This proposal agrees with the findings that high myopia in humans is associated with a thinner sclera, particularly at the posterior pole of the eye (Curtin and Teng, 1958). Greene (1980) stated that the peak force capabilities of the extraocular muscles were 250 times greater than that of the ciliary muscles, indicating that convergence must mechanically dominate the near response. This result is supported in a biometric study of the eye during convergence at near in the states of accommodation and non-accommodation (with the use of cycloplegia) (Bayramlar et al., 1999). Bayramlar and coworkers (1999) found that transient axial elongation at near fixation, mainly due to an increase in vitreous length, resulted from the effect of accommodative convergence rather than accommodation itself.
In addition to the greater mechanical stress on the sclera, Greene (1980) also believed that it was convergence per se that gave rise to the elevated IOP. There is evidence indicating that the contraction of the extraocular muscles during near work results in an increase in IOP (Collins et al., 1967; Coleman and Trokel, 1969; Saunders et al., 1981; Moses et al., 1982). However, these studies involve vigorous co-contraction of the extraocular muscles and sustained extreme gaze, which does not reflect the true effect of convergence during typical near tasks. Nevertheless, the changes in IOP during convergence appear to be relatively small, less than 2 mm Hg on nasal gaze (Moses et al., 1982). This small difference is within the normal diurnal variation of IOP in the human eye (Duke-Elder, 1952; Drance, 1960; Phelps et al., 1974). Thus, the small increase in IOP as a result of convergence is not likely a causative factor in myopigenesis.

1.3.2 Effect of near heterophoria

Under close viewing conditions, the two eyes will converge to bring the visual axes to the object of regard so that single vision is retained. The phoria position of the eyes is the position adopted by the two visual axes with respect to one another when all stimuli to fusion have been eliminated. It is usually measured by dissociating the two eyes images, causing diplopia in one direction and using prisms to realign the images in the orthogonal direction. Most people are orthophoric at distance or nearly so (Carter, 1963; 1965). In contrast, the near phoria tends to vary considerably from one individual to another and from one type of refractive error to another. A retrospective review of records from juvenile patients found that children who become myopic were more esophoric (1 Δ eso) at near compared to those who remained emmetropic (2 Δ exo) (Goss, 1991).

Clinical studies report that near esophoria accompanies the progression of myopia in children, and perhaps even precedes its development (Goss, 1991; Drobe and de Saint-Andre, 1995). A prospective study to examine clinical optometric findings prior to the onset of myopia in children shows that the presence of near heterophorias outside the range of 3 Δ exo to 1 Δ eso is a risk factor for myopia (Goss and Jackson, 1996). In both data sets, there is a convergent shift in the near heterophoria of 3-4 Δ eso over an approximate 2-year period, beginning before the onset of myopia. Goss (1990) reported for patients with habitual near heterophorias within ortho to 6 Δ
exophoria, that the mean rate of myopia progression was −0.39 D/yr, while the mean rate for patients with esophoria was −0.5 D/yr, patients with near exophoria greater than 6 Δ had a mean progression rate of −0.45 D/yr. Therefore both esophoria and large exophoria at near are linked with the development of myopia.

A possible explanation for the observance of high exophoria value in some children is that the exophoria at near is secondary to an abnormally high lag of accommodation (Scheiman and Wick, 1994; Goss, 1995). The hyperopic retinal defocus resulting from this associated lag of accommodation is proposed to trigger axial elongation of the globe. For the esophoric patients, the esophoria could result from an increased accommodative response producing excess accommodative convergence, but they typically also exhibit a higher lag of accommodation (Scheiman and Wick, 1994). To maintain single binocular vision, these esophoric patients use negative fusional vergence at near accompanied by a reduced convergent accommodation. As a result, the subsequent lag of accommodation would lead to hyperopic retina defocus, a possible precursor to axial elongation myopia (Goss and Zhai, 1994; Goss and Wickham, 1995; Hung et al., 1995; Wallman and McFadden, 1995). Alternatively, the near esophoria may be produced by vergence adaptation during prolonged near fixation (Carter, 1963; Schor, 1983). Forrest (1960) reported eso shifts in heterophoria after 5 minutes of reading, while Ehrlich (1987) noted that two hours of a visual search task with binocular fixation at 20 cm resulted in a shift of 1.6 Δ esophoria at 33 cm. Therefore, the esophoric shift at near accompanied by a lag of accommodation is a possible causative link for myopia development.

1.4 Crosslink interaction of accommodation and convergence in myopigenesis
For close viewing distances, accommodation and convergence work in a synchronised fashion to produce a clear and single image under normal binocular conditions. There are interactions taking place between accommodation and vergence in which optically stimulated accommodation evokes convergence (accommodative vergence) (Alpern and Ellen, 1956) and disparity stimulated vergence evokes accommodation (convergence accommodation) (Fincham and Walton, 1957). The magnitude of these interactions is quantified as the AC/A ratio (ratio of accommodative convergence to accommodation) and the CA/C ratio (ratio of convergence accommodation to convergence). The AC/A ratio averages 4.0±2.0
Δ/D in normal subjects (Morgan, 1968). Measures of the CA/C indicate a ratio of about 0.02 to 0.08 D/Δ in the general population (Tsuetaki and Schor, 1987). To understand how the AC/A and CA/C ratios are related to myopia, a review of the mathematical model of the crosslink interaction of accommodation and vergence is required.

1.4.1 Mathematical model of accommodation and vergence

Accommodation and vergence together form a tightly coupled motor system that has been modelled using bio-engineering principles in order to simulate their responses mathematically (Krishnan and Stark, 1977; Hung and Semmlow, 1980). The later models (Schor, 1992; Jiang, 1997; Hung and Ciuffreda, 1991; 1999) usually have more inputs (e.g. adaptive elements) added to complement the accommodation and vergence systems. However, the static dual interactive feedback model developed by Hung and Semmlow (1980) is a sufficient model to explain the effect of accommodation and convergence interaction on myopigesis in this review. This quantitative model of accommodation and vergence is shown in Figure 1.

A basic feature of this model is that blur-driven accommodation and disparity driven vergence are controlled by two negative feedback loops, and interactions between the two systems are represented by two feed-forward crosslinks from the controller outputs, so that the accommodative controller can initiate a vergence response (accommodative vergence or AC) and, conversely, the vergence controller can initiate an accommodative response (vergence accommodation or CA). The gains of AC and CA are represented by the accommodative vergence to accommodative ratio (AC/A ratio) and the vergence accommodation to vergence ratio (CA/C ratio). The interaction is defined as open-loop when the negative feedback is suspended. On the other hand, a closed-loop system refers to a condition where negative feedback is operational. For example, under binocular viewing conditions both accommodation and vergence are under closed-loop conditions, whereas, when one eye is occluded the feedback to vergence (disparity) is removed, the vergence is open-looped. Similarly the accommodation system can be open-looped by placing 0.5 mm pinholes in front of the eyes, so as to increase the depth of focus and prevent negative feedback from a blur signal. The dead space element for each system accounts for the sensory aspects of the stimulus that is introduced into the loop. For the
Figure 1. Quantitative model of accommodation and vergence (Hung and Semmlow 1980). AS and VS are the stimulus to accommodation and vergence. AE and VE are the errors prevailing in the system (accommodative lag and fixation disparity for accommodation and vergence respectively). DS=Dead space element (depth of focus and Panum’s fusional area for accommodation and vergence respectively). ACG and VCG are the accommodative and vergence controllers. ABIAS and VBIAS are the tonic inputs of accommodation and vergence. AC and CA are the crosslinks accommodative convergence and convergent accommodation. AR and VR are the accommodation and vergence response. Each system is connected by negative feedback loops. These loops allow the response to be maintained by giving constant input to the system about the error prevailing in the system.

accommodation system it represents the depth of focus (usually around ± 0.32 D) and for the vergence system it constitutes Panum’s fusional area (± 0.01 MA) (Hung and Ciuffreda, 2000). Any stimuli presented to each of these systems that are below the magnitude of this dead space will not invoke a change in the accommodation or vergence response. The controller block of the model has two actions. First, it responds as a reflex to any stimulus that is presented through the loop and secondly, it feeds in as the input to the crosslink interactions namely the AC and CA. Finally the responses of each system are summed up at a summing junction where the tonic input feeds in. The error (stimulus− response) that remains from the response to the stimulus is fed back to the controller through the negative feedback mechanism in
order that the responses are kept stable and ready to act for subsequent stimuli. This negative feedback is a basic characteristic of accommodation and vergence control systems.

1.4.2 Convergent accommodation and myopia

Convergent-accommodation refers to the accommodation response elicited by retinal disparity by way of the synkinetic link from disparity vergence to the accommodative system. It is assessed with blur-driven accommodation rendered open-loop, i.e. without visual feedback on the degree of blur in the retinal image. Convergent-accommodation may be differentiated from disparity-induced accommodation, the latter of which is measured under closed-loop conditions, i.e. with normal visual feedback regarding retinal blur, with accommodation now being driven primarily by both disparity and blur (Ong and Ciuffreda, 1997).

Rosenfield and Gilmartin (1988b) assessed the CA/C ratio in populations of late-onset myopes, early-onset myopes and emmetropes, and found no significant refractive group difference in the CA/C ratio. The mean CA/C value was approximately 0.4 D/6 Δ in all groups. The absence of refractive group difference has been supported by subsequent studies (Jones, 1990; Jiang, 1995). For disparity accommodation, Rosenfield and Gilmartin (1988b) measured the closed-loop accommodative response to a near target in populations of emmetropes and late-onset myopes with the introduction of 0, 3 and 6 Δ base-out prism. With zero supplementary disparity stimuli, the accommodative response of the late-onset myopic group was significantly lower than that of the emmetropes. However, the accommodative response of myopes increased with base-out prism and became equivalent to that of emmetropes when a 6 Δ base-out prism was introduced. Since no refractive group difference in CA/C was found, the introduction of a disparity stimulus should not induce a greater amount of convergent accommodation in the myopes. Instead, the increase in disparity-induced accommodation in the late-onset myopes was proposed to result from a failure to relax blur-driven accommodation. Indeed, subsequent studies (Bullimore et al., 1992; Gwiazda et al., 1993; Rosenfield and Abraham-Cohen, 1999; Vasudevan et al., 2006) demonstrated that myopes compared to emmetropes were less sensitive to the presence of blur. These studies suggested that the larger average lag of accommodation found in myopes was due to
a greater blur detection threshold and the hyperopic retinal defocus resulting from the increased accommodative error might play a significant role in myopia progression. However, there were other studies (Jiang and Morse, 1999; Schmid et al., 2002) found no significant difference in blur detection thresholds between myopes and emmetropes.

1.4.3 Accommodative convergence and myopia

The relationship between accommodative convergence and myopia has been investigated in both adults and children over many years. Manas (1955) selected random patient records for groups of myopes and hyperopes, and calculated stimulus AC/A ratio from phoria measurements in a large population (n=200). The AC/A ratio of myopes (5.1±2.1 Δ/D) were significantly greater than that of hyperopes (4±2.2 Δ/D). Rosenfield and Gilmartin (1987a; 1987b) studied response AC/A ratios in populations of emmetropes, and early- and late-onset myopes, and found that early-onset myopes showed greater amounts of accommodative convergence than late-onset myopes and emmetropes. They suggested that the higher AC/A ratios in early-onset myopes might be due to an increased crosslink gain.

There is also evidence that AC/A ratios differ in stable and progressing myopes. In a longitudinal investigation of college students over a 2-3 year period, Jiang (1995) reported that the response AC/A ratio increased during the development of myopia and that a high response AC/A ratio was a risk factor for further myopia development in a group of progressing myopes. Moreover, it was found that subjects with increased AC/A as compared to other subjects with normal or low AC/A had increased accommodative lag at near. This greater accommodative lag is believed to lead to increased hyperopic defocus, which may act as an error signal for axial elongation and myopia.

Gwiazda et al. (1999) reported similar data in her study on children; higher AC/A ratios in myopic children who showed reduced accommodation and enhanced accommodative convergence. The researchers also noticed that esophoric children under-accommodated at near and suggested that the purpose of this was to reduce their accommodative convergence so as to maintain single binocular vision. The reduction in accommodation response would produce blur during near work, which
could trigger myopia, as shown in animal models (Irving et al., 1991; Schaeffel et al., 1988; Schmid and Wildsoet, 1996). In a study to determine if the presence of a higher AC/A ratio was a risk factor for the onset of myopia, Mutti et al. (2000a) also showed that an elevated response AC/A ratio was associated with myopia and was an important risk factor for its rapid onset. Further to this, Gwiazda et al. (2005) found that those emmetropic children who became myopic had elevated response AC/A ratios both at 1 and 2 years before the onset of myopia, in addition to at onset of and 1 year after myopia development. The significantly higher AC/A ratios in the children who became myopic were a result of significantly reduced accommodation. In myopes, accommodative convergence was significantly greater only at onset. From the findings of these studies, it is apparent that elevated AC/A ratios are associated with myopia development.

1.5 Bifocal control of myopia
Many clinicians and researchers have recommended the use of bifocal lenses for young myopes to reduce their accommodative demand, believing that myopia occurs as a result of accommodation at near (Mandell, 1959; Miles, 1962; Roberts and Banford, 1967; Oakley and Young, 1975; Shotwell, 1981; Neetens and Evens, 1985; Goss, 1986; Grosvenor et al., 1987; Hemminki and Parssinen, 1987; Jensen, 1991; Fulk and Cyert, 1996; Leung and Brown, 1999; Edwards et al., 2002; Fulk et al., 2000; 2002; Gwiazda et al., 2003). Based on review of the accommodation and convergence literature there are two plausible hypotheses to explain how bifocal lenses might slow myopia progression. During near work, accommodation may cause scleral expansion and myopia via an increase in IOP or an increase in the mechanical forces created by the activated ciliary-choroid complex. Bifocal lens wear reduces accommodation at near, which in turn should reduce the biomechanical forces and myopia progression. On the other hand, recent evidence indicates myopic children have a reduced accommodative response at near (Ramsdale, 1979; McBrien and Millodot, 1986; Rosenfield and Gilmartin, 1988a; Tokoro, 1988; Bullimore et al., 1992; Gwiazda et al., 1993). A lag of accommodation at near would cause the image to be focused behind the retina, creating hyperopic defocus and mimicking conditions related to lens-induced myopia in animals. Bifocal lens wear is believed to focus the near-point image more precisely on the retina, thereby slowing myopia progression.
Although the literature on myopia contains numerous reports about the use of bifocals and multifocal lenses to control myopia, these studies have produced conflicting results. A statistically significant effect of bifocals on reduction of myopia progression has been reported by Miles (1962), Roberts and Banford (1967), Oakley and Young (1975), Neetens and Evens (1985), Goss (1986), Leung and Brown (multifocal, 1999), Fulk et al. (2000), Gwiazda et al. (multifocal, 2003). However, the myopia inhibiting effect of bifocals is not significant in the studies by Mandell (1959), Shotwell (1981), Grosvenor et al. (1987), Hemminki and Parssinen (1987), Jensen (1991) and Edwards at al. (multifocal, 2002). Given that several studies document a beneficial effect of bifocals and multifocals, the negative results of other studies may have arisen from procedural differences that masked or weakened a real but small positive effect (Birnbaum 1993). The following summarise and evaluate the various retrospective and prospective studies on bifocal and multifocal treatment of myopia, and discuss how bifocal treatment can be modified to effectively control myopia.

1.5.1 Bifocal studies based on retrospective analysis of private practice records

The early clinical studies analysed the records of practitioners who routinely prescribed bifocals for myopic patients. Many of these retrospective bifocal studies suffer from non-standardized measurement techniques, unclear time factors, patient selection issues and measurement bias. Yet they provide a strong argument that bifocals might control myopia in some children. The outcomes of these bifocal studies are described below, with particular emphasis on study methodology and implications for future clinical trials in this area. The results of these retrospective studies are summarized in Table 1.

**Table 1: The results of retrospective bifocal wear studies**

<table>
<thead>
<tr>
<th>Study</th>
<th>Age (yr) and location</th>
<th>Number</th>
<th>Time (yr)</th>
<th>Type and power of bifocal</th>
<th>Rate of myopia progression (D/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mandell (1959)</td>
<td>SV=17.1, BF=14.3, California</td>
<td>SV=116, BF=59</td>
<td>Checked at least twice before 30</td>
<td>Not known</td>
<td>Not calculated</td>
</tr>
<tr>
<td>Miles (1962)</td>
<td>SV=6-14, BF=8-16, St. Louis</td>
<td>SV=103, BF=48</td>
<td>2</td>
<td>28 mm flat top, centred for slight base-in effect</td>
<td>SV=−0.75, BF=−0.35</td>
</tr>
</tbody>
</table>
Roberts and Banford (1967) Examined at least twice before 17; New York State
SV=396 BF=85 Checked at least twice before 17 Type unknown, most adds +0.75 to +2.00D
SV=-0.41 BF=-0.31 Significant p<0.02

Oakley and Young (1975) SV=6-17 BF=6-17 Oregon SV=275 BF=269 3-4 Flat top with top at pupil, +1.50 to +2.00D add
Caucasian SV=-0.53 BF=-0.02 Significant p<0.001
Native American SV=-0.38 BF=-0.10 Significant p<0.05

Neetens and Evans (1985) SV=8-9 BF=8-9 Holland SV=733 BF=543 9-10 Myopia up to 3D, total near-point power equal to 0; Myopia ≥ 3D, +2.50D add
SV=-0.45 BF=-0.30 Significant p<0.001

Goss (1986) SV=6-15 BF=6-15 Illinois, Iowa and Oklahoma SV=52 BF=60 Checked four times or more from 6-15 Type unknown, most adds +0.75 and +1.00D
Ortho or Exo SV=-0.44 BF=-0.45 Not significant
Eso SV=-0.54 BF=-0.32 Significant p<0.05

SV = Single vision lenses, BF = Bifocal lenses. ¹Mean change in refraction was not reported, but it was concluded that bifocals did not reduce progression of myopia more than would have occurred by chance alone. ²A cross-over study in which subjects wore single vision lenses for 2 years and then bifocal lenses for the following 2 years.

Mandell (1959) reviewed clinical records of 175 myopic patients in a practice in California, United States. There were 59 bifocal wearers with an average initial age of 14.3 years and average initial refractive error of −2.75 D. The 116 single vision lens wearers had a mean initial age of 17.1 years with a mean initial refractive error of −1.48 D. On the basis of visual inspection of the plot of myopia as a function of age, Mandell (1959) concluded that bifocals did not eliminate or reduce the progression of myopia. However, there are a number of weaknesses in this study, the power of the addition in the bifocals prescribed was not reported; the initial age and refractive errors of the two treatment groups were not matched; and the reported myopia progression was not adjusted for these group differences. There were also many single-vision wearers who were more than 20 years of age and therefore no longer at risk of fast myopia progression. Combined these factors mean that the study of Mandell (1959) has low research validity.
Miles (1962) fitted 28 mm wide flat-top segment bifocals to some myopic children in his practice in St. Louis, United States. He also decentred the lenses to give a small base-in prism effect. During a 2 year period, 103 myopes (aged between 6 and 14 years) wearing single vision lenses progressed at a mean rate of $-0.75 \text{ D/yr}$. When 48 of these myopes (now aged between 8 and 16 years) were subsequently refitted with bifocal spectacle lenses, the annual progression rate reduced to $-0.40 \text{ D/yr}$. Unfortunately, the power of the near addition was not reported, and more importantly, the older age of the children could have attributed to the reduced rate of myopia progression in the bifocal lens group. Nevertheless, inspection of the graph suggests that over common age spans, progression of myopia was slower in bifocal lens wearers.

Robert and Banford (1967) studied data for myopic patients refracted at least twice before age 17 years from three practices in New York State, United States. Forty-seven girls and 38 boys wore bifocal lenses with near addition power ranging from $+0.75$ to $+2.00 \text{ D}$, and 231 girls and 165 boys wore single-vision lenses exclusively during that period. After adjusting the data for slight age differences between the groups, the mean rate of myopia progression for bifocal wearers was $-0.31 \text{ D/yr}$ whereas progression was slightly higher, $-0.41 \text{ D/yr}$, for single vision wearers. The difference was statistically significant at the 0.02 level. Additionally, children prescribed lower near addition powers ($+0.75$ and $+1.00 \text{ D}$) were found to progress considerably slower than those with higher addition powers ($+1.25$ to $+2.00 \text{ D}$). This relatively well-designed study was able to show that bifocal treatment had an effect on myopia progression, but the control of only $-0.10 \text{ D/yr}$ does not justify the clinical use of bifocals for myopia control in all myopic children. Moreover, there were many more single vision spectacle wearers than bifocals lens wearers and this reduces the power of the study to some degree.

Oakley and Young (1975) compared the myopia progression rates for 269 bifocal wearers and 275 single vision wearers from records in a practice in Oregon, United States. The distance portion of the bifocals and the single vision lenses typically contained a 0.50 D under-correction of the children’s myopia. The near addition in the flat top segment bifocals was usually $+1.50$ to $+2.00 \text{ D}$. The two treatment groups were matched on the basis of gender, initial age, and initial amount of
myopia. Mean rates of progression of Caucasian children were $-0.02$ D/yr in the 226 bifocal wearers and $-0.53$ D/yr in the 192 single vision wearers. For American Indians, the mean rates were $-0.10$ D/yr in 43 bifocal wearers and $-0.38$ D/yr in 83 single-vision wearers. The difference was statistically significant in the Caucasian children but not the American Indian children, presumably because of the many fewer American Indian children in the study. The reduction in progression rates with bifocals in Caucasian subjects (control $-0.51$ D/yr) was greater than that reported in other published papers; the authors attributed this to the high placement of the reading portion of the lens, and also a high prevalence of esophoria in their sample. Another possible explanation is that this group of Caucasian myopes had a high rate of myopia progression (as found in the single vision group of $-0.53$ D/yr) that allowed the bifocal myopia control effect to be shown.

Neetens and Evens (1985) reported data for myopic children whom they examined between 1959 and 1982 in a University based practice in Holland. The report included children who initially had myopia of 1.00 D or greater at age 8 or 9 years. Exclusion criteria were anisometropia of more than 1.00 D, and moderate or large amounts of exophoria or esophoria. The bifocal addition power prescribed varied with the amount of myopia. The near addition power was the same in magnitude as the best sphere distance prescription for myopia less than 3 D (to give a total nearpoint power of plano), for distance refractions greater than 3 D, a +2.50 D add power was used. The mean manifest subjective refractive error at 18 years for the 733 single vision wearers was $-5.07$ D and for 543 bifocal wearers was $-3.55$ D. The mean progression rates were approximately $-0.30$ D/yr for the bifocal wearers and $-0.45$ D/yr for the single-vision wearers. The difference was statistically significant ($p<0.001$). Near addition powers prescribed in this study ranged from +1.00 to +2.50 D and as no further analysis of the differential effect of lens power on myopia progression was undertaken (as found in Robert and Banford 1967) clinical decisions regarding bifocal lens prescribing based on this study cannot be made.

The most recently published retrospective study was carried out by Goss (1986) who studied the clinical records of three optometric practices in the United States where bifocals were sometimes prescribed for myopic children. The examined records described patients who had received four or more refractions between 5 and 15 years
of age, and had either worn bifocals with add power of +0.75 D or +1.00 D or single-vision lenses for the entire period. The selection criteria included myopia of at least 0.50 D, astigmatism of 2.50 D or less, no strabismus or amblyopia, no contact lens wear, and no ocular or systemic disease that might affect ocular findings. Mean rates of myopia progression for the 52 bifocal wearers were −0.37 D/yr and for the 60 single vision wearers were −0.44 D/yr. This difference was not statistically significant. However, for esophoric children, the rates were −0.54 D/yr in the single vision group and −0.32 D/yr in the bifocal group. This difference of −0.22 D/yr was statistically significant (p<0.05). This differential bifocal treatment effect on myopia progression for individuals with different near phoria status supports the notion of Birnbaum (1993) who states that only a subgroup of children (e.g. esophores) will benefit from bifocal spectacle lens wear.

1.5.2 Prospective clinical trials of bifocals/multifocals (progressive) in myopia prevention

Given that the results of retrospective bifocal studies were equivocal and not well controlled in design; prospective randomized clinical trials were conducted in later years. These prospective studies usually had the baseline characteristics of the subjects in different treatment groups matched, and if this was not achieved, myopia progression was adjusted to account for any intergroup differences. The results of the published prospective bifocal and multifocal lens studies in myopic children are summarized in Table 2.

Table 2: The results of prospective bifocal and multifocal spectacle lens wear studies in myopic children

<table>
<thead>
<tr>
<th>Study</th>
<th>Age (yr) and location</th>
<th>Number</th>
<th>Time (yr)</th>
<th>Type and power of bifocal</th>
<th>Rate of myopia progression (D/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shotwell (1981; 1983)</td>
<td>United States Naval Academy, Maryland</td>
<td>SV=21; PP=27; BF=13</td>
<td>4</td>
<td>+1.25 D single vision with 2Δ base-in; 25 mm flat top, 3 mm above lower lid, +1.50D add</td>
<td>SV=−0.06; PP=−0.07; BF=−0.04 (Not significant)</td>
</tr>
<tr>
<td>Study</td>
<td>Age (yr) and location</td>
<td>Number</td>
<td>Time (yr)</td>
<td>Type and power of bifocal, drug treatment</td>
<td>Rate of myopia progression (D/yr)</td>
</tr>
<tr>
<td>--------------------------</td>
<td>------------------------</td>
<td>--------</td>
<td>-----------</td>
<td>------------------------------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>Schwartz (1976; 1981)</td>
<td>7-13 Washington, DC</td>
<td>25</td>
<td>3.5</td>
<td>Type not known, +1.25D add, tropicamide</td>
<td>SV=−0.27 tBF=−0.24 Not significant</td>
</tr>
<tr>
<td>Jensen (1991)</td>
<td>Children in 2nd through 5th grades Denmark</td>
<td>49</td>
<td>2</td>
<td>35 mm flat top, lower pupil margin, +2.00D add, timolol</td>
<td>SV=−0.57 BF=−0.48 TBF=−0.59 Not significant</td>
</tr>
<tr>
<td>Shih et al. (2001)</td>
<td>6-13 Taipei</td>
<td>61</td>
<td>1.5</td>
<td>Progressive (Multifocal), power unknown, atropine</td>
<td>SV=−0.93 MF=−0.79 AMF=−0.27 Significant p&lt;0.001</td>
</tr>
</tbody>
</table>

**Bifocal lenses/progressive lenses and drug treatment/ lens combination**
## Progressive lenses

<table>
<thead>
<tr>
<th>Study</th>
<th>Age (yr) and location</th>
<th>Number</th>
<th>Time (yr)</th>
<th>Type and power of bifocal</th>
<th>Rate of myopia progression (D/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leung and Brown (1999)</td>
<td>9-12 Hong Kong</td>
<td>SV=32</td>
<td>2</td>
<td>Progressive, +1.50D and +2.00D add</td>
<td>SV=−0.62, +1.50D MF=−0.38 Significant p&lt;0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+2.00D MF=−0.33 Significant p&lt;0.001</td>
</tr>
<tr>
<td>Edwards et al. (2002)</td>
<td>7-10.5 Hong Kong</td>
<td>SV=133</td>
<td>2</td>
<td>Progressive, +1.50D add</td>
<td>SV=−0.63, MF=−0.56 Not significant</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MF=121</td>
<td></td>
<td></td>
<td>Eso (n=21) SV=−0.63 (n=21) MF=−0.45 Not significant</td>
</tr>
<tr>
<td>Gwiazda et al. (2003)</td>
<td>6-11 Boston, Philadelphia, Birmingham, Houston</td>
<td>SV=234</td>
<td>3</td>
<td>Progressive, +2.00D add</td>
<td>SV=−0.49, MF=−0.43 Significant p=0.004</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MF=235</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gwiazda et al. (2004)</td>
<td>6-11 Reanalysis of Gwiazda et al. (2003) data from Boston, Philadelphia, Birmingham, Houston</td>
<td>SV=234</td>
<td>3</td>
<td>Progressive, +2.00D add</td>
<td>Lag of Acc. (≥0.43) with eso (≥2Δ) (n=34) SV=−0.57 (n=42) MF=−0.36 Significant p&lt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MF=235</td>
<td></td>
<td></td>
<td>Lag of Acc. (≥0.43) with short reading distance (&lt;31.2 cm) (n=52) SV=−0.56 (n=64) MF=−0.41 Significant p&lt;0.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lag of Acc. (≥0.43) with less baseline myopia (≥−2.25) (n=60) SV=−0.53 (n=44) MF=−0.37 Significant p&lt;0.05</td>
</tr>
</tbody>
</table>

SV = Single vision lenses, BF = Bifocal lenses, MF = Multifocal lenses, PP = +1.25 D single vision spectacles with 2Δ base-in each eye, tBF = Tropicamide and bifocal lenses, TBF = Timolol and bifocal lenses, AMF = Atropine and multifocal lenses

### Bifocal lenses

Shotwell (1981; 1983) studied myopia progression in subjects aged 17 to 21 years, from the United States Naval Academy, over a 4 year period. Subjects were divided into three groups which received a different spectacle lens treatment, (1) a placebo control group prescribed pink tinted single vision lenses, (2) single vision glasses...
with +1.25 D and 2 Δ base-in over the distance correction, (3) +1.50 D 25 mm flat top bifocal set 3 mm above the lower lid margin. Refractive data were obtained by subjective refraction after instillation of one drop of 1 % cyclopentolate. The mean initial refractive error of subjects was −0.13 D for group 1, −0.14 D for group 2 and −0.13 D for the bifocal group 3. Sixty-one of the original 235 recruited subjects completed the study. The mean rates of myopia progression were −0.06 D/yr for group 1, −0.07 D/yr for group 2, and −0.04 D/yr for the bifocal group 3. There were no significant differences between the myopic shifts in the placebo and the experimental groups. It is important to point out that the subjects of this study were more than 14 years of age when the study commenced, they had very low initial levels of myopia, and the study had an exceedingly high drop out rate; these factors mean that the myopia of subjects wearing the single vision lenses was unlikely to progress by a large amount over the treatment period and thus the bifocal effect is unlikely to be observed.

In a study conducted at the University of Houston, College of Optometry (Grosvenor et al., 1987), subjects were randomized to a single vision control group, a +1.00 D bifocal and a +2.00 D bifocal group. Inclusion criteria were myopic children aged 6-15 years with, spherical equivalent refractive errors −0.25 D or more minus, normal visual acuity, normal binocular vision, good ocular health, and no contact lens wear. The bifocal lenses were CR39 plastic Executive bifocals with the top of the reading segment 2 mm below the center of the subjects’ pupil. The single vision lenses were made of polycarbonate. The distance correction was based on the maximum plus for best binocular visual acuity subjective refraction technique. One hundred and twenty-four (58 males and 66 females) of the 207 subjects completed the 3-year study. The rate of myopia progression was calculated as the difference in spherical equivalent refractions of the right eye at the first and last visit divided by 3. Progression rates averaged −0.34 D/yr for the 39 single vision lens wearers, −0.36 D/yr for the 41 +1.00 D add bifocal lens wearers, and −0.34 D/yr for the 44 +2.00 D add bifocal lens wearers. The group differences were not statistically significant. However, it is now known that children with very low degrees of myopia tend to progress more slowly than those with higher levels of myopia (Cheng et al., 2007), the low initial myopia of children in this may thus have affected the ability of this study to show a bifocal lens treatment effect. This possible reason for the lack of a
treatment effect was also suggested by the authors who stated that the rates of progression for single vision lens wearing myopic children in this study were lower than that reported for similar groups previously (e.g. 0.34 vs 0.44 D in Goss 1986).

In Finland, a group of ophthalmologists (Hemminki and Parssinen, 1987; Parssinen and Hemminki, 1988; Parssinen et al., 1989) enrolled myopia subjects for a bifocal lens wear study with the following inclusion criteria: a spherical equivalent error of −0.25 to −3.00 D, anisometropia not greater than 2.00 D, astigmatism not greater than 2.00 D, no strabismus, Maddox wing horizontal phorias between 10 Δ eso and 9 Δ eso, vertical phoria of not more than 1 Δ, no previous or current spectacle wear and no ocular or systemic diseases. The treatment groups were (1) full-time wear of full distance correction single vision lenses, (2) full correction single vision lenses worn only for distance vision, (3) bifocals with +1.75 D add in a 28-mm wide flat top reading segment worn full-time. For the bifocal lens fitting, the top of the reading segment was placed 2-3 mm below pupil center. The mean age of subjects at entry into the study was 10.9 years in all three groups. Refraction data were obtained 45-60 minutes after the instillation of two drops of 1% cyclopentolate. Seventy-nine subjects from a total of 240 children (121 girls and 119 boys) were left in each group at the end of the study, however follow-up times varied from 2.0 to 5.1 years. The follow-up periods were between 3.0-3.1 years for 95% of the subjects. Mean right eye changes in spherical equivalent error were: −1.48 D for group 1, −1.76 D for group 2 and −1.67 D for the bifocal group 3. For the left eye, changes were −1.46 D, −1.88 D and −1.58 D respectively. Changes in the bifocal and full-time single vision lens wear groups were not significantly different. Unfortunately, this well-designed study also recruited children with low levels of myopia and no information is provided as to whether the magnitude of initial myopia affected the follow-up duration. There have been no analyses of the differential effect of initial myopia magnitude on myopia progression and detailed information on follow-up times was not provided, so it is not surprising that a bifocal lens treatment effect was not shown.

Fulk et al. (2000) conducted a randomized clinical trial to test the hypothesis that bifocals slow myopia progression in children with near-point esophoria. Eighty-two myopic subjects were recruited: 43 boys aged between 6 and 12.9 years and 39 girls
aged between 6 and 11.9 years. Inclusion criteria included myopia of at least 0.50 D, an esophoria at 40 cm through the distance refraction, near acuity of at least 6/7.5 under binocular conditions and stereoacuity of at least 40 sec arc, anisometropia of no more than 2.00 D, no previous or current contact lens and/or bifocal lens wear, and myopia of no more than 6 D for children under 9 years of age and 8 D for children over 9 years. The subjects were randomized to single vision glasses or to 28 mm wide flat-top segment bifocals with a +1.50 D add and were followed for 30 months. Refraction was obtained by Nidek ARK 900 auto-refractor 30 min after instillation of 2 drops of 1% tropicamide. The initial average level of myopia was −2.52 D for the single vision group and −2.12 D for the bifocal lens group. Myopia progression averaged −0.99 D for bifocals wearing children and −1.24 D for single vision wearers over the 30 month trial. The difference between the two lens types was statistically significant at p=0.046; it was concluded that bifocal lenses seemed to slow myopia progression in children with near-point esophoria to a slight degree. This finding is in agreement with the study of Goss (1986) in which rate of myopia progression in the single vision group is significantly higher than in the bifocal group for esophoric children.

**Bifocal lenses/multifocal lenses and drug combination treatment**

Schwartz (1976; 1981) studied 12 female and 13 male monozygotic twin pairs for 3.5 years. One member of each twin pair was fitted with bifocal lenses with +1.25 D near-addition power and instilled one drop of 1 % tropicamide in each eye at bed time. The other twin wore best correction single vision distance spectacles. To be included in the trial children also had to be aged between 7 and 13 years, have bilateral myopia, 20/20 or better visual acuity, normal stereoacuity, 1.00 D or less astigmatism, 1.00 D or less anisometropia, good ocular and general health. The twin pairs had to have similar refractive errors, i.e. a difference in refractive error between twin pairs of no more than 1.50 D in the more myopic eye. Average cycloplegic spherical equivalent refractions at the beginning of the study were not statistically different in the two groups: −2.33 D in the tropicamide/bifocal group and −2.22 D in the single vision group. The rate of myopia progression for all subjects was −0.26 D/yr. The progression rate was only −0.03 D/yr less in the tropicamide/bifocal group than the single vision group, i.e. there was no statistically significant difference in myopia progression of the two groups. In his discussion, Schwartz stated that his
subjects exhibited a low rate of myopia progression, i.e. the myopia of children fitted with single vision lenses only progressed one quarter dioptre per year, and therefore he was reluctant to conclude that there would be no treatment effect in myopes with faster progression.

Jensen (1991) conducted a 2-year clinical trial and compared myopia progression in a single vision group and two treatment groups. In one treatment group children wore plastic bifocal lenses with a +2.00 D 35 mm wide reading segment. The top of the segment was placed at the lower edge of the pupil when eyes were in a straight ahead position. The other treatment group comprised single vision lens wearers with daily administration of timolol eye drops. 159 (145 completed) children in 2nd through 5th grades with myopia of −1.25 D to −6.00 D at the start of the study were randomly assigned to the three groups. Analysed refraction data were right eye spherical equivalent measured using the Topcon RM A-5000 autorefractor after instillation of two drops of 1% cyclopentolate. The mean change in myopia in 2 years was −0.57 D/yr for the 49 subjects in the single vision group, −0.48 D/yr for the 51 in the bifocal group and −0.59 D/yr for the 55 in the timolol group. The differences in progression rates were not statistically significant. However, the amount of progression was significantly less with bifocals versus single vision lenses for children with intraocular pressure of 17 mm Hg or greater at the start of the study (i.e. −0.97 vs −1.32 D in 2 years, p=0.04). The author suggested that bifocals lenses should be considered in children with a high intraocular pressure but the mechanism at which bifocals only work in children with high IOP is uncertain. Timolol had no beneficial effect on myopia progression further pointing to the conclusion that high IOP is not a major cause of myopia development.

Shih et al. (2001) assessed the effect of atropine and/or multifocal lenses on the rate of myopia progression over a minimum of 18 months. 227 (188 retained) myopic schoolchildren aged from 6 to 13 years, were randomly assigned to one of three treatment groups; 0.5% atropine combined with multifocal spectacle lens wear, multifocal spectacles, and single vision spectacles. Refraction data were obtained using the Topcon RK3000 autorefractor 30 min after instillation of 3 drops of 1% tropicamide. The average baseline refractive errors were −3.28 D, −3.34 D and −3.20 D respectively for the three treatment groups. The mean progression rate of myopia
over the 18 month treatment period was significantly less in the group treated with atropine combined with multifocal spectacles \( (n=66, -0.42\pm 0.07 \text{ D}) \) compared to the groups that received only multifocal lenses \( (n=61, -1.19\pm 0.07 \text{ D}) \) or single vision lenses \( (n=61, -1.40\pm 0.09 \text{ D}) \) \( (p<0.0001) \). There was no significant difference between myopia progression in the multifocal and single vision lens groups \( (p=0.44) \). Unfortunately, this study did not report the power of the near addition used in the multifocal lenses. In addition, the \( p \)-value of 0.44 reported for comparison of the two lens types appears to be unreasonably high. A difference of 0.21 D with a standard error of 0.08 D and 120 degrees of freedom gives a \( p \)-value of 0.01 on a non-paired \( t \)-test pointing towards a real, though small, benefit of the multifocal lenses.

**Progressive lenses**

Leung and Brown (1999) followed 68 myopic children at the Hong Kong Polytechnic University for two years. These children were 9-12 years of age, had myopia \(-1.00 \) to \(-5.00 \text{ D}\), astigmatism of no more than 1.50 D, anisometropia of no more than 1.25 D, visual acuity better than 6/9, stereoacuity better than 100 sec arc, and myopia progression more than \(-0.4 \text{ D/yr}\). Thirty-two subjects wore single vision lenses, 22 subjects wore \(+1.50 \text{ D} \) progressive lenses and 14 wore \(+2.00 \text{ D} \) progressive lenses. The mean rate of progression over the two years of the study was \(-0.62 \text{ D/yr}, -0.38 \text{ D/yr} \) and \(-0.33 \text{ D/yr} \) for the single vision lens, \(+1.50 \text{ D} \) bifocal and \(+2.00 \text{ D} \) bifocal lens respectively. The rate of myopia progression was significantly less in both bifocal groups compared with the single vision group. The authors attributed their success to the higher prevalence and faster progression of myopia in Chinese populations than in Caucasian populations. Indeed, the rate of myopia progression of \(-0.62 \text{ D/yr} \) in the single vision group is one of the highest reported in the published bifocal/multifocal myopia control literature. A major potential weakness of this study is that refractive errors were measured by non-cycloplegic subjective refraction by an unmasked examiner; this could have lead to possible bias in the refraction measurements.

Edwards et al. (2002) carried out a 2 year prospective industry sponsored clinical trial in Hong Kong to compare the progression of myopia in a group of 138 (121 retained) children wearing progressive lenses with a \(+1.50 \text{ D} \) add to that of a group of 160 (133 retained) children wearing single vision lenses. Subjects were aged
between 7 and 10.5 years at the time of first data collection. Subjects had equivalent spherical refractive errors of −1.25 to −4.50 D, astigmatism and anisometropia of not more than 1.50 D, visual acuity of 0.00 logMar or better, no history of contact lens or bifocal lens wear, and no ocular or systemic conditions that might affect refractive development. Initial refractive errors averaged −2.82 D for the progressive lens group and −2.92 D for the single vision lens group. There was no statistical difference in the average amount of myopia progression of the single vision (−1.26 D) and progressive lens groups (−1.12 D). In possible explanation of why their findings differed to that of Leung and Brown (1999), the authors pointed out that the older children in the study of Leung and Brown (1999) might be more compliant in regard to the use of the progressive spectacles. The authors did not consider that the lack of a myopia progression inclusion criterion of at least 4 D/yr (adopted in Leung and Brown 1999) had affected the results. However, if only fast myopia progressors benefit from progressive lens wear, then the multifocal lens treatment effect would have been more accurately evaluated for this group of children in Leung and Brown (1999), since all the children in their study had a high rate of myopia progression and might benefit from the multifocal lens wear, compared to Edwards et al. (2000) study, where just a portion of children had high myopia progression and had the possibility of a benefit.

In the Correction of Myopia Evaluation Trial (COMET) conducted in the United States, Gwiazda et al. (2003) enrolled 469 children (aged 6-11 years) with myopia between −1.25 and −4.50 D. The children were randomly assigned to receive progressive lenses with a +2.00 D addition (n=235) or single vision lens (n=234) and were followed for three years. Inclusion criteria included astigmatism of no more than 1.50 D, anisometropia of no more than 1.00 D, visual acuity of 0.20 logMar or better, no strabismus, birth weight not less than 1250 g, no prior contact lens or bifocal lens wear, and no ocular or systemic condition that might affect refractive development. Baseline refractive errors averaged −2.40 D for the progressive lens group and −2.37 D for the single vision lens group. Mean 3-year increases in myopia were −1.28 D in the progressive lens group and −2.37 D for the single vision lens group. Mean 3-year increases in myopia were −1.28 D in the progressive lens group and −1.48 D in the single vision group. The 3-year difference of 0.20 D was statistically significant (p=0.004), but not large enough to recommend bifocals for myopic children from a clinical perspective. Gwiazda et al. (2004) reanalysed the data in COMET and reported that progressive
spectacle lenses were effective in slowing myopia progression in children with relatively large lags of accommodation (>0.43 D) (myopia control −0.33 D), and in those children with large lags of accommodation in combination with nearpoint esophoria (myopia control −0.64 D), shorter reading distances (myopia control −0.44 D), or lower baseline myopia (myopia control −0.48 D). Contrary to earlier reports (Goss, 1986; Fulk et al., 2000) that bifocal spectacle lenses were more effective at controlling myopia in esophoric children, COMET showed that progressive lenses were more effective for children with large lags of accommodation and that the beneficial effect was greatest in those children with a combined large accommodative lag and esophoria, but that progressive lenses were not effective at controlling myopia in children with esophoria alone. This further suggests that the link between the accommodation and vergence system are important in myopia development and lens treatment.

1.6 Bifocal treatment and near oculomotor mechanism

Published studies to this point have shown that bifocal and multifocal lenses are not particularly effective at controlling myopia progression in children. Many studies support the suggestion that bifocal lenses inhibit myopia development in children, but the beneficial effect is only small and they are only effective in subsets of children. Those myopes who have a high lag of accommodation and are esophoric at near seem to benefit the most. The lack of individualisation of the treatment (for example a set near addition power is usually given) and the disregard for the state of the convergence system are important factors that could explain the poor outcomes observed. How an individualised bifocal lens treatment, that might more effectively inhibit myopia progression, could be determined from the near oculomotor response is discussed.

1.6.1 Bifocal treatment and accommodative lag

In the majority of published bifocal and multifocal myopia control studies the power of the prescribed near addition is usually the same for all children with the power chosen based the past experience and beliefs of the researchers conducting the study. For example, all children may receive a +1.00 D (Grosvenor et al., 1987), +1.25 D (Fulk et al., 2000), +1.50 D (Leung and Brown, 1999; Edwards et al., 2002), +1.75 D (Hemminki and Parssinen, 1987), or +2.00 D addition (Grosvenor et al., 1987; Leung
and Brown, 1999; Gwiazda et al., 2003;), i.e. the same addition power is prescribed to all children. This prescription approach was often carried out in the belief that the addition would always help to improve the near focus and that the data analysis would be simplified if only one add power was used.

In fact, not only does the magnitude of the lag of accommodation show large variability amongst individuals, the effect of the near addition on the accommodative error may be quite different, even for individuals in which the magnitude of the accommodation lag is the same. Some individuals even over accommodate at near, i.e. have a lead of accommodation, and the near addition makes the lead even greater (Rosenfield and Carrel, 2001; Seidemann and Schaeffel, 2003; Jiang et al., 2007). Individual variations in measured lags of accommodation range from 0.10 D (young adults: Abbott et al., 1998) to more than 1 D (young adults: Seidemann and Schaeffel, 2000; children: Mutti et al., 2001; Gwiazda et al., 2003; Gwiazda et al., 2005; children and young adults: He et al., 2005), for a near target at 33 cm. In addition, the optimal lens power to minimize these errors also varies across subject groups, for example, optimal lens powers of +1.00 D (Seidemann and Schaeffel, 2003) and +1.28 D (Jiang et al., 2006) for a 33 cm target have been reported for myopic adults. In emmetropic adults, +2.00 D lenses were reported in one study to create the least amount of accommodative error in young emmetropic adults (Seidemann and Schaeffel, 2000), whereas later studies report significant leads of accommodation with +2.00 D lenses (young adults: Seidemann and Schaeffel, 2003; Shapiro et al., 2004; Jiang et al., 2006). Collectively, the results of these studies suggest that a single near-addition power would not be optimal for all individuals. Therefore, if positive lenses are to be prescribed to minimize the accommodation lag in myopic children, it is important to monitor the actual accommodation of the children wearing the lenses.

1.6.2 Bifocal treatment and convergence bias
Positive lenses at near because they reduce the accommodation demand and thus accommodation response, will decrease accommodative convergence due to the accommodation convergence linkage. This would result in the phoria shifting to a more divergent position (i.e. relatively more exophoria would be measured). Therefore, the near addition not only reduces the accommodative lag, it also creates a
higher demand on positive fusional vergence, especially for individuals with near exophoria (Jiang et al., 2006; 2007). In contrast, positive lenses would decrease both the lag of accommodation and the measured esophoria in esophoric individuals, reducing the demand on negative fusional vergence and enhancing the equilibrium between accommodation and vergence. This suggests that in terms of the vergence system, positive lenses at near would only benefit esphoric myopic children (Jiang et al., 2007).

There have been both retrospective (from clinic records, bifocal lenses: Goss, 1986) and prospective studies (bifocal lenses: Fulk et al., 2000) showing that, incorporating a near addition is more effective in reducing the rate of myopia progression in individuals demonstrating baseline esophoria at near through the distance correction, compared to those that are exophoric at near under the same circumstances. Data from the COMET study (Gwiazda et al., 2004) showed the importance of the accommodation vergence link; children with larger lags of accommodation ($\geq 0.43$ D) and esophoria ($\geq 2$ $\Delta$) had the greatest benefit of the progressive lens, i.e. their myopic progression was slowed compared to children with the same characteristics wearing single vision lenses. Published data suggest (although this has not been directly tested) that the subgroup of children who achieve the best oculomotor equilibrium, as advocated by the oculomotor interactive theory, (Hung and Ciuffreda, 2000) would benefit the most from the near addition. In future work, the phoria state of myopic children both with and without the near addition in place should be assessed.

1.6.3 A systematic approach to bifocal treatment

Although it is clear that near work and myopia are associated, at this time there is still no convincing evidence in humans that the presence of a large lag of accommodation to a near target is the primary cause of myopia development. Since near-work involves an increased level of accommodation and convergence, perhaps it is more relevant to find a method to reduce these near oculomotor stimuli for myopia control. It is therefore the purpose of this study to find an ophthalmic lens design which will reduce the demand on both accommodation and convergence at near, and as such the lag of accommodation and lens-induced exophoria would also be reduced. It is postulated that a bifocal with base-in prism incorporated into the
near addition can fulfill this requirement because such a lens design would simulate
distance vision, to a certain extent, whenever near work is performed.

The effect of prism bifocals will be tested by investigating the effect of positive-lens
additions and base-in prisms on accommodation accuracy and near horizontal phoria.
This work will also demonstrate how the accommodation and convergence of
myopic children can be modified to reduce the accommodation lag and positive lens-
induced exophoria. The ultimate goal of this research is to conduct a 3-year
longitudinal clinical trial to determine if prism bifocals are effective at inhibiting
myopia development in school children.

References
accommodation stimulus response curves of adult myopes and emmetropes.
Abdalla, M. I. and Hamdi, M. (1970) Applanation ocular tension in myopia and
Alpern, M. and Ellen, P. (1956) A quantitative analysis of the horizontal movements
of the eyes in the experiment of Johannes Mueller: II. Effect of variation in target
Armaly, M. F. and Jepson, N. C. (1962) Accommodation and the dy namics of the
Arch. Ophthalmol. 65, 415-23.
changes during accommodation with the IOLMaster. Optom. Vis. Sci. 81, 283-
286.
486-490.
accommodation cause axial-length elongation at near? A biometric study in
teens. Ophthalmic Res. 31, 304-308.


Chapter 2: Myopia Prevalence in Chinese-Canadian Children in an Optometric Practice

Desmond Cheng, Katrina L. Schmid and George C. Woo
(Optom Vis Sci. 2007;84:21-32)

Introduction
In urban East Asian countries, at least 50-60% of children by the age of 12 years are myopic,\(^1\)\(^-\)\(^4\) whereas the prevalence of myopia in Caucasian children of similar age is merely 10-20% (Europe,\(^5\) United States\(^6\) and Australia\(^7\)). This difference in prevalence appears a relatively recent occurrence, with more Chinese children today being myopic compared to in the past and also compared to the portion of older Chinese people that are myopic.\(^8\) For example, in Taiwan, using a myopia definition of \(\leq -0.25\) D the prevalence of myopia in Chinese children has increased 6.7 times (from 3 to 20.2 %) and doubled (from 29 to 60.7%) for children aged 7 and 12 years respectively (year 2000 compared with 1986).\(^4\),\(^9\),\(^10\) In Singapore, Chinese male conscripts in the late 80’s had a myopia prevalence of 40-50% with myopia defined as a visual acuity of \(<6/18\)\(^1\),\(^1\)\(^2\) and in a mid 1990’s study\(^1\)\(^3\) with myopia defined as \(\leq -0.5\) D, the prevalence had increased to 80%. Similarly, in family studies of myopia over three generations in Hong Kong, the prevalence of myopia increased significantly from one generation to the next.\(^1\)\(^4\),\(^1\)\(^5\) Such a difference is also found in Singapore, where the prevalence of myopia (\(\leq -1\) D ) in Chinese adults aged between 40 and 49 years is approximately 50%,\(^1\)\(^6\) which is lower than that of younger groups (e.g. 82.2% for young adults aged 17-19 years with a myopia cut-off \(\leq -0.5\) D ).\(^1\)\(^3\) In Europe and North America, a similar longitudinal increase in the prevalence of myopia has also been noticed, but the prevalence has not risen to the level seen in East Asian countries.\(^8\) Among the prevalence of myopia data for Europe and North America, the highest ever reported is 49.7% (cut-off \(\leq -0.5\) D) in Sweden\(^1\)\(^7\) for children aged 12 to 13 years.

In addition to the high prevalence rate, the speed at which the refraction shifts in the myopic direction in Chinese children is particularly high. The average rate of refractive change of Hong Kong children aged 7-12 years was \(-0.32\) D per year in the 1990s.\(^3\) This progression rate is more than three times the rate that is reported for Caucasian children of a similar age (6-11 years; \(-0.09\) D per year).\(^1\)\(^8\)
Hong Kong study, the average rate of refractive change of children aged between 5-16 years was \(-0.40\, \text{D per year}\). In Singapore, the mean rate of refractive change in a group of primarily Chinese children aged 8-9 years was 0.57-0.80 D per year. Though direct comparison of the progression rate data from these studies is complicated by the differences in the age range of the children and other characteristics of the population, it appears in general that the rate of myopic shift in Chinese children has increased in recent times.

The high prevalence of myopia in certain ethnic populations, such as Chinese and Japanese people, suggests that genetic input plays a role in myopia development, but the rapid increase in prevalence over the last few decades indicates environmental factors are also important. It is generally believed that the genetic characteristics of East Asian children predispose them to myopia development and faster myopia progression, and that this genetic background coupled with an increasingly competitive educational environment has contributed to the upward trend in myopia prevalence. One piece of evidence for genetic and environment interaction is that male Chinese conscripts (82.2\%) have a higher prevalence of myopia than that of male Indian conscripts (68.8\%) in Singapore, but male Indian conscripts in Singapore have a higher prevalence of myopia than that of young adults in Indian (10.8\%). The difference in prevalence between Chinese and Indian people living in a relatively common environment could be genetic or cultural (e.g. Chinese children perform more near work) in origin, but environmental influences appear to result in much higher prevalence levels for Indian people living in Singapore compared with those living in India. Further support of the environmental influences on myopia, are reports that the prevalence of myopia in Chinese children living in urban Hong Kong is higher than that for children in rural China (by at least 20\%) and this urban rural difference is also found in other countries e.g. in Malaysia, India, and Japan. These rural localities presumably have a less competitive educational environment than the large urban centres. The increased education demands especially in Asian urban cities has resulted in children spending longer hours reading and studying, and the prolonged periods of near work activity are believed to be related to the higher myopia prevalence. Although the process by which near work exacerbates myopia has yet to be fully determined, studies on different occupational groups, educational environments and animal myopia models suggest
that near work plays an important role in myopia development. A higher prevalence of myopia is observed in microscopists, in children who spent more time doing close work and in populations with higher levels of educational achievement.

Two reports have suggested that the large number of Asian migrants in recent decades has contributed to an overall increase in the prevalence of myopia in children living in Australia and the United States. However, there have been limited studies on the effect of ethnic demographics on the prevalence of myopia in Western countries, and there have been no reports of prevalence data for ethnic Chinese children living in Western countries. A related study on University students in the United Kingdom (UK) reveals no significant difference in the prevalence of myopia (~50%) between White and Asian (non-Chinese, South Asian) students educated exclusively under the UK educational system. These results suggest a predominant environmental influence in a sample of high educational achievement. A question that remains unanswered is whether the prevalence of myopia in Chinese children will be high regardless of where the urban environment they live in.

To determine a meaningful comparison of myopia prevalence data, the refractive error information of a large group of ethnic Chinese children living in a Western country is required; finding such a population has its own difficulties. In the late 80’s and early 90’s a large number of Chinese people from Asian countries such as Hong Kong, China and Taiwan migrated to Western countries for political and educational reasons. These 1st generation migrants provide an excellent opportunity to study myopia prevalence of ethnic Chinese people living in a Western influenced environment. This study aimed to determine whether Chinese children who have migrated to Western countries with less congested living space and presumably less intensive schoolwork systems will have lower myopia prevalence and slower progression. A questionnaire was also administered to determine if these Chinese children have adapted to a Western lifestyle (in terms of their visual activities).

METHODS

Subjects
Refraction data of Chinese children aged 6-12 years were collated from the clinic records of an optometric practice in Canada (Dr. Desmond Cheng & Associates,
Mississauga, Ontario, Canada, 1997-2003). According to 2001 census data, the total population of Mississauga was 610,815; of this the ethnic Chinese population was 35,959 (5.9%), with 3700 Chinese children aged 6-12 years (10.3% of the total Chinese community). The majority (at least 80%) of the ethnic Chinese people were 1st generation emigrants from Hong Kong with a first spoken language of Cantonese. There were 1489 optometric records of ethnic Chinese children identified, representing 40% of the Chinese children in this age group living in Mississauga. The 2211 Chinese-Canadian children not in the studied sample were examined by another 90 optometrists in the area. Of the 1489 records identified, 21 children had ocular pathology or other visual problems, and their data were excluded from the analysis. These 21 children included 3 children with esotropia, 8 with exotropia, 9 with anisometropia (>1.50 D) including 8 with amblyopia, and 1 with corneal disease, leaving the records of 1468 children with normal vision or only refractive problems. The total number of children included 729 boys (49.66%) and 739 girls (50.34%).

In Ontario, children’s eye examinations are covered by the Ontario Health Insurance plan (OHIP), and the public is aware of the importance of an early eye examination for their children. Therefore data collected from this optometric practice should avoid strong bias towards high income families or at risk populations. In predicting the potential bias of this clinic sample, refraction data of 6-year-old Canadian Caucasian children were also collated from the practice to compare to that of a 1998 prevalence of myopia study on a province-wide sample of 6-year-old children in New Brunswick, Canada.

Two hundred and fifty-two (252) optometric records of 6-year-old Caucasian children with normal vision or only refractive problems were identified. The prevalence of myopia in Chinese children from the clinic sample was then adjusted by this bias factor to determine the prevalence of myopia of Chinese children living in Canada. In addition, information on the prevalence of parental myopia of the Chinese-Canadian children was also evaluated for comparison purposes. Refraction data of 665 male parents and 777 female parents of age between 40-49 years were collated from the clinical records to determine if the prevalence of myopia in Chinese-Canadian adults (i.e. the parents of the children) was also high.
**Examination details**

In the annual comprehensive eye examination, the preliminary testing had included monocular and binocular unaided and/or corrected visual acuities, unilateral and alternate cover test, near-point of convergence, pupil reactions and stereopsis (Stereofly test, Stereo Optical, Chicago). Refraction had been measured objectively using a non-cycloplegic auto-kerato-refractor (TOPCON KR7000, Topcon Corporation, Tokyo) followed by non-cycloplegic subjective refraction at 6 m. The subjective refraction had been carried out by the same practitioner (Dr. Cheng) throughout the study period. The end-point chosen for the subjective refraction was maximum plus power for best visual acuity. Intraocular pressure had been measured by a non-contact tonometer (Reichart AT550, Reichart Ophthalmic Instruments, Buffalo). Ocular health of the anterior segment had been assessed using slit lamp biomicroscopy and that of the posterior segment using fundus biomicroscopy (90 D lens with the slit lamp). Cycloplegic refraction and dilated pupil fundus examination had been performed on indication (e.g. hyperopia > 1 D or a family history of retinal detachment). A total of 63 children had cycloplegic refractions.

To study issues surrounding the visual activities of the children, a questionnaire was administered by mail, with a follow up phone call if required, to 300 Chinese children and 300 Caucasian children randomly selected from the clinic records. The format of the questionnaire was adopted from the Orinda Longitudinal Study of Myopia except for additional questions on the time the child spent engaged in portable games and in computer work. The questionnaire has previously been reported to provide a valid assessment of near work. In addition to the 30 to 32 hours per week Canadian children spent at school, the questionnaire asked parents on average how many hours per week their child spent performing each of the following activities outside of school: studies or does school assignments (computer work not included), engages in computer work (assignments, games and internet), reads for pleasure, watches television or plays television based games (e.g. playstation), plays gameboy or other small hand held portable games, engages in outdoor/sport activities.
**Statistical analyses**

In the analysis of refraction data, only refractive error data for right eyes were used. For the purpose of determining myopia prevalence, myopia was defined as a spherical equivalent refraction (SER) ≤−0.50 D. Since retrospective cross-sectional refraction data from clinical records included both dependent (data from the same child appeared in more than one age group) and independent (data from some children only appeared in one age group) data, the results pertaining to the prevalence of myopia and refractive error distributions have been restricted to graphical analysis and descriptive statistics. The refractive error distribution is described by skewness and kurtosis. The skewness for a normal distribution is zero, and any symmetric data should have a skewness near zero. Kurtosis is a measure of whether the data are peaked or flat relative to a normal distribution. That is, data sets with high kurtosis tend to have a distinct peak near the mean, decline rather rapidly, and have heavy tails. A standard normal distribution has a kurtosis of zero.

Data were grouped into 6 age bands [6 to 7 (n=196), 7 to 8 (n=244), 8 to 9 (n=304), 9 to 10 (n=306), 10 to 11 (n=313) and 11 to 12 years (n=289)] to determine yearly rate of refractive change and the yearly cumulative incidence of myopia. Refraction data of children who had two years consecutive measurements were used. The yearly rate of refractive change in a given age band (e.g., 6 to 7) was the difference between the refraction measured in the “second” (e.g., 7 years) to that measured in the “first” year (e.g., 6 years). The 1-year cumulative incidence of myopia for a given age band (e.g., 6 to 7) was the percentage of previously non-myopic children (e.g., 6 years) who became myopic (≤−0.50 D) in the following year (e.g., 7 years). With this method of analysis, some children did not have their refraction data included in any of the age bands (e.g. if their refractive error was not measured in consecutive years), some children would have their refraction data only in one age band, whereas others would have refraction data in more than one age band (e.g., if their refractive error was measured for more than 2 years consecutively). There were also some children with refraction data in two or more discrete age bands (e.g., age band 6 to 7 and age band 10 to 11). As a result, the refraction data across age bands includes both dependent and independent data; this is unavoidable in a retrospective analysis. To satisfy statistical laws of comparison, only independent data were used for statistical analysis; those dependent data were randomly removed when the significance of gender and age on refractive error was determined by the analysis of variance.
ANOVA); p<0.05 indicated that the effect was significant. The normality of refractive error distributions was determined using the Shapiro-Wilk test.

RESULTS

Prevalence of myopia

The prevalence of myopia (≤–0.50 D) showed a positive correlation with age for both girls and boys (Figure 1) ($r^2=0.97$ and $p<0.05$ for girls and $r^2=0.99$ and $p<0.05$ for boys). The myopia prevalence increased from 26.6% for girls and 23.3% for boys at age 6 to 73.2% for girls and 69.2% for boys at age 12. Girls had a slightly higher prevalence of myopia than boys except for a similar prevalence value of 41.5% at age 8. When data for girls and boys were grouped together, the prevalence of myopia increased from 24.9% at age 6 to 71.2% at age 12. The prevalence of hyperopia (>0.75) was initially low and also decreased; from 3.5% for girls and 7.4% for boys at age 6 years to 1.4% for girls and 1.8% for boys at age 12. Girls had a slightly lower prevalence of hyperopia.

Figure 1. Prevalence of myopia in Chinese children living in Canada aged 6 to 12 years. The prevalence of myopia for the combined sample of girls and boys is 25% at 6 years with the prevalence increasing steadily to reach 71% for 12 year old children.
Refractive error distribution

At each age the refractive error distribution was significantly different ($p<0.001$) from a normal distribution (Figures 2a and b, 3a and b). The percentage of children with myopia has been shown rather than the actual numbers to better reflect the pattern of change. At age 6, the curve was leptokurtic with more data concentrated about the mean (value for kurtosis was 13.0 for girls and 20.4 for boys) and the most common error was between $+0.12$ and $+0.87$ D for both girls and boys. The value representing skewness of the refractive distribution at age 6 was more negative ($-1.3$) for girls due to a high myopic data point at $-6$ to $-6.87$ D and more positive ($2.8$) for boys due to a high hyperopic data point at $+7$ to $+7.87$ D. If these two data points were removed, the value became 0.1 for girls and 0.4 for boys indicating only a slight skew towards hyperopia. At age 12, the leptokurtosis of the distribution decreased (value for kurtosis was 0.81 for girls and 0.84 for boys) as the refractive data became more spread. At this later age (12 years) the distribution showed a greater skewness towards myopic refractive errors, giving a negative tail with a skew value of $-0.87$ for girls and $-0.93$ for boys.

The leptokurtosis and skewness in refractive error distribution were similar for girls and boys, except that starting from age 9 slightly more girls than boys become myopic and by 12 years 19.7% of girls but only 13.4% of boys were highly myopic ($\geq 4$ D of myopia). When the girls and boys data were grouped together, the proportion of children with emmetropia (refractions between $-0.25$D and $+0.75$D) was greatest at age 6, with 68.6%, and decreased at older ages, with 27.2% at age 12. At 6 years of age, 0.3% of children had $\geq 4$ D of myopia and no children had myopia $\geq 8$ D, by 9 years of age 5.2% had $\geq 4$ D of myopia and 0.2% had myopia $\geq 8$ D. By 12 years these numbers had increased such that 16.7 % of children had $\geq 4$ D of myopia and 0.9% more than $\geq 8$ D of myopia.

The average refractive error of all children at age 6 years was $-0.02\pm 1.02$ D and for just the myopic children was $-1.12\pm 0.86$ D, whereas at 12 years the average refractive error of all children was $-1.97\pm 2.04$ D and it was $-2.97\pm 1.82$ D for just the myopic children. There were very few hyperopes ($>+0.75$ D) ($\sim 1.5\%$ for age 12
years) but for those that were hyperopic the average amount of hyperopia was +1.73±1.57 D at 6 years and +1.95±0.87 D at 12 years.

Figure 2. Refractive error distribution for girls (a) at 6 years and (b) at 12 years in 1 D refractive error bands. The distribution is highly leptokurtic around 0 to 1 D of hyperopia at age 6 years, with age the leptokurtosis decreases and there is a shift toward myopia and also towards higher degrees of myopia.
Figure 3. Refractive error distribution for boys (a) at 6 years and (b) at 12 years in 1 D refractive error bands. The distribution is highly leptokurtic around 0 to 1 D of hyperopia at age 6 years, with age the leptokurtosis decreases and there is a shift toward myopia and also towards higher degrees of myopia.
Incidence of myopia

The 1-year cumulative incidence of myopia for a given age band (e.g., 6 to 7) was the percentage of previously non-myopic children (e.g., 6 years) who became myopic ($\leq -0.50$ D) in the following year (e.g., 7 years) (Figure 4). Girls and boys showed a slightly different age-related change in the cumulative incidence. For girls, the incidence increased with age from age 6 at 19.4% to age 10 at 35.1% and then decreased to 19.0% at age 11. Boys, however, showed a less consistent change in incidence with age. The incidence increased from 18.4% at 6 to 22.5% at age 7 years, followed by a slight drop in incidence at 8 years (17.2%), and then an increase again to 10 years (25.8%) before the incidence declined again (to 17.6% at 11 years). For all ages, girls had a higher incidence of myopia than boys. When the data of boys and girls were pooled, the incidence of myopia peaked between 9 and 10 years of age at around 30% and then declined to 18.3% at 11 years of age. This decline was presumably due to the fact that so many children were by then already myopic.

**Figure 4.** One-year cumulative incidence of myopia from 6 to 12 years in Chinese children living in Canada. The incidence of myopia of Chinese-Canadian children reaches a peak between 9 and 10 years of age for both girls (~35%) and boys (~25%) before declining to age 11 years. High incidence values cannot be sustained once the majority of children are already myopic.
Refractive shift

The plot for the mean spherical equivalent refractive error (SER) in a given age band (e.g., 6 to 7) has two bars for each gender representing the “first” (e.g., 6 years) and the “second” year (e.g., 7 years) refraction data (Figure 5a). The refractive change within an age band was a longitudinal measure which only included refraction data of children measured for two years consecutively. The pattern of the age-related change in mean spherical equivalent refractive error (SER) was similar for girls and boys (Figure 5a). The mean SER at 6 years for girls was $–0.21±0.83$ D and for boys was $+0.19±1.00$ D and at 12 years was $–2.21±2.08$ D and $–1.98±2.06$ D for girls and boys respectively. Girls had a higher amount of myopia than boys and this gender difference was statistically significant ($p<0.01$).

The 1-year rate of refractive change in a given age band (e.g., 6 to 7) was the difference between the refraction measured in the “second” year (e.g., 7 years) to that measured in the “first” year (e.g., 6 years) (Figure 5b). Girls showed a higher annual myopic shift than boys ($p<0.05$) but the difference was not significant at ages 6 and 8 (Bonferroni t-test). Compared with age 6, the annual refractive shift at all other ages was significantly higher ($p<0.01$). The highest annual change for girls occurred at 9 years ($–0.71±0.42$ D per year) and for boys occurred one year later (10 years, $–0.51 ±0.32$ D per year). The average annual rate of refractive change for all ages was $–0.52±0.42$ D per year. For just the myopic children, their average annual myopia progression was $–0.90±0.40$ D per year and the highest annual progression of $–1.15±0.51$ D per year occurred at age seven. There were 14 children with refraction measured every single year from 6 to 12 years and their mean annual refractive change was $–0.48±0.45$ D per year.

Bias of the clinic sample

Of the refraction data of 6-year-old Caucasian children collated from the 252 clinical records in the practice, 18 had myopia less than $–0.25$ D, giving a prevalence of myopia of 7.1%. The mean spherical equivalent was $+0.55±0.95$ D. The definition of myopia of $<–0.25$ D was chosen to match that of a Canadian screening study. In a province-wide vision screening program using non-cycloplegic retinoscopy in New Brunswick, Canada, the prevalence of myopia ($<–0.25$ D) of 10,616 children aged 6 years was 6.4% and the mean refractive error was $+0.62±0.91$ D. Using the
Figure 5. (a) Mean spherical equivalent refractive error (SER) with standard error for Chinese-Canadian children in 1-year age bands from 6-12 years. The plot for the mean SER in a given age band (e.g., 6 to 7) has two bars for each gender representing the “first” (e.g., 6 years) and the “second” year (e.g., 7 years) refraction data. The mean SER is consistently higher in the “second” year for both girls and boys. Girls have a higher degree of myopia than boys for all age bands. (b) One-year rate of refractive change for Chinese-Canadian children from 6 to 12 years. The highest annual progression for girls occurs at 9 years (–0.71 D per year) and for boys occurs 1 year later at 10 years (–0.51 D per year). For just the myopes the peak progression is earlier at 7 years and the progression rate is greater (–1.15 D per year).
prevalence of 6.4% as the population reference, the bias factor for this clinic sample was 6.4/7.1 giving a value of 0.90. The adjusted prevalence of myopia for the general population of Chinese-Canadian children was then 22.4% (6 years), 28.5 % (7 years), 37.5 % (8 years), 46.4 % (9 years), 53.3 % (10 years), 60.22 % (11 years) and 64.1% (12 years).

Based on the refraction data collated from the clinical records of the parents (aged 40 to 49 years) of the Chinese-Canadian children, 60.3% of fathers (n=665) and 58.2% of mothers (n=777) were myopic (≤−0.50). If the bias factor of 0.90 were to apply for this clinic sample, the adjusted prevalence of myopia was 54.3% for male and 52.4% for female parents. In Japan, the prevalence of myopia was 70 % for male and 60 % for female adults in the same age range and using the same myopia criteria. Reported data from Singapore gives the prevalence of myopia of 45.2 % for male and 51.7% for female adults in the age range 40 to 49 years but using a myopia cut-off of ≤−0.50 D. Thus the prevalence of myopia of the parents of the Chinese-Canadian children was similar to that of similarly aged adults in East Asian countries.

**Questionnaire results**

The mean age of the randomly selected children that completed the questionnaire was 9.8±2.1 years for Chinese-Canadian children and 9.4±2.4 years for Caucasian-Canadian children and their mean refractive error was −1.06±1.70 D and +0.39±0.79 D respectively. The questionnaire on weekly visual activities showed that Chinese-Canadian children spent significantly more time on homework, computer, leisure reading and portable games but significantly less time on outdoor activities than did Caucasian-Canadian children. Chinese-Canadian children spent an average of 23.9 hours per week performing near work whereas Caucasian-Canadian children spent 17.8 hours per week giving a difference of 6.1 hours per week (Table 1). The data from a study in an urban city Tianjin, China have been included for comparison purposes. In that year of the study (1994), computer and portable games were not common and therefore data were not available. Overall, Chinese-Canadian children spent an additional 2.8 hours per week on near work compared with the children in Tianjin, China who spent only 21.1 hours per week on near work. Although statistical comparison between the two groups was not possible since only the
average values were reported in the Tianjin study, the high amount of near work and lack of outdoor activities were similar findings for the two groups of children.

Table 1. Number of hours per week (mean±SD) Chinese-Canadian children (n=300) and Caucasian-Canadian (n=300) children spend performing different visual activities.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Chinese-Canadian</th>
<th>Caucasian-Canadian</th>
<th>Tianjin Children</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homework</td>
<td>9.8±6.2*</td>
<td>6.9±4.9</td>
<td>13.0</td>
</tr>
<tr>
<td>Computer</td>
<td>8.3±5.4*</td>
<td>6.6±4.7</td>
<td>-</td>
</tr>
<tr>
<td>Leisure reading</td>
<td>5.3±4.2*</td>
<td>4.0±3.8</td>
<td>8.2</td>
</tr>
<tr>
<td>Portable games</td>
<td>0.5±0.3*</td>
<td>0.3±0.3</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total near-work</strong></td>
<td><strong>23.9</strong></td>
<td><strong>17.8</strong></td>
<td><strong>21.1</strong></td>
</tr>
<tr>
<td>TV/Videogames</td>
<td>10.7±6.2</td>
<td>11.3±6.0</td>
<td>9.4</td>
</tr>
<tr>
<td>Outdoor activities</td>
<td>6.1±4.5*</td>
<td>10.5±6.1</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Comparisons between Chinese-Canadian and Caucasian-Canadian children are significant as marked * p<0.005. The data from a study in Tianjin, China² (Yap et. al. 1994) are included for comparisons.

**DISCUSSION**

The main findings of this research are that many ethnic Chinese children living in Canada are myopic and that high levels of myopia are common. Chinese-Canadian children, like their East Asian counterparts, have comparable myopia development and their myopia progresses rapidly. The implications of this data in terms of causes of myopia are discussed.

The Chinese-Canadian sample drawn from the clinical records in the optometric practice introduces a potential bias of the data towards more children with refractive problems. To measure the bias effect, the refraction data of a control group of Caucasian children in the clinic was also analysed and compared to that of the children in a province-wide sample in New Brunswick, Canada.³⁵ This adjustment for clinical bias in the Chinese-Canadian sample is based on the assumption that the prevalence data in this neighborhood province is similar to that in Ontario, Canada, and that the same factors influence the Caucasian-and Chinese-origin population. The latter assumption is highly unlikely given the markedly different prevalence of myopia in the two groups. This comparison yielded a bias factor of 0.90 indicating the bias of this clinic sample was relatively low. The estimated bias factor was used
for adjusting prevalence values of all age groups as only data of 6-year-old children was reported in the province-wide sample. This may underestimate the bias effect of older age groups as it is possible that emmetropic children are less likely to return for regular eye examinations. Although there are weaknesses in the current method to determine bias, the approach represents a way to deal with the clinical bias to some degree using the only population data available in Canada.

As the refractive error data in this retrospective study were derived from non-cycloplegic subjective refraction, the prevalence of myopia might have been overestimated. In previous studies comparing non-cycloplegic and cycloplegic refraction using retinoscopy or subjective refraction,\textsuperscript{37-39} the difference in the two refractive measurements was within ±0.50 D for myopic patients. For hyperopes, cycloplegic refraction revealed a significant increase in measured hyperopia but only in younger patients (aged 6-10 years)\textsuperscript{39} and children with high levels of hyperopia (+4.00 to +8.00 D).\textsuperscript{37} For myopes and low-level ametropes of all types, cycloplegia failed to reveal an increase in measured hyperopia or a decrease in myopia.\textsuperscript{38,39} Therefore, the risk for inaccuracies in the myopia prevalence estimates resulting from a lack of routine cycloplegia and thus low-grade hyperopes being classified as low myopes should be very low, particularly given the −0.50 D requirement for myopia categorization. Since the influence of cycloplegia was of least concern for myopes and low-grade hyperopes, and Chinese-Canadian children suspected of being hyperopic (≥+1 D) were cyclopleged, the prevalence of myopia would not have been significantly different if cycloplegic refractions had been used for all children. In support of this are two recent studies in Sydney,\textsuperscript{7,40} one using non-cycloplegic retinoscopy\textsuperscript{7} with careful fogging techniques and the other using cycloplegic autorefraction;\textsuperscript{40} both yielded similar myopia prevalence results for children aged 6 to 7 years. In contrast, if the method of refraction is autorefraction, the prevalence of myopia is found to be overestimated when cycloplegics are not used.\textsuperscript{41} The inaccuracies with non-cycloplegic autorefraction are due to inadequate fogging methods and therefore accommodation of the subjects. Nonetheless, the accuracy of subjective refraction is highly dependent on the technique, skill and experience of the examiner which are likely to vary from site to site; cycloplegic autorefraction is still the recommended refraction method for future prevalence studies.
Twenty-two percent (22.4%) of the Chinese-Canadian children were already myopic by 6 years; this was only slightly less than the 28% reported for children aged 6 to 7 years in a Hong Kong based study conducted in 1991 that used the same definition of myopia. In a province wide Canadian study with the definition of myopia $<-0.25$ D, the prevalence of myopia of 6-year-old Canadian children was merely 6.4%, although the data might also include some Chinese children. In other countries such as Australia, America and South Africa, the prevalence of myopia (cut-off $\leq -0.5$ D) in 6-year-old children has usually been reported to be less than 6%. The high prevalence of myopia in Chinese-Canadian children at age six means that the age of onset of myopia for many Chinese-Canadian children is earlier than 6 years of age. Chinese-Canadian children also have a higher risk of developing high myopia presumably because of the earlier onset. From age six onwards, more children become myopic and this change coincides with the age of primary school entry in Canada at which schooling with intensive near work begins. The adjusted prevalence of myopia in the Chinese-Canadian children increased to 64.1% at age 12. This trend of increasing myopia prevalence with age is similar to that reported for Chinese children living in Hong Kong and Taiwan, but more of the Chinese-Canadian children appear to be myopic by 12 years. The reported prevalence of myopia (cut-off $\leq -0.5$ D) at the age of 12 years varies from 40 to 50% for the Chinese children living in Tianjin China (study conducted in 1993) to 55 to 58% for Chinese children living in Hong Kong (study conducted from 1991-1996). More recently (1998-2000), the prevalence of myopia in Hong Kong schoolchildren has been quoted to be 48.2% at age 10 years. In another study comparing prevalence of myopia in local and international schools in Hong Kong, 88.2% (2001) of Hong Kong children aged 13 years were myopic. This data may thus indicate a real prevalence difference between these locations or possible variations in the study design.

Another potential reason for differences in myopia prevalence between the published myopia prevalence studies may be when the studies were conducted. A question related to this, is whether the greater prevalence of myopia found here indicates that myopia is becoming even more common? To further investigate this, the adjusted prevalence data of the present study (Chinese-Canadian children, the majority are Hong Kong migrants) were plotted along with data of previous Hong Kong studies for ease of comparison (Figure 6). These prevalence plots have a similar
trend of greater myopia prevalence with increasing age but results from latter studies consistently show higher prevalence values. For example, the prevalence of myopia of children at age seven through to age 12 is least for the study that was conducted the longest time ago (Hong Kong 1996, 11% to 57%).³ This increase in myopia prevalence over time is also observed in Taiwan where the myopia prevalence (cut-off ≤−0.25 D) at 12 years has increased from 29.0% in 1986 to 55.4% in 1995 to 60.7% in 2000, and such increases are also seen in children aged 6 to 15 years.⁴,⁹,¹⁰

**Figure 6.** Clinic bias adjusted prevalence of myopia of children in the present study compared to that of children in previous studies conducted in Hong Kong.³,¹⁰,⁴³ The year in parentheses denotes the final year of data collection and the number in braces denotes the reference number. This data show that there is a similar trend of greater myopia prevalence with increasing age but results from later studies consistently show higher prevalence values.

From 6 to 12 years of age, the average refractive error of the Chinese-Canadian children becomes more myopic; this trend has been shown in many previous studies of Chinese children in East Asia.¹,³,⁴,⁹,¹⁰ The refractive error distribution was significantly different from a normal distribution for all ages. The distribution was
highly leptokurtic and slightly skewed towards hyperopia at age 6. The leptokurtosis of the distribution decreased at age 12 as more children became myopic. These values of kurtosis and skewness are comparable to that of a Hong Kong study.³ At age 12, the average amount of myopia was −2.97±1.82 D with 16.7% have ≥4 D myopia. Since myopia tends to continue to progress into adolescence and sometimes beyond, this implies that a large percentage of Chinese-Canadian children will develop high myopia (≥6 D) by the time they reach adulthood. These high myopes are more susceptible to macular degeneration, glaucoma, cataract and retinal detachment.⁴⁴ Such a concern is also found in Singapore;²⁰ where 16.8 % of children aged 9 to 11 years have myopia ≥6 D myopia. In contrast, only 0.4% children at age 12 have myopia ≥4 D in Sydney, Australia.³²

The 1-year cumulative myopia incidence for the children aged 6 to 12 years in this study should not be viewed as being the same as a cumulative incidence for children who are studied longitudinally from age 6 to 12 years. The latter type of study will have the total cumulative incidence add to <100% and is referred to as 6-year cumulative incidence of myopia, an example of such a longitudinal study is Edwards (1999).³ In contrast, the total incidence for studies using an initial cross-sectional survey (e.g., children aged 6 to 12 years) and then longitudinal follow-up (e.g. 1-year) could be added up to more than 100%, examples of such studies are Fan et al. (2004)¹⁹ and Zhao et al (2002).⁴⁵ The yearly cumulative incidence of myopia for the Chinese-Canadian children reached its highest level at 9 and 10 years of age for girls (~35%) and boys (~25%). Girls had a slightly higher incidence of myopia than boys for all ages. Since many children have already become myopic before the age of 11 years, the incidence then decreases to 19.0% for girls and 17.6% for boys at 11 years; high incidence values cannot be sustained once the majority of children are already myopic. An earlier 5-year longitudinal study based in Hong Kong showed that the myopia incidence increased with increasing age, from 9% at age 7 years to 18 to 20% at age 12 years.³ A similarly high incidence of myopia to that found in this study has been reported in 10 year-old Chinese boys and 11 year-old Chinese girls living in Hong Kong, with a reported annual incidence of 20 % and 27.6 % respectively.¹⁹ Collectively this shows that the incidence of myopia in these children is greatest between the ages of 9 and 11 years, suggesting that any treatment designed to prevent myopia in these groups should commence well before this.
The yearly rate of refractive change was the highest at 9 years of age for girls (–0.71±0.42 D), 10 years for boys (–0.51±0.42 D) and 7 years for just the myopic children (–1.15±0.51 D). Girls had a significantly higher refractive shift than boys and a similar gender difference was also found in 7- to 9-years-old Singaporean children (majority Chinese), but there was no gender difference reported in a Hong Kong study of children aged 6 to 17 years. The fact that the peak progression rate for myopic children occurs between 7 years implies that children with early onset myopia should begin prevention treatment well before 7 years. The average refractive shift of all the Chinese-Canadian children aged 6 to 12 years was –0.52±0.42 D per year and myopia progressed by –0.90±0.40 D/yr for children who were already myopic (≤–0.50 D) at the beginning of the study. Refractive shifts of –0.32 D per year to –0.63 D per year for children who were already myopic (≤–0.5 D) have been reported in Hong Kong. In a myopia control clinical trial in Singapore, a myopia progression rate of –0.56 D per year was found in children aged 6 to 12 years with <2.00 D myopia and –0.65 D per year for those with myopia ≥2.00 D. In another school based study in Singapore, the reported rate of annual refractive change was –1.03 D per year for the 7-year-olds compared to –0.49 D per year in 12-year-olds. The authors attribute the high myopic shift to the predominance of ethnic Chinese children in their subject population. The data of these studies suggest that the rate of refractive change in Chinese-Canadian children is comparable to that found in Chinese children in East Asian countries.

From the questionnaire data these ethnic Chinese children who are mostly 1st generation migrants still spend an average of 23.9 hours per week on near work, which is significantly greater than that of Caucasian-Canadian children and slightly more than that of Chinese children living in an urban city, Tianjin, in China (Table 1). The idea that the Canadian based Chinese children may perform less near work than those children living in Asia was found not to be true. Chinese-Canadian children may even need to work harder to compensate for their language barrier and ensure they meet their parent’s scholastic expectations. Some of these parents even teach their children how to read numbers and alphabets and/or send them to private school as early as 2 years of age, although formal schooling for Canadian children starts at age four. These children also spent a large amount of time using computers and portable games, and these types of near activities could also impact on myopia.
progression. Outdoor activities that might be considered anti-myopiagenic, were performed infrequently by these children; 6.1±4.5 hrs/week compared to 10.5±6.1 hrs/week for similar age Caucasian-Canadian children. We surmise that the longer and colder winter in Canada in some way may preclude these Chinese children whose families may be used to living in areas with milder climates, from participating in outdoor winter sports like skiing, skating and snowboarding. Consequently, these children spend more time on indoor activities such as reading and using computers during winter months (4 to 6 months of the year). In support of this idea, a follow-up phone survey of the children who had not developed myopia by age 12 revealed that 16 out of 20 of these non-myopic children performed much less computer or reading tasks (~15 hrs/week) but participated more in outdoor activities (~11 hrs/week) than their myopic counterparts.

The findings of this study are different to those of the Sydney Myopia Study, where the prevalence of myopia in children of East Asian origin at both 6 years (3.6 %) and 12 years (39.8 %) has been reported to be higher than that of the Caucasian group but very much lower than that reported for similar children living in urban East Asia, suggesting a predominant influence of environmental exposures rather than genetic input. This is related to the interpretation of the data from Singapore on differences between ethnic groups in the prevalence of myopia. Environmental influences appear to result in much higher prevalence of myopia in male Indian conscripts (68.8%) in Singapore than those young adults in Indian (10.8%), but their prevalence is not quite as high as that of the male Chinese conscripts (82.2%) in Singapore. The difference in prevalence between Chinese and Indian people living in a relatively common environment could be genetic, but given the available evidence that Chinese are more successful than Indians in education in Singapore, there is a perfectly plausible “environmental” explanation as well. A related study on University students in the United Kingdom reveals no significant difference in the prevalence of myopia (~50%) between White and Asian (non-Chinese, South Asian) students educated exclusively under the United Kingdom education system from the start of their schooling. The similar prevalence values suggest susceptibility of South Asian students to environmental influence in the United Kingdom, although this study concerns a sample selected for educational success. In contrast, the results of this study suggest little change in both myopia and risk factors, and thus are
compatible with both genetic and environmental aetiologies. Chinese-Canadian children may have brought both their genes and their families cultural attitudes with them. Despite the fact that Chinese-Canadian children commence schooling at an early age in Canada, their even earlier age of onset of myopia (22.4% at age 6 years are already myopic) also provides some evidence that Chinese children have a stronger genetic predisposition to myopia. Since the ethnic Chinese children living in Canada have experienced the same or more academic pressures compared with those living in Asian countries, the idea that a “healthier” environment in Canada can reduce myopia progression does not really hold. Perhaps, only if the Western lifestyle becomes more influential in the 3rd or 4th generation Chinese-Canadian population, will these children become less myopic than those living in East Asian countries.

CONCLUSIONS
Chinese children living in Canada develop myopia comparable to those living in Asian countries; migration to Canada does not lower their myopia risk.

ACKNOWLEDGMENTS
We thank Elaine Chan, Annie Wong, Alice Leung and Natalie Leung for their assistance in the collection of the questionnaire data. We also thank the topical editor and reviewers for their helpful comments. This research was completed as part of the PhD program at the School of Optometry and Institute of Health and Biomedical Innovation, Queensland University of Technology.

REFERENCES
Chapter 3: The Effect of Positive-Lens Addition and Base-In Prism on Accommodation Accuracy and Near Horizontal Phoria in Chinese Myopic Children

Desmond Cheng, Katrina L. Schmid and George C. Woo

Introduction

For typical viewing conditions at near distances most individuals do not accommodate adequately to bring the target into complete focus on the retina (Grosvenor, 1982). This under-accommodation, referred to as a lag of accommodation, creates a hyperopic defocus with the near target’s best image being localized slightly behind the retina (Gwiazda et al., 1993). If this hyperopic defocus is prolonged and sustained, as may be the case for extended near work, it is thought to contribute to the progression of myopia and axial elongation of the eye (Gwiazda et al., 1993). Interruption of this hyperopic defocus by wearing positive lenses has been suggested to be a prophylaxis against progression of myopia in children (Zhu et al., 2003). This proposal is consistent with the observation that brief periods of myopic defocus imposed by positive lenses prevent myopia caused by daylong wearing of negative lenses (i.e. hyperopic defocus) in an animal study (Zhu et al., 2003).

Such a lens approach has been used to attempt to retard myopia progression in children, here positive lenses at near are prescribed in the form of bifocal or progressive lenses (Grosvenor et al., 1987; Hemminki and Parssinen, 1987; Leung and Brown, 1999; Fulk et al., 2000; Shih et al., 2001; Edwards et al., 2002; Gwiazda et al., 2003). The near addition reduces the accommodation demand and also the accommodative error (Grosvenor et al., 1987; Hemminki and Parssinen, 1987) with the hope that this decrease in hyperopic defocus may then prevent myopia formation. Unfortunately, bifocal and progressive lenses have not been proven to be very effective myopia control treatments in children (review in Goss and Zhai, 1994; Hung and Ciuffreda, 2000). A small but statistically significant reduction in the rate of myopia progression has been reported by Leung and Brown (1999), Fulk et al. (2000), and Gwiazda et al. (2003), whereas studies by Grosvenor et al. (1987), Hemminki and Parssinen (1987), and Edwards et al. (2002) found wearing near
addition lenses of no benefit to myopic children. A number of factors such as subject inclusion criteria (e.g., age and degree of myopia), the power of the near addition, subject compliance (e.g., how much the addition is used at near) and subject characteristics (e.g., status of the binocular vision system) are thought to underlie this variability in effectiveness.

In the majority of published myopia control studies, the power of the prescribed near addition is usually predetermined for practical reasons. For example, all children may receive a +1.00 D (Grosvenor et al., 1987), +1.25 D (Fulk et al., 2000), +1.50 D (Edwards et al., 2002; Leung and Brown, 1999), +1.75 D (Hemminki and Parssinen, 1987), or +2.00 D addition (Grosvenor et al., 1987; Leung and Brown, 1999; Gwiazda et al., 2003), i.e., the same addition power is prescribed to all children. This prescription approach was often carried out in the belief that the addition would always help to improve the near focus. In fact, not only does the magnitude of the lag of accommodation show large variability amongst individuals, the effect of the near addition on the accommodative error may be quite different (some individuals even over accommodate at near, i.e., have a lead of accommodation: Rosenfield and Carrel, 2001; Seidemann and Schaeffel, 2003; Jiang et al., 2007), even for individuals in which the same magnitude accommodation lag has been measured. The variability in the measured lags of accommodation ranges from 0.10 D (young adults: Abbott et al., 1998) to more than 1 D (young adults: Seidemann and Schaeffel, 2000; children: Mutti et al., 2001; Gwiazda et al., 2003; Gwiazda et al., 2005; children and young adults: He et al., 2005) for a near target at 33 cm. In addition, the optimal lens power to minimize these errors also varies, for example +2.00 D lenses have been found to create the least amount of accommodative error in young emmetropic adults (Seidemann and Schaeffel, 2000), whereas later studies report significant leads of accommodation with +2.00 D lenses (young adults: Seidemann and Schaeffel, 2003; Shapiro et al., 2005; Jiang et al., 2006). Much lower optimal lens powers of +1.00 D (Seidemann and Schaeffel, 2003) and +1.28 D (Jiang et al., 2006) for a 33 cm target have also been reported. Differences in the subject population, measurement methods, instrument calibration and fixation targets could be responsible for this variability. It has also been suggested that the near addition power required to reduce the accommodation error to zero depends on the magnitude of the initial accommodative error (Rosenfield and Carrel, 2001). Collectively, the
results of these studies suggest that a single near addition power would not be optimal for all individuals. Therefore, if positive lenses are to be prescribed to retard myopic progression in myopic children, it is important to know more about how accommodative responses vary with lens power in this group of children.

Related to this issue, is the status of the convergence system, which is linked to and co-varies with the accommodation system (Hung and Semmlow, 1980). Therefore, the near addition not only reduces the accommodative lag, it also creates a higher demand on positive fusional vergence, especially for individuals with near exophoria (Jiang et al., 2006; Jiang et al., 2007). In contrast, positive lenses would decrease both the lag of accommodation and the measured esophoria in esophoric individuals, reducing the demand on negative fusional vergence and enhancing the equilibrium between accommodation and vergence. This suggests that in terms of the vergence system, positive lenses at near may only benefit esophoric myopic children (Jiang et al., 2007).

There have been both retrospective (from clinic records, bifocal lenses: Goss, 1986) and prospective studies (bifocal lenses: Fulk et al., 2000) showing that, incorporating a near-addition is more effective in reducing the rate of myopia progression in individuals demonstrating baseline esophoria at near through the distance correction, compared to those that are exophoric at near under the same circumstances. The positive effect of near addition for children showing near baseline esophoria has also been found with progressive lenses (Brown et al., 2002; Gwiazda et al., 2004). In addition, data from the COMET study (Gwiazda et al., 2004) showed the importance of the accommodation vergence link; children with larger lags of accommodation (≥0.43 D) and esophoria (≥2Δ) had the greatest benefit of the progressive lens, i.e. their myopic progression was slowed compared to children with the same characteristics wearing single vision lenses. These studies do not report the phoria of the children with the near addition lenses in place and thus it is not known if the degree of benefit was related to this. One suggestion is that the subgroup of children who achieve the best oculomotor equilibrium, as advocated by the oculomotor interactive theory (Hung and Ciuffreda, 2000), would benefit the most from the near-addition. To understand this more, the phoria state of myopic children both with and without the near-addition needs to be assessed.
Thus, the aim of this study was to determine how both accommodative errors and the horizontal near phoria of myopic children vary as a function of positive lens power. Since the near-addition will shift the phoria state to a relatively more exophoric position (lens-induced exophoria) this study will also determine the effect of the incorporation of base-in prism. Finally, the combination of positive-lens addition and base-in prism that minimizes both near focusing errors and latent horizontal deviations will be determined.

Methods

Sample size estimation
This study used a randomized block design (repeat measures) where the accommodation errors and phoria of the same subject were measured with lenses of +0.75 D increment and prisms of 3 Δ increment. Multiple measures on the same subject (a block of tests) should eliminate error variance due to subject differences (Kuehl 1994). Based on published data on the oculomotor characteristics of myopic children (Gwiazda et al., 1999; Chen et al., 2003), the expected change in the accommodation error was 0.30 D for the + 0.75 D lens increment and that in the phoria was 3.0 Δ for the 3 Δ prism increment. Assuming the standard deviation of difference (SD) was 0.30 D for accommodation measures, a minimum of 14 subjects were required to find a statistically significant lens effect on the lag, with a two-sided alpha level of 0.01 and 90 % power (Lenth, 2006). Using the same alpha and power criteria (Lenth, 2006), a minimum of 8 subjects were needed for a statistically significant prism effect on the phoria (the assumed SD was 3 Δ). To allow for probable subject dropout and to increase the accuracy of graphical analysis, this study recruited 30 myopic children.

Subject characteristics and inclusion criteria
Chinese-Canadian children were recruited from an optometric practice in Ontario, Canada. The prevalence and degree of myopia in this group of children have been found to be comparable to that of Chinese children living in South East Asian countries (Cheng et al., 2007). These children visited the practice yearly for annual eye examinations, and they had to satisfy the inclusion criteria before enrolment into the study. Only myopic children (−1.00 to −5.00 D) with myopia progression equal to or greater than −0.50 D per year were recruited. The rationale for choosing only
young progressing myopes was that they were the group of myopes who would benefit the most from near-addition lens treatments. This inclusion criterion was also critical if the likely treatment effect of the near addition was to be later evaluated. Other inclusion criteria included: astigmatism and anisometropia less than 1.5 D; best corrected monocular visual acuity of at least 6/6 at distance and 0.4 M at near; stereoacuity of at least 40 sec of arc at 40 cm; non-strabismic; able to respond to subjective testing; no history of systemic or ocular diseases which have potential effects on refractive error; and single vision spectacles wear with no history of bifocal spectacles and contact lenses use. Once the child was determined to meet the inclusion criteria in the assessment, the examiner sought informed consent of the child and parent. Thirty children were initially recruited but one did not return for assessment. The twenty-nine myopic Chinese-Canadian children participated in the study were aged 8-13 years (mean: 10.3 ± 1.9 years) with a mean spherical equivalent refractive error of $-2.73 \pm 1.31$ D. Refraction was measured objectively using a non-cycloplegic auto-kerato-refractor (TOPCON KR7000, Topcon Corporation, Tokyo, USA) followed by non-cycloplegic subjective refraction at 6 m. The end-point chosen for the subjective refraction was maximum plus power for best visual acuity. Cycloplegia was not used in refraction because previous studies (Bannon, 1947; Rengstorff, 1966) had indicated that cycloplegic subjective refraction did not reveal less myopia for both low and high-level myopes than did non-cycloplegic subjective refraction. All children had their spectacle prescription upgraded to full correction about 1 week before the measurement. The mean near phoria through the distance correction was $-0.8 \pm 5.0$ Δ (exophoria), with 8 esophores ($\geq 2$ Δ eso), 9 exophores ($\geq 2$ Δ exo) and 12 orthophores (between 1 Δ eso and 1 Δ exo). The categorization of the near phoria as esophoric, exophoric or orthophoric followed that of the COMET study (Gwiazda et al., 2004).

The study followed the tenets of the Declaration of Helsinki and was reviewed and approved by the Queensland University of Technology, Human Research Ethics Committee. Verbal informed consent to participate was obtained from all children and written consent from the parents.
Refraction, accommodation and phoria measurements

The experiment was performed a minimum of one week after any new spectacles were dispensed. To simulate normal viewing conditions, the children’s distance refractive errors were corrected by trial frame and lenses during measurement. The frame was fitted with a pantoscopic tilt of about 10 degrees and with the lens adjusted to a back vertex distance of 12 mm. The accommodation viewing target was the numbers on the Howell-Dwyer near phoria card; a print size approximately 20/30. Accommodation responses were measured using the Shin-Nippon SRW-5000 open-field auto-refractor (Shin-Nippon, Tokyo, Japan). This instrument incorporates an infrared reflection mirror which allowed monocular measurement of the refractive state while the children viewed real targets under closed-loop binocular conditions. The Shin-Nippon auto-refractor has been shown to be reliable in measuring refraction in adults (Mallen et al., 2001) and in children (Chat and Edwards, 2001). The near horizontal phoria was measured using the Howell-Dwyer near phoria card (Cyclopean Designs, Melbourne, Australia). This phoria card has been shown to have greater repeatability in young adults than the von Graefe continuous presentation method (Wong et al., 2002).

Children were asked to keep the number “0” on the phoria card as clear as possible during testing. The instructions given to subjects in accommodation studies are very important as variation in instruction is known to affect the accommodation response (Stark and Atchison, 1994). The card distance was set at 33 cm and the mean luminance was 100 cd/m² measured by a luminance meter LS-100 (Konica Minolta Sensing Americas Inc., Ramsey, NJ, USA). The children were asked to view and read the numbers on the card before measurements to allow the accommodation response to stabilize. The accommodative state of the right eye was measured ten times, with the average values calculated by the auto-refractor, while the subject viewed the target binocularly. Anomalous auto-refractor readings characterized by large cylindrical error (>1.00 D) due to blinking and fixation loss were disregarded and the average was re-calculated manually. If more than three anomalous auto-refractor readings were found, the measurements would be repeated until a minimum of seven relevant readings were obtained by the auto-refractor. A 6 Δ base-down prism was then introduced in front of the left eye to dissociate the target for the measurement of horizontal phoria. The subject was asked whether two vertically
dissociated images were seen one above the other and to report the number in the lower image to which the arrow of the upper image was pointing. The direction (eso or exo) and the magnitude (to the nearest 0.5 Δ) of the heterophoria were recorded.

Both the accommodative state and horizontal phoria were measured for 15 combinations of positive-lens addition and base-in prism power. The positive-lens addition powers included binocular 0, +0.75, +1.50, +2.25, and +3.00 D were introduced in the form of trial lenses and the base-in prism powers included binocular 0, 1.5, and 3 Δ were introduced in the form of flippers and their effect randomly assessed by placing them over the child’s trial frame.

The accommodation and phoria data were analyzed graphically and the lens and prism powers that minimized both the accommodative errors and near phoria determined for each child. In deriving the magnitude of the accommodative lag, the effective power of the spectacles was determined according to the method and equations of Gwiazda et al. (1993). Even though the target was placed at the same distance for all children the accommodative demand will vary as a function of the power of the refractive correction. Factors such as distance correction, positive addition power and back vertex distance were taken into account in calculating the effective accommodative demand and response. The trial lens back vertex distance was adjusted to 12 mm in all subjects. Since the subjective refraction was performed at 6m, a corrective factor of −0.17 D was added to adjust the refraction value to infinity.

Effective accommodative demand (AD)

\[
\frac{1}{D} - (L + A) + Rx + B \times \frac{1}{D} \times (L + A - Rx) \\
\frac{1}{1 - B \times (L + A + Rx)}
\]

Accommodative response (AR)

\[
\frac{Rx}{1 - B \times Rx} - \frac{L + A}{1 - B \times (L + A)} - R
\]

Accommodative lag = AR−AD

85
D = distance from the corneal apex to the target (m), L = spherical equivalent of the lens (D), A = positive-lens addition power (D), B = back vertex distance of the lens to the corneal apex measured by a distometer (0.012 m), R = spherical equivalent measurement from the auto-refractor, Rx = subjective refraction at 6m minus 0.17 D (D) (convert to optical infinity).

Data analysis
The lag of accommodation and phoria were the two measured variables in this study. The experiment was designed to test these variables at 5 levels (0, +0.75, +1.50, +2.25, +3.00 D) of near-addition power and 3 levels (0, 3, 6 Δ) of base-in prism power. There were 29 independent replicates (subjects) of each of the 5×3=15 treatment combinations. To determine if there existed a treatment effect, the mean of the measured variables for the different treatment combinations was compared using the analysis of variances (ANOVA) in a randomized complete block (subject) design. A graphical analysis was conducted to study how the lag of accommodation and phoria varied with the change of near-addition power at three levels of base-in prism power. The kind of relationship and its strength were examined by regression and correlation analysis. The regression equation relating lag/phoria and the lens power was used to predict the lens/prism power that would give zero amount of lag/phoria.

Since increasing lens power would decrease the lag but increase the lens induced exophoria (see results), the lens power that produced zero lag would be different from the lens power that produced zero phoria. Thus this study also aimed to determine a lens power that could minimize both the lag and phoria (i.e. closest to zero) simultaneously. This could be achieved by coupling the accommodative error and the phoria by their amount of change per unit change of the lens power (details in Results).
Results

*The effect of positive-lens addition and base-in prism on the accommodation response*

Under normal viewing conditions through the distance prescription alone, i.e. at 0 D lens and 0 Δ prism powers, the average accommodative lag was $-0.96 \pm 0.67$ D (lag). A lag of accommodation was measured in twenty-eight children, and it varied in degree from $-0.41$ to $-2.37$ D. One child had a lead of accommodation of 1.14 D. The accommodation lag was not correlated with the refractive error ($r$-value = 0.02, $p = 0.91$) or age ($r$-value = 0.15, $p = 0.44$) of the subjects.

Viewing through positive lenses had a highly significant effect on the accommodation lag of the children irrespective of the power of the base-in prism ($F_{4, 400} = 223.14, p<0.001$). Positive lens power had a negative linear relationship with the lag giving an $r$-value of 0.56, 0.64 and 0.67 for 0, 3 and 6 Δ prism respectively ($p<0.001$). For the 0 Δ condition, the lag of accommodation decreased as the positive lens power increased until a lead was measured at +2.57 D (Figure 1). Based on regression analysis the lag decreased by an average 0.39 D per 1 D increase in positive-lens power. If individual data were evaluated, all subjects showed a similar trend in terms of changes in the accommodative error but differences in both the initial accommodative error and its rate of change amongst individuals led to a different zero-error point for the lens powers ($-2.7$ to +6.9 D).

The relationship of the zero-error lens powers for each individual and their initial accommodative errors were also evaluated by regression analysis (Figure 2) to determine if there existed a robust correlation as proposed by a previous study (Rosenfield and Carrel, 2001). The initial accommodative error was found to have a poor correlation ($r=0.32$ and $p=0.09$) with the zero-error lens power and therefore was not a strong predictor of the positive-lens power required to eliminate the accommodation error for a given individual.

For 3 and 6 Δ conditions the lag became a lead when the near-addition was +2.73 and +2.96 D respectively as shown in Figure 1. The addition of base-in prism to the viewing conditions significantly altered the accommodative lag for all tested positive lens powers ($F_{2, 400} = 24.02, p<0.001$). For the 0 D condition (i.e. viewing through
Figure 1. Lag of accommodation (D) with standard error for different near-addition power. Regression lines and their linear equations are included for comparison. Lag of accommodation decreased as the lens power increased until a lead was measured (~+2.50 D for 0 Δ).

Figure 2. Correlation between the required near-addition power (D) to give zero accommodative error and the initial accommodative error (D). Minus values indicated a lag and plus values a lead. The correlation was weak with r-value of 0.32 and p-value of 0.09.
just the distance prescription), the 6 ∆ base-in prism shifted the lag of accommodation from 0.96 D to 1.39 D. Base-in prism always increased the lag; by an average 0.061 D per 1 ∆ increase in base-in prism power for 0 D and by an average 0.031 D per 1 ∆ increase in base-in prism for +2.50 D. When individual data were evaluated, there were 8 children (28 % of the sample) who did not show this increase in lag with base-in prism as found for the group data. Instead, the base-in prism had only a small effect on the lag and sometimes increased the lag for some lens powers (one example is provided in Figure 3), implying that the average effect of base-in prism should not be generalized to all individuals.

![Graph showing lag of accommodation with different near-addition power at three levels of base-in prism power.](https://example.com/graph.png)

**Figure 3.** Lag of accommodation (D) with different near-addition power (D) at three levels of base-in prism power. This was one example of the 8 individuals whose trend of changes at 0, 3, and 6 ∆ base-in prism was not clear cut and sometimes the lag was greater with lower base-in prism power.

*The effect of positive-lens addition and base-in prism on near horizontal phoria*

Under normal viewing conditions through the distance prescription alone, i.e. at 0 D lens power and 0 ∆ prism power, the average near phoria was −0.8 ± 5.0 ∆ (exophoria). There were 8 esophores (≥2 ∆ eso), 9 exophores (≥2 ∆ exo) and 12 orthophores (between 1 ∆ eso and 1 ∆ exo) in the group. The phoria was not
correlated with the refractive error (r-value = 0.30, p = 0.11) or age (r-value = 0.01, p = 0.95) of the subjects.

Positive lenses significantly shifted the phoria in the exophoric direction for all prism conditions ($F_{4, 400} = 252.21, p<0.001$). The greatest exophoric shift, $-9.1\pm4.1\Delta$, was measured for the +3.00 D and 0 $\Delta$ condition (Figure 4). Lens power was positively correlated with the phoria giving an r-value of 0.54, 0.51 and 0.51 for 0, 3 and 6 $\Delta$ prism respectively ($p<0.001$). Based on regression analysis, for the 0 $\Delta$ prism condition the exophoria increased by an average 2.72 $\Delta$ per 1 D increase in positive-

![Figure 4](image)

**Figure 4.** Phoria ($\Delta$) with standard error for different near-addition power (D). Regression lines and their linear equations are included for comparison. The phoria became more exophoric as the lens power increased (e.g. up to $-9.1\pm4.1\Delta$ with +3 D and 0 $\Delta$). A 6 $\Delta$ base-in prism totally controlled the exophoria induced by a +1.50 D addition ($-0.3\pm5.0\Delta$), but the accommodative lag was still considerable ($-0.69\pm0.54$ D) (in Figure 1).

lens power. Base-in prism significantly altered the phoria for all positive-lens power conditions ($F_{2, 400} = 200.27, p<0.001$). For the 0 D and 3 D positive-lens power condition, the exophoria decreased by 0.78 and 0.73 $\Delta$ per 1 $\Delta$ increase in base-in prism power respectively. A 3 $\Delta$ base-in prism totally controlled the exophoria
induced by a +0.75 D addition (−0.3±5.0 ∆) and a 6 ∆ base-in was appropriate for a +1.50 D addition (−0.3±4.3 ∆) (Figure 4). With the +0.75 D/3 ∆ combo, 16 children were orthophoric (between 1 ∆ eso and 1 ∆ exo) and with the +1.50 D/6∆ combo, slightly fewer children, 14 children, were orthophoric. However, the accommodation lag measured with the +1.50 D/6 ∆ combination was lower than that of the +0.75 D/3 ∆ combination (-0.69±0.54 D vs -0.86±0.53 D) (Figure 1).

*The combination of lens and prism power that minimized the accommodative lag and phoria*

Figures 1 and 4 showed that the positive-lens addition and the base-in prism had opposing effects on the lag of accommodation and phoria. The positive-lens addition decreased the lag but introduced a large increase in exophoria. The base-in prism decreased this lens-induced exophoria but increased the lag. The opposing effects of positive lenses and base-in prism led to the question of what the optimal combination of lens and prism power to minimize both the lag and the exophoria in the majority of children was. This optimal combination was determined by coupling the lag and phoria data presented in Figures 1 and 4. The method was similar to the evaluation of the response AC/A ratio in which the amount of change of both the lag (A) and phoria (AC) per unit change of lens power was derived from the slope of the regression equation. In Figures 1 and 4, (A) was 0.39 D/D and (AC) was −2.72 ∆/D derived from the slope of the regression equation for 0 ∆. The response AC/A ratio was therefore 7 (i.e. 2.72/0.39). Based on this ratio, the lag (in the primary vertical axis) and the phoria (in the secondary vertical axis) were then plotted against the lens power (Figure 5). The scale on the primary and the secondary vertical axis was set to a ratio equal to that of the response AC/A ratio such that for any chosen lens power, the accommodative lag would always be linked to the phoria by a ratio of 7. This final graph would include both the accommodation regression line (−ve sloped) and the phoria regression line (+ve sloped) forming an X-pattern plot. The significance of this plot was that the point where the two regression lines intersected was the lens power at which the lag and phoria were simultaneously closest to zero.
Figure 5. Lag of accommodation (D) and phoria (Δ) interaction. The lag and phoria data in Figure 1 and Figure 4 were combined for interaction analysis. By using the values of the slope in the regression lines, the phoria was found to change 7Δ per 1 D change in the lag for the 0 Δ as shown in the linkage. The points of significance were where the accommodation lines and phoria lines intersected (marked with circle) which indicated the optimal positive-addition power for the base-in prism power chosen. The best combination is the near-addition of +2.25 D with a 6 Δ base-in prism which minimized both the lag and lens induced exophoria the most (−0.33 D and −2.4 Δ).

Figure 5 showed the three points where the accommodation regression lines and the phoria regression lines intersected (marked with circle), indicating the optimal positive-lens addition power for the three levels of base-in prism power. For the 0Δ, this occurred at +1.125 D add, for the 3 Δ, it was at +1.675 D and for the 6 Δ, it was at +2.25 D. If the optimal lens and prism power values were put into the regression equations, the lag and exophoria were −0.56 D and −3.8 Δ, −0.46 D and −2.9 Δ, and −0.33 D and −2.4 Δ for the 0, 3, 6 Δ respectively. The optimal combination determined from these values was +2.25 D lens with a 6 Δ base-in prism which minimized both the lag and lens-induced exophoria the most. This lens-prism combination decreased the positive-lens induced exophoria by 4.5 Δ compared to a +2.25 D lens alone (2. 4 Δ vs −6.9 Δ from regression equation). The number of
subjects who would benefit from the +2.25 D addition and 6 Δ base-in prism combination was further analyzed by examining the lag and phoria data. This lens-prism combination was effective in reducing the lag for 27 out of 29 children (93%). For the two children with increased lag, one had a habitual lead of accommodation, and one had a large esophoria (7 Δ eso). This combination also improved or maintained the near phoria in 24 out of 29 children (83%) (<2 Δ exo increase or phoria stayed between 3 Δ exo and 1 Δ eso). All esophoric children had less eso-deviation and 2 exophores and 3 orthophores had greater near exophoria.

If this method of analysis was to apply to each individual, there was a large variation in the final optimal lens and prism combination (Figure 6). Some individuals had

![Figure 6](image_url)

**Figure 6.** The optimal near-addition power (D) and base-in prism power (Δ) combinations for all individuals. The range of required near-addition lens power showed large variability for the three levels of prism power and there was no single lens and prism combo that would suit all individuals.

more than one optimal lens-prism combination because of the equal amounts of lag at different levels of prism power. There were three individuals (one with a lead and
two with large exophoria) removed from the analysis because their regression lines did not intersect within the measured lens power range. The average optimal lens and prism combination for the remaining 26 individuals was $+2.13\pm0.61$ D and $3.98\pm1.94$ $\Delta$. This optimal combination was similar to the $+2.25$ D lens and $6$ $\Delta$ base-in prism combination found in the group as a whole.

**Discussion**

The data here clearly show that positive lenses at near while reducing lags of accommodation also result in large exophoric shifts, and that base-in prism can limit the degree of the induced exophoria. Thus an interpretation of this study is that prescribing base-in prism at near, along with the positive-lens addition, should result in a more comfortable binocular vision posture in young progressing myopes when plus at near is used to try to control the myopia progression. Issues related to prescribing positive-lens addition and base-in prism to young progressing myopes are discussed.

**Magnitude of the lag of accommodation for the myopic group**

In this study, the average lag of accommodation measured in the myopic children was $0.96$ D for a target at $33$ cm. However, a large variability in the measured lag of accommodation has been reported in previous studies. The average lag of accommodation for a natural $3$ D target has been found to range from $0.1$ D (myopic adults, Canon R1 autorefractor: Abbott et al., 1998), $0.16$ D (myopic adults, Grand Seiko autorefractor: Nakatsuka et al., 2003), $0.16$ D (myopic adults, Canon R1 autorefractor: McBrien and Millodot, 1986), $0.23$ D (emmetropic adults, PowerRefractor: Seidemann and Schaeffel, 2003), $1.00$ D (myopic children, Canon R1 autorefractor: Gwiazda et al., 1993), $1.25$ D (myopic children, Canon R1 autorefractor: Gwiazda et al., 1999) and $1.4$ D (myopic children, Canon R1 autorefractor: Gwiazda et al., 2005). Factors such as type of refractor, monocular or binocular viewing, refractive errors and age of the subjects are presumably responsible for the variability (Seidemann and Schaeffel, 2003). Even given this variability, in general, it appears that myopic children have a greater lag of accommodation. The average lag of $0.96$ D found in the young progressing myopes is comparable to that reported in studies using myopic children as subjects (average lag range of $1$ to $1.4$ D).
The effect of positive-lens addition on the lag of accommodation

This study also shows that the positive-lens addition decreases the accommodative lag of myopic children until on average a lead is seen with a lens power of approximately +2.5 D. Many previous studies have sought to determine the effect of single vision reading glasses on the accommodative state. Seidemann and Schaeffel (2000) used the PowerRefractor to study the effect of +1 D and +2 D reading glasses on accommodation errors for 3 D, 4 D and 5 D reading demands, accommodation errors were least when the +2 D lenses were worn. However, a later study by the same authors reported that +2 D lenses produced a significant lead of accommodation (Seidemann and Schaeffel, 2003). In another study using the technique of stigmatoscopy to evaluate a wider range of positive lenses (0, +0.75, +1.50, +2.00, and +2.50 D) for a 2.5 D demand, Rosenfield and Carrel (2001) reported that a positive-lens addition did not always produce a clearer retinal image, and in fact might actually increase the magnitude of the accommodation error. The authors suggested that the near-addition power must be determined for each individual on the basis of the initial accommodation error. However, our study on the relationship between the optimum lens power and the initial accommodation error did not show a particularly strong correlation (r=0.32 and p=0.09) between the two variables implying that the initial accommodation error was not a good predictor of the final optimum lens power in these subjects. Differences in subject characteristics (young progressing myopes here vs young adults with mixed refractive errors in Rosenfield and Carrel, 2001) and the methodology (autorefractor here vs stigmatoscopy in Rosenfield and Carrel, 2001) could partly explain the different findings. Further variability of the effect of positive lenses is shown in the study of Shapiro et al. (2005). Using the PowerRefractor they found that subjects binocularly over-accommodated by approximately 0.9 D (45%) of the power of a +2 D lens and 1.12 D (37%) of the power of a +3 D lens at 33 cm. In a more recent study of Jiang et al. (2007), young adults were found to over-accommodate 0.22 D (11%) with +2.00 D lenses under binocular viewing conditions at 40 cm. It is apparent from this collection of data that the accommodation response to a positive-lens addition shows large variability amongst individuals and should be measured before bifocal or progressive lenses are prescribed in a myopia control study. In comparison to the results of previous studies, the +2.50 D lens power required in this study to reduce the accommodation error to zero seems high, however this may be due to the age and
refractive errors of the subjects in the sample, i.e. young progressing myopes. In addition to the factors associated with different measurement methods, previous studies (Seidemann and Schaeffel, 2000; Rosenfield and Carrel, 2001; Seidemann and Schaeffel, 2003; Shapiro et al. 2005; Jiang et al., 2007) mainly recruited young adults in their twenties and thirties and some also include both emmetropes and myopes as subjects. Young adults especially those with emmetropia usually have more accurate accommodation responses (McBrien and Millodot, 1986; Abbott et al., 1998; Gwiazda et al., 1993; Gwiazda et al., 1995; He et al., 2005;) and therefore would require less plus power to eliminate these low errors than that of myopic children with higher accommodation errors. The higher accommodative controller gain value (ACG) and higher CA/C ratio in children found in the accommodation and vergence interactive model (Bobier, 1999) also indicates that the oculomotor characteristics of children are different from those of adults, and therefore the lower optimum plus lens power values determined for adults should not be directly applied to children with progressing myopia.

The effect of positive-lens addition on near horizontal phoria
The average phoria of the myopic children in this study is 0.8 Δ exophoria which is within the range of 1.0 Δ eso and 2.3 Δ exo reported in previous studies (Drobe and de Saint-André, 1995; Goss, 1991; Goss and Jackson, 1986). The positive-lens addition increased the average exophoria to 6 Δ when the power reached +2 D and 9 Δ for +3 D. An exophoric shift of 4.2 Δ with +2 D lens for a target at 33 cm (Sreenivasan et al., 2006) and 5.8 Δ with +2 D for a target at 40 cm (Jiang et al., 2007) have been reported previously, though the latter study used young adults as subjects. Under closed loop binocular viewing conditions, a positive-lens addition relaxes accommodation which in turn reduces the accommodative convergence, shifting the phoria to a more divergent position (relatively more exophoric). This creates a higher demand on positive fusional vergence (Goss, 1986), shifting the tonic vergence in the direction of increased fusional demands. The resultant increase in adaptable tonic vergence will lead to an esophoric shift, a risk factor linked to myopia progression (Goss and Zhai, 1994; Jiang, 1995). Vergence adaptation has been shown to reduce +2 D lens-induced exophoria and the associated convergence accommodation (Sreenivasan et al., 2006). Therefore a high near-addition power may reduce accommodative error more but it may also lead to oculomotor imbalance.
resulting in eyestrain (Goss, 1986). Since myopic children also have a higher AC/A ratio (Jiang, 1995; Rosenfield and Gilmartin, 1987a; Gwiazda et al., 1999), the lens-induced exophoria could be significant with a high add power especially for children with near exophoria (Jiang et al., 2006; Jiang et al., 2007). A refractive error development model also demonstrates that high add power under binocular viewing conditions can lead to a conflict in the accommodation and vergence stimuli demands and interactive-based changes in the system’s steady state level (Hung and Ciuffreda, 2000). In a recent study, lower add powers in the range of +0.20 D to +1.28 D were shown to create the least error in accommodation and vergence responses (Jiang et al., 2006). However, in children with esophoria high add powers not only reduce the accommodation errors but also the demand on negative fusional vergence, enhancing oculomotor balance (Jiang et al., 2007). This may partly explain why myopic children with esophoria benefit more from the bifocal or progressive lens corrections (Goss, 1986; Goss and Grosvenor, 1990; Fulk et al., 2000; Gwiazda et al., 2003). Therefore, in prescribing near-addition to control myopia in children, not only is the residual accommodative error with the near-addition important, the lens-induced phoria change also is likely to have a role in affecting myopia control. It is probable that the uncontrolled phoria state of the subjects is one of the underlying causes of the conflicting outcomes in previous myopia control studies.

The effect of the incorporation of base-in prism on lens-induced exophoria and the lag of accommodation

The incorporation of base-in prism into the positive lens addition reduces the lens-induced exophoria but it also increases the lag of accommodation. The lag increased by an average 0.061 D per 1 Δ increase of base-in prism power for an addition power of 0 D. The accommodation change induced by the introduction of base-in prism measured under closed-loop conditions as in this study is referred to as disparity-induced accommodation and is driven by retinal blur and disparity feedback (Rosenfield and Gilmartin, 1987b; Ciuffreda, 1992). In a study of disparity-induced accommodation as a function of refractive group for a 3.25 D accommodation and 4 Δ base-out disparity stimulus, the disparity-induced accommodation was found to average 0.065 D/Δ for both early- and late-onset myopes (Rosenfield and Gilmartin, 1987b). In a later study, for a target demand of 3 D with 3 and 6 Δ base-out prism, the disparity-induced accommodation for late-onset myopes was 0.25 D (0.083 D/Δ)
and 0.34 D (0.057 D/Δ) respectively (Rosenfield and Gilmartin, 1988), these relationships are comparable to that of the present study. The small change in disparity-induced accommodation induced by the prism in all of these studies implies that base-in prism can be safely prescribed without much detrimental effect on the lag.

In addition to reducing lens-induced exophoria, base-in prism also decreases the amount of convergence required at near. Convergence during near tasks has been suggested to be associated with the development of myopia, although this association may be controversial (review in Ong and Ciuffreda, 1997). Early researchers suggested that the pull of the extraocular muscles imposed mechanical stress on the globe and the related increase in vitreous pressure during near work would cause the sclera to stretch and lead to myopia (Luedde, 1932; Greene, 1980). However, the relatively small changes in vitreous pressure (<2 mm Hg) are believed to be insufficient to produce axial elongation (Ong and Ciuffreda, 1997). Moreover, the increase in intraocular pressure found in myopes has been shown in a longitudinal study to occur following the onset of myopia and cannot be the cause of myopia (Edwards and Brown, 1996). Although the effect of convergence on myopia could be small and its exact mechanism on myopia has yet to be established, base-in prism may be beneficial for the purpose of reducing positive lens-induced exophoria.

The optimal lens and prism power combination that minimized both the lag of accommodation and lens-induced exophoria

Determination of the best lens and prism power for the subjects was complicated by the opposing effect of the positive-lens addition and the base-in prism on the accommodation error and phoria. Higher addition powers decrease the lag more but introduce a greater increase in exophoria and higher base-in prism powers decrease this lens-induced exophoria but increase the lag. The graphical method in Figure 5 is a means of combining these two variables to analyze them concurrently. The intersection of the accommodation and phoria regression lines in the graph show the best combination of lens and prism power at which the accommodative error and exophoria are both minimized. When base-in prism is not included in the addition (i.e. 0 Δ prism), +1.125 D is the best lens power, and this is within the best addition power range of +0.20 D and +1.28 D for a target at 33 cm found in a recent study.
using young adults as subjects (Jiang et al., 2006). For the group of children studied, a lens power of +2.25 D with a 6 Δ base-in prism minimizes both the lag and lens-induced exophoria the most (~0.33 D and ~2.4 Δ). To further reduce the lag and exophoria, a higher addition power and base-in prism power are required as found by extrapolation of the graph. However, prism powers of 4 Δ (in each eye) or more are not recommended because the transverse chromatic aberration of prism (especially with polycarbonate lens materials) becomes significant in reducing visual acuity (Hampton et al., 1991).

To test for robustness of the current method, the number of children whose accommodation and phoria benefited from the +2.25 D and 6 Δ base-in prism combination was analyzed. Although the majority of the studied children had reduced lag (93%) and better oculomotor balance (83%) with this form of near correction, a few children did not benefit from the positive addition and/or the incorporation of prism. Therefore it is recommended that the lag and phoria be measured with different positive-lens additions and base-in prism powers so that the near prescription can be customized for individual myopic child. The large variability in the optimal lens and prism combinations found for individuals also demonstrated the need to customize the near prescription.

**Conclusions and future work**

The incorporation of near base-in prism when prescribing bifocal lenses may help to reduce oculomotor imbalance for young progressing myopes with positive-lens induced exophoria. The lens combination of +2.25 D with 6 Δ base-in prism had the greatest beneficial effect on the accommodation error and phoria for the majority of children in this study. Future work will aim to study whether the effect of this positive-lens addition and base-in prism combination will be maintained during wear, for example the visual system of young progressing myopes could adapt to the lens and prism over time and the beneficial effect of the lens on the accommodation and oculomotor systems may reduce.
Acknowledgments
The authors thank Ernest Tang for assistance in the experiment. This work was presented at the 11th International Myopia Conference, Singapore, 16-18 August 2006.

References


Goss, D. A. (1991) Clinical accommodation and heterophoria findings preceding
bifocals as a function of nearpoint phoria: consistency of three studies. Optom.
Vis. Sci. 67, 637-640.
Goss, D. A. and Jackson, T. W. (1986) Clinical findings before the onset of myopia
relationship of accommodation and convergence function with refractive error. A
Greene, P. R. (1980) Mechanical considerations in myopia: relative effects of
Press, Chicago, ILL, USA, pp. 55.
Myopia control Study: A randomized clinical trial. Part II. Final report by the
convergence, and response AC/A ratios before and at the onset of myopia in
between myopia and blur-driven accommodation in school-aged children. Vision
Res. 35, 1299-1304.
Gwiazda, J., Grice, K. and Thorn, F. (1999) Response AC/A ratios are elevated in
Gwiazda, J., Hyman, L., Hussein, M., Everett, D., Norton, T. T., Kutz, D., Leske, M.
A randomized Clinical trial of progressive addition lenses versus single vision


Chapter 4: A Randomized Trial of Bifocal and Prismatic Bifocal Spectacles on Myopia Progression: Results After 24 Months

Desmond Cheng, Katrina L. Schmid, George C. Woo and Björn Drobe
(Submitted for publication)

INTRODUCTION

Myopia is a common refractive problem, particularly in South East Asia where reported prevalence values in children, by the age of 12, can be as high as 50 to 60%.\(^1\text{–}^4\) Myopia prevalence is also high amongst Asian children living in Western countries.\(^5\) There have been a number of well-designed prospective studies completed to investigate the effect of positive lenses, in bifocal or multifocal form, on myopia progression in children.\(^6\text{–}^{14}\) However, bifocals and multifocals have proven to be relatively ineffective myopia control treatments in children.\(^15\text{,}16\) Of the many of these myopia control studies, it is clear that the study of Leung & Brown\(^9\) showed the greatest treatment effect (multifocals: myopia control \(-0.47\text{D/2yr}\)). The high prevalence of myopic subjects in Hong Kong permitted this study to recruit only myopic children with a high myopia progression rate (>\(0.4\text{D/yr}\)). A later multifocal study conducted in Hong Kong,\(^11\) not using myopia progression rate as a selection criteria failed to replicate the results (multifocals: myopia control \(-0.14\text{D/2yr}\), no significant treatment effect). Thus myopia progression rate appears to be an important factor in the determination of multifocal lens treatment effect in children.

Characteristics of the near phoria position, have also been reported in a retrospective study to influence the degree of myopia inhibition observed with bifocal lens wear.\(^17\) Children with near esphoria have been found to benefit more from bifocal lens wear than children with other phoria types.\(^17\) This finding is later supported by prospective studies.\(^10\text{,}14\) However, other studies\(^8\text{,}11\text{,}12\text{,}18\text{,}19\) have been unable to demonstrate such an effect. Even so, since myopic children have been found to have high response AC/A ratios,\(^20\) children with orthophoria and exophoria wearing positive lenses will have a significant exophoric shift resulting in a higher demand for positive fusional vergence.\(^21\text{,}22\) The disrupted oculomotor equilibrium has been proposed to reduce the positive-lens treatment effect as advocated by the oculomotor interactive theory.\(^16\) Following on from this proposal, it has been shown that incorporating near base-in
prism when prescribing near additions for myopic children can reduce the positive-lens induced exophoria in children.\textsuperscript{21} However, there have been no reports in the literature of a prospective clinical trial to evaluate this potential treatment option in myopia.

The purpose of this study was to determine whether bifocal spectacles compared with single vision spectacles could control myopia in children with high rates of myopia progression ($\geq 0.5$D in the preceding year) and to investigate the effect of incorporating near base-in prisms along with the near-addition lenses (prismatic bifocal spectacles) on myopia progression. This paper presents the outcome measurements of cycloplegic auto-refraction and ocular components after 24 months of lens wear and data collection of a 36 month (3 year) randomized clinical trial.

**METHODS**

**CONDUCT OF THE STUDY**

Myopic children were recruited to the study and randomly assigned to one of three treatment groups: (i) single vision distance lenses (SVL), (ii) bifocal lens with $+1.50$D near addition (BFL), (iii) prismatic bifocal with $+1.50$D and $3\Delta$ base-in prism in the near segment (PBFL). Verbal informed consent to participate was obtained from all children and written consent from the parents. The study followed the tenets of the Declaration of Helsinki and was reviewed and approved by the Queensland University of Technology, Human Research Ethics Committee.

**STUDY POPULATION**

Chinese-Canadian children were recruited from an optometric practice in Mississauga, Ontario, Canada. The prevalence and degree of myopia in this group of children have been found to be comparable to that of Chinese children living in South East Asian countries.\textsuperscript{5} Clinical records were selected for children who had their eyes examined in the last 9 to 18 months. Only myopic children ($\geq 1.00$D of myopia) with myopia progression equal to or greater than 0.50D in the preceding year were recruited. Myopia progression at the time of recruitment was determined by analysis of the refractive change (non-cycloplegic subjective refraction) reported in previous clinic records over the preceding 9 to 18 months. A summary of the inclusion criteria is shown in Table 1.
Table 1. Inclusion Criteria for Children Recruited to This Study

<table>
<thead>
<tr>
<th>Participant Inclusion Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age: 8 to 13 years</td>
</tr>
<tr>
<td>Myopia: −1.00 to −5.50 D</td>
</tr>
<tr>
<td>Myopia progression: ≥0.50 D in preceding year</td>
</tr>
<tr>
<td>Astigmatism and anisometropia: ≤ 1.50 D</td>
</tr>
<tr>
<td>Distance monocular visual acuity: 6/6 or better</td>
</tr>
<tr>
<td>Near monocular visual acuity: 0.4 M or better</td>
</tr>
<tr>
<td>Stereoacuity: ≤ 40 sec of arc at 40 cm</td>
</tr>
<tr>
<td>No strabismus</td>
</tr>
<tr>
<td>Able to respond to subjective testing</td>
</tr>
<tr>
<td>No history of systemic or ocular diseases</td>
</tr>
<tr>
<td>Single vision distance spectacle lens wear</td>
</tr>
<tr>
<td>No history of bifocal lens wear and/or contact lens use</td>
</tr>
<tr>
<td>Consent of the child and parent to participate in the study</td>
</tr>
</tbody>
</table>

RANDOMIZATION

Children were primarily selected by review of their clinic records (n=200) and were recruited through letters addressed to their parents. Other children were recruited through the public media (n=29, e.g. via a poster in the optometric practice) or during regular eye examinations (n=27). Children that appeared to meet the inclusion criteria for eligibility (Table 1) underwent an ocular assessment to determine final eligibility.

Randomization was implemented by putting the file numbers of the subjects on paper slips and by drawing the paper slips from a container at random (conducted by the first author). The first 50 subjects’ file numbers drawn were assigned to the control group; the second 50 numbers drawn were assigned to the bifocal group and so forth.

OUTCOME VARIABLES

The primary outcome variable was myopia progression which was the difference between the mean cycloplegic spherical equivalent measured by an automated refractor at the baseline visit and subsequent 6-monthly visits for 24 months. The secondary outcome variable was eye growth which was the difference between mean axial lengths measured by ultrasonography at the baseline visit and subsequent 6-monthly visits for 24 months. Both autorefraction and ultrasonography were performed by the examiner. Only the data of the right eye were used.
**MASKING**

The subjects and the investigator were aware of the treatment assignments. It has been reported that whether subjects are masked or unmasked as to their treatment allocation does not affect the outcome of this type of study.\(^\text{23}\) The primary and secondary outcome variables were measured by objective methods to minimize possible bias of the unmasked investigator (the first author).

**PROTOCOL DESIGN**

At the preliminary visit, a comprehensive oculo-visual assessment was conducted to measure baseline readings and to ensure eligibility. After eligibility was determined, the examiner discussed with the parent and child exactly what participation in the study involved, emphasizing the requirement of a willingness to wear either bifocal or single vision spectacles for the duration of the study and attend 6-monthly for ocular examinations. Children were re-examined at 6-monthly intervals for the 24 months period, making five examinations conducted to date. These visits were denoted baseline (1), 2, 3, 4 and 5. These visits included cycloplegic autorefraction, cycloplegic subjective refraction and ultrasonography. A questionnaire (Appendix) was administered to the child and parents to determine if the child used the spectacles correctly. Subjects were instructed at each visit on the proper use of the bifocal lens. The distance prescription was upgraded if the equivalent sphere of the subjective refraction changed by 0.50D or more in either eye.

Cycloplegic auto-refraction (average of 5 measurements using Topcon KP7000, Tokyo, Japan) and cycloplegic subjective refraction (for determination of the distance prescription for the spectacles) were determined 30min after instillation of 2 drops of cyclopentolate (Cyclogyl 1%) with 5min between instillations. The axial length of the eyes was then measured with A-scan ultrasonography (average of 10 measurements, Quantel Medical Axis II PR, Montana. USA) following topical anaesthesia with 1 drop of proparacaine (Alcaine 0.5%). Both instruments were calibrated with the manufacturers’ test eyes to check for precision on a weekly basis and they were found to be accurate throughout the course of the study.

Accommodation responses were measured using the Shin-Nippon SRW-5000 open-field auto-refractor (Shin-Nippon, Tokyo, Japan). The viewing target was the
numbers on the Howell-Dwyer near phoria card at 33cm (~3D accommodation demand); a print size of approximately 20/30. The near horizontal phoria was measured using the Howell-Dwyer near phoria card (Cyclopean Designs, Melbourne, Australia). The direction (eso or exo) and the magnitude (to the nearest 0.5Δ) of the heterophoria were recorded. The mean luminance of the accommodation target was 100cd/m² (Luminance meter LS-100, Konica Minolta Sensing Americas Inc., New Jersey, USA). Both accommodation and phoria measurements were performed a minimum of one week after any new spectacles were dispensed.

**INTERVENTION**

The bifocal used in this trial was a custom-made polycarbonate executive bifocal with a front base curve of +3.25D supplied by Essilor, Etobicoke, Canada. The single vision lens was also made from polycarbonate and manufactured with the same front base curve as the bifocal lenses. There were two bifocal lens designs: (i) an executive bifocal with near-addition power of +1.50D, and (ii) an executive bifocal with near-addition power of +1.50D and 3Δ base-in prism in the reading segment of each lens (6Δ in total). The bifocal segment height was set 2mm above the lower limbus to increase the likelihood that subjects used the near segment of the lens for near vision. The powers of near addition and prism chosen were based on a previous study in Chinese-Canadian children. The +1.50D near-addition power was chosen as it reduced the accommodation lag but did not induce a large amount of near exophoria in the standard bifocal group. The addition of 6Δ base-in prism to the near segment reduced the lens-induced exophoria to close to zero in the prismatic bifocal group.

**AUXILIARY DATA**

Parents and/or guardians also completed a questionnaire regarding the child’s vision habits and birth parents’ refractive errors (Appendix). The most recent refractive error measurement of the parents was obtained from the clinical records (n=263 parents). If the parent had seen other optometrists or ophthalmologists, the refractive error was obtained by neutralizing their spectacles on the lensometer (n=5 parents) or by performing auto-refraction with Topcon KR7000 (n=2 parents). Questions regarding how much time the children spent reading and how much time they spent outdoors were included.
STATISTICAL ANALYSIS

Sample size estimation is dependent on the expected difference between the means and the within-group variability of individual measurements (standard deviation). Based on published data on the effect of multifocals on myopia progression in fast progressing myopes, the following calculation was performed. The expected increase in myopia was 1.88D over a 3-year period and a statistically significant myopia control treatment effect was considered to be a slowing of progression by half, i.e. a difference of 0.94D. Assuming a standard deviation of 0.75D for the refractive error change, the number of subjects that would give a 95% chance of finding a statistically significant difference between two sample means, at a two-sided 0.01 alpha level test of significance, was 28. To allow for probable subject dropout (~14% in Leung and Brown, ~15% in Edwards et al.), the study aimed to recruit 50 children per treatment group.

To test for balance of the randomized assignment of subjects, the baseline characteristics (age, gender, degree of myopia, axial length, initial myopia progression, near phoria, lag of accommodation, total near work and total outdoor activities performed, and number of myopic parents) of the children in the single vision and the two bifocal groups were compared by the analysis of variances (ANOVA) for continuous variables and the Chi² test for categorical variables. The analysis of the data followed the intention to treat approach and the method to deal with subject lost to follow up was to use the last progression information (i.e. carry forward). The effect of the treatment was assessed by the ANOVA after adjusting for baseline characteristics as covariates. These covariates were further tested in separate interaction models for any differential effect of the bifocal treatment.

RESULTS

SUBJECT CHARACTERISTICS

One hundred and fifty children were recruited and randomized to the single vision control group (n=50), bifocal group (n=50) and prismatic bifocal group (n=50) (Figure 1). Nine children in the control group did not receive allocation because the parents were disappointed that their child was not assigned to a bifocal group. However, six of these nine children, which were not officially in the study, were still
**Figure 1.** Flow diagram for randomization, assignment, follow up and analysis of participants.

**Assessed for eligibility**
(n=256)

**Enrolment**

**Randomized**
(n=150)

**Children excluded**
(n=106)
- Did not meet inclusion criteria (n=58)
- Declined participation (n=48)

**Single vision**
Allocated (n=50)
- Received allocation (n=41)
- Declined single vision allocation (n=9)

**Bifocal**
Allocated (n=50)
- Received allocation (n=48)
- Excluded due to cycloplegic agent (n=2)

**Prismatic bifocal**
Allocated (n=50)
- Received allocation (n=46)
- Excluded due to cycloplegic agent (n=4)

**Lost to follow-up**
(n=3)
- Relocated (n=2)
-Commenced orthokeratology (n=1)

**Lost to follow-up**
(n=0)

**Lost to follow-up**
(n=1)
- Commenced orthokeratology (n=1)

**Analyzed**
(n=41)
- 5 measurement points (n=38)
- 3 measurement points and carry forward (n=3)

**Analyzed**
(n=48)
- 5 measurement points (n=48)

**Analyzed**
(n=46)
- 5 measurement points (n=45)
- 4 measurement points and carry forward (n=1)
examined annually in the practice. These six children had an average (mean±SE) initial myopia of \(-3.27±0.67\)D and average 24-month myopia progression of \(-1.83±0.21\)D. Two children in the bifocal group and four in the prismatic bifocal group did not receive the allocation because of the anterior eye stinging and blurred vision they experienced following cycloplegia. The 24 months follow-up period was completed by 38 of the 41 children in the control single vision lens group, all 48 children in the bifocal group and 45 of the 46 children in the prismatic bifocal group. Of the 4 children who did not complete the wearer trial, two relocated with their families to other areas, and two commenced orthokeratology treatment. For those children who completed the study, data from the questionnaire indicated that all children wore the spectacles full time during waking hours. All children in the bifocal groups reported that they were able to use the positive-lens addition for near work. No children mentioned any difficulties in adapting to any of the lens designs. Two children who wore the standard bifocals complained about the appearance of the spectacles but both of these children decided to complete the trial. The total number of prescription (spectacles) upgraded for the 24-month period was 58 for SVL, 44 for BFL and 35 for PBFL.

Baseline characteristics of children in the three treatment groups were similar but axial length and lag of accommodation varied with group; children in the single vision group had slightly shorter axial lengths and lower lags of accommodation (Table 2). Whether the difference in baseline axial length and lag of accommodation had an effect on the bifocal treatment was evaluated by the analysis of covariance model.

**OUTCOMES**

The average increase (mean±SE) in myopia across the 24 month period was \(-1.55±0.12\)D, \(-0.96±0.09\)D and \(-0.70±0.10\)D for the SVL, BFL and PBFL respectively (Figure 2). There was a significant effect of lens design on the degree of myopia progression (ANOVA p<0.001). Compared to the SVL, the magnitude of myopia progression was\(-0.59\)D less (p<0.001) and \(-0.85\)D less (p<0.001) with the BFL and PBFL respectively. Myopia progression over the 24 months was \(-0.26\)D less with the PBFL compared to BFL, and this difference was statistically significant.
### Table 2. Baseline Characteristics of The Myopic Children by Treatment Group

<table>
<thead>
<tr>
<th>Baseline Characteristics</th>
<th>Control (n=41)</th>
<th>Bifocal (n=48)</th>
<th>Prismatic bifocal (n=46)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>10.34±0.28</td>
<td>10.12±0.25</td>
<td>10.42±0.27</td>
<td>0.71</td>
</tr>
<tr>
<td>Gender (# female) (%)</td>
<td>24 (59)</td>
<td>24 (50)</td>
<td>25 (54)</td>
<td>0.72</td>
</tr>
<tr>
<td>Spherical equivalent (D)</td>
<td>−2.92±0.19</td>
<td>−3.03±0.16</td>
<td>−3.27±0.16</td>
<td>0.41</td>
</tr>
<tr>
<td>Axial length (mm)</td>
<td>24.21±0.12</td>
<td>24.63±0.11</td>
<td>24.74±0.12</td>
<td>0.009*</td>
</tr>
<tr>
<td>Progression (D/ preceding yr)</td>
<td>−1.06±0.05</td>
<td>−0.94±0.05</td>
<td>−1.02±0.07</td>
<td>0.25</td>
</tr>
<tr>
<td>Near phoria (Δ)</td>
<td>−1.34±0.84</td>
<td>−3.08±0.67</td>
<td>−1.39±0.63</td>
<td>0.35</td>
</tr>
<tr>
<td>Lag of accommodation (D)</td>
<td>0.98±0.05</td>
<td>1.17±0.07</td>
<td>1.04±0.06</td>
<td>0.05*</td>
</tr>
<tr>
<td>Total near work (hr/wk)</td>
<td>19.64±1.71</td>
<td>22.00±1.92</td>
<td>23.24±1.74</td>
<td>0.38</td>
</tr>
<tr>
<td>Total outdoor activities (hr/wk)</td>
<td>4.83±0.56</td>
<td>4.55±0.57</td>
<td>4.85±0.47</td>
<td>0.91</td>
</tr>
</tbody>
</table>

| # of children with            |               |               |                         |       |
| 0 myopic parents             | 3             | 2             | 3                       | 0.86  |
| 1 myopic parents             | 10            | 16            | 15                      |       |
| 2 myopic parents             | 28            | 30            | 28                      |       |

Spherical equivalent, axial length and myopia progression are reported for right eyes.
Abbreviations: # = number
* indicates significant difference on ANOVA

After adjusting for the covariates with significant effects (gender, p=0.007; age, p<0.001; initial myopia progression, p=0.02) (ANOVA unadjusted p=0.06; adjusted p=0.03). Adjusting for the baseline axial length (p=0.51) and lag of accommodation (p=0.63) did not affect the outcome. The reduction in the rate of myopia progression with both bifocal types was observable after 6 months of wear, the magnitude of the rate of reduction appeared to increase from 6 months to 18 months, and then remained relatively constant until 24 months.

The average increase (mean±SE) in axial length across the 24 months of the study was 0.62±0.04mm, 0.41±0.04mm and 0.41±0.05mm for the SVL, BFL and PBFL respectively (Figure 3). There was a significant effect of lens design on the degree of axial elongation (ANOVA, p=0.001). Axial elongation over this period was 0.21mm less in both BFL and PBFL compared to SVL (p<0.005 for both comparisons). The magnitude of axial elongation observed in both bifocal groups was similar over the 24 months period. The reduction in the rate of axial elongation with
Figure 2. Change of refraction from baseline to 24 months in 6-monthly intervals. The reduction in myopia progression with both bifocal types was observable after 6 months of wear.

Figure 3. Change of axial length from baseline to 24 months in 6-monthly intervals. Similar to change of refraction, the reduction in the rate of axial elongation with both bifocal types was observable after 6 months of wear.
both bifocal lens types was observable after 6 months of wear and, like the data for change of refraction, the magnitude of reduction appeared to increase from 6 months to 18 months and then remained relatively constant until 24 months. Myopia progression was significantly correlated with change of axial length (Pearson correlation: \( r = 0.62 \) for SVL; \( r = 0.68 \) for BFL; \( r = 0.62 \) for PBFL; \( p < 0.001 \)).

**ANCILLARY ANALYSES**

The baseline characteristics were tested for possible interaction with the treatment effects. A median split method by number of children was used to divide the characteristics: age (< 10.33yr vs ≥ 10.33yr) initial myopia progression (< 1.00D vs ≥ 1.00D), baseline myopia (< -3.00D vs ≥ -3.00D), lag of accommodation (<1.01D vs ≥1.01D), hours of close work conducted per week (<18.5hr vs ≥18.5hr), hours of outdoor activities conducted per week (<4.5hr vs ≥4.5hr) and parental myopia (2 myopic parents vs 0 or 1 myopic parents). Gender was analysed as boys versus girls. Near phoria was analysed as orthophoria (−1.5Δ to +1.5Δ), esophoria (> +1.5Δ) and exophoria (<−1.5Δ). Of all the covariates tested in the interaction analysis, only lag of accommodation showed some evidence of interaction with the treatment effect (\( p = 0.09 \)) (Table 3). For that reason and also based on data of others,\(^{27,28} \) the lag of accommodation was further analysed by dividing the children into high and low lag subgroups. Since near phoria had been shown to influence the degree of myopia control with bifocal and multifocal lenses,\(^{14,17} \), data was also further analysed by dividing children based on near phoria.

**Table 3. Interaction Analysis of Covariates and Treatment**

<table>
<thead>
<tr>
<th>Covariate*Treatment</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age*Treatment</td>
<td>0.38</td>
</tr>
<tr>
<td>Gender*Treatment</td>
<td>0.90</td>
</tr>
<tr>
<td>Baseline Myopia Progression*Treatment</td>
<td>0.61</td>
</tr>
<tr>
<td>Baseline Rx*Treatment</td>
<td>0.32</td>
</tr>
<tr>
<td>Lag of accommodation*Treatment</td>
<td>0.09*</td>
</tr>
<tr>
<td>Near phoria*Treatment</td>
<td>0.55</td>
</tr>
<tr>
<td>Close work*Treatment</td>
<td>0.53</td>
</tr>
<tr>
<td>Outdoor activities*Treatment</td>
<td>0.40</td>
</tr>
<tr>
<td>Parental myopia*Treatment</td>
<td>0.30</td>
</tr>
</tbody>
</table>

* indicated some evidence of significance
The rate of myopia progression (mean±SE) for high and low accommodation lag subgroups has been plotted in **Figure 4**. For children with high lags of accommodation, the rate of myopia progression was \(-1.76±0.18\)D (n=20) for SVL, \(-0.88±0.11\)D (n=23) for BFL and \(-0.84±0.14\)D (n=24) for PBFL. ANOVA showed the effect of treatment was statistically significant (p<0.001) and that both of the bifocal lens types significantly reduced the myopia progression in children with high accommodative lags compared to the single vision lens (p<0.001 for both bifocal groups). In contrast, there was no difference between the effect of the two bifocal lens types on myopia progression of children with high accommodative lags (p=0.84).

![Figure 4](image)

**Figure 4.** Rate of myopia progression for children with high and low lags of accommodation. Both bifocal groups significantly reduced myopia progression in children with high lags compared to SVL (p<0.001). For children with low lags, PBFL had a lower rate of myopia progression compared to SVL (p=0.001) and BFL (p=0.018); BFL did not significantly reduce myopia progression compared to SVL (p=0.18).

For children with low lags of accommodation, the rate of myopia progression was \(-1.35±0.15\)D (n=21) for SVL, \(-1.07±0.13\)D (n=25) for BFL and \(-0.58±0.15\)D (n=22) for PBFL. ANOVA showed the effect of treatment was statistically significant for children with low accommodative lags (p=0.001); PBFL had a lower rate of myopia progression compared to both the SVL (p=0.001) and BFL (p=0.018).
For children with low lags of accommodation BFL did not significantly reduce myopia progression compared with SVL (p=0.18).

The rate of myopia progression (mean±SE) based on near phoria status has been plotted as function of lens treatment (Figure 5). For children with baseline esophoria, the rate of myopia progression was −1.19±0.26D (n=8) for SVL, −0.84±0.14D (n=12) for BFL and −0.68±0.24D (n=9) for PBFL. BFL and PBFL were not statistically significant at reducing myopia progression in esophoric children (ANOVA, p=0.27); however the lack of statistical significance is likely due to a lack of power as a result of the small number (total 29) of esophoric children in this study. For children with orthophoria, the rate of myopia progression was −1.58±0.16D (n=20) for SVL, −1.10±0.11D (n=25) for BFL and −0.76±0.13D (n=19) for PBFL. BFL (p=0.01) and PBFL (p<0.001) significantly inhibited myopia progression in the orthophoric children; there was statistically no difference between

![Figure 5](image-url)

**Figure 5.** Rate of myopia progression based on near phoria status. BFL and PBFL were not significant at reducing myopia progression in esophoric children (ANOVA, p=0.27). For orthophores, BFL (p=0.01) and PBFL (p<0.001) significantly inhibited myopia progression compared to SVL but no difference between the two bifocal groups (p=0.08). For exophores, BFL (p=0.007) and PBFL (p=0.002) significantly inhibited myopia progression compared to SVL but no difference between the two bifocal groups (p=0.64).
the two bifocal lens types (p=0.08). For children with exophoria, the rate of myopia progression was $-1.73\pm0.24\text{D}$ (n=13) for SVL, $-0.80\pm0.22\text{D}$ (n=11) for BFL and $-0.65\pm0.19\text{D}$ (n=18) for PBFL. BFL (p=0.007) and PBFL (p=0.002) significantly inhibited myopia progression in the exophoric children; there was statistically no difference between the two bifocal lens types (p=0.64). Collectively, there was no consistent interaction of phoria with treatment (p=0.55); the two bifocal lens types reduced myopia progression regardless of the near phoria position.

ADVERSE EVENTS

No adverse events were reported in the intervention group.

COMMENT

Both bifocals and prismatic bifocals were found to significantly control the rate of myopia progression compared to the single vision lens group. Prismatic bifocals prevented more myopia progression than the standard bifocals and the effect was significant after adjusting for three covariates (gender, age and initial myopia progression). Therefore adding base-in prism to the bifocal lens design improved the bifocal treatment effect to some extent. However, the prism effect was small and was not demonstrated in the outcome measure of axial length. For that reason, base-in prisms should not be unanimously incorporated into standard bifocals when prescribed for myopia control in children.

The reason that the myopia control effect of base-in prism was not shown in the axial length measurement could also be related to the contact method of A-scan ultrasound measurement of axial length. Since ultrasonography could be affected by variability in globe indentation and measurement axis, the procedure was more challenging and less accurate when performed on children.\textsuperscript{29} To increase the precision, children’s eyes were cyclopleged and anaesthetized and ten measurements were taken to get the average axial length. The IOLMaster (Zeiss, Oberkochen, Germany) was not used in the current study because its accuracy had not been documented at the time of the study design. Recent studies have shown that the partial coherence interferometry (PCI) method like the IOLMaster has a greater repeatability\textsuperscript{29} and is more accurate\textsuperscript{30} than ultrasonography because it does not indent the globe and provided the subjects fixate properly, the measurement axis will be close to the visual axis. Therefore, the
IOLMaster should be considered as a standard for future ocular biometry studies in children.

Our study recruited myopic children with myopia progression of at least 0.50D in the preceding year. This resulted in a mean initial myopia progression rate of about \(-1\)D per year at baseline for each group. Such an inclusion criterion would avoid children with low rates of myopia progression being recruited to the study and allow the treatment effect of bifocals to be more effectively evaluated. The value of using this criterion to identify children with high myopia progression is confirmed, as the 24 months rate of myopia progression of \(-1.55\)D in the single vision group (control group) is greater than those of previous myopia control studies. Our study supports the findings of others that bifocals are effective at inhibiting myopia progression for myopic children with high myopia progression; this conclusion is in agreement with the study of Leung & Brown using a similar inclusion criterion. The slightly better myopia control effect in this study could be related to the use of bifocal instead of multifocal lenses because the segment line provides feedback to the children such that they can deliberately use the reading portion of the bifocal lenses whenever close work is performed. In contrast, children who wear multifocal lenses do not consistently use the near-addition portion of the spectacles during reading.

The differential analysis for children with high and low accommodative lags showed that interaction existed between the lag and treatment effect. Standard bifocals were only effective for children with high lags; a finding in agreement with the reported outcomes of COMET. For children with low accommodative lags, prismatic bifocals produced the superior control effect. We speculated that for children with high lags, reducing the accommodation lags with standard bifocals is adequate to control myopia progression. In contrast, for children with low lags, bifocals are more effective if the convergence demand and lens induced exophoria are also reduced, and such a state of oculomotor equilibrium could be achieved with the addition of base-in prisms. Given that these ancillary analyses are based on a subgroup with a smaller number of subjects, we consider our conclusion for prismatic bifocals to be suggestive.
Our study did not find that bifocal lenses were more effective in children with esophoria. The lack of an effect may be related to the fact that a large portion of esophoric children will have significant lens-induced exophoria with the bifocals in place because of the high response AC/A ratio usually found in this group of children. This also explains why previous studies of bifocals on esophoric children do not show a strong myopia control effect. We speculate that in prescribing bifocals for myopia control, it is the state of lens-induced near phoria instead of baseline near phoria that plays a role in determining success; because it is this uncontrolled phoria that disrupts the oculomotor equilibrium.

Ethnic Chinese children living in Canada have been found to develop myopia comparable in prevalence and magnitude to those living in urban East Asian countries; the findings of this study could reasonably be generalized to Chinese children living in Asian countries, but not to children of other ethnicities. To date, there has been no consensus on what magnitude of myopia reduction constitutes a clinically significant myopia control effect. In our opinion, the treatment effect of bifocal in this study, though greater than those of others, is still modest. Therefore, bifocal spectacles, as a myopia control treatment, should be offered to myopic children with caution in clinical practice. As has been suggested, the modest benefit should be weighed against factors such as the increased cost of the lenses, poor cosmetic appearance and attitude of the parent and child if bifocal spectacles are to be prescribed for the purpose of controlling myopia.

A recent study suggests that bifocal soft contact lenses are an effective myopia control treatment because myopes over-accommodate when wearing the bifocal contact lenses. Our study does not report the lag and near phoria of the individuals with the bifocal lens in place; therefore the direct effect of the prismatic bifocal on binocular vision and the relationship of this to myopia progression has yet to be established. When the 3-years of this clinical trial are complete, a paper on the final results will also report those findings.

CONCLUSIONS

Both bifocals and prismatic bifocals could control myopia in children with high rates of myopia progression.
ACKNOWLEDGEMENTS

Author Contributions: Dr Cheng had full access to all of the data in the study and takes responsibility for the integrity of the data and accuracy of the data analysis.

Funding/Support: This work was supported in part by Essilor International of France.

Previous Presentations: This study was presented at the 12th International Myopia Conference; July 9, 2008; Queensland, Australia.

REFERENCES


APPENDIX

Questionnaire Administered to the Child and Accompanying Parent(s) at Each Follow-Up Examination to Determine If the Child Use the Bifocal Lens Properly

1. How often do you use your glasses for outdoor activities?
   __I use my glasses for all outdoor activities.
   __Sometimes I remove my glasses for outdoor activities.
   __I usually remove my glasses for outdoor activities.

2. How often do you wear your glasses for close work, for example reading, writing, computer and gameboy?
   __I wear my glasses for all close work.
   __Sometimes I remove my glasses for close work.
   __I usually remove my glasses for close work.

3. Do you have difficulties wearing the glasses?
   Yes □  (go to 4)  No □

4. What are the difficulties?

_____________________________________________________________________
_____________________________________________________________________

Questionnaire Administered to the Child and Accompanying Parent(s) at the Baseline Visit to Evaluate the Child’s Visual Habits and Parents’ Refractive Error

1. On average, how many hours per week does your child spend in each of the following activities outside of school?
   Studies or does school assignments (computer work not included) ___ h per week
   Engages in computer work (assignments, games and internets) ___ h per week
   Reads for pleasure ___ h per week
   Watches television or play TV games ___ h per week
   Plays gameboy or other portable video games ___ h per week
   Engages in outdoor/sport activities ___ h per week
This question refers to the child’s birth mother.

2. What are the findings of your most recent refractive error measurement?

2a. From the clinical record: (If not available, go to 2b)

OD________________________
OS________________________

2b. Reading of glasses on lensometer: (If not available, go to 2c)

OD________________________
OS________________________

2c. Average of ten readings from the Topcon KR7000 autorefractor:

OD________________________
OS________________________

This question refers to the child’s birth father.

3. What are the findings of your most recent refractive error measurement?

3a. From the clinical record: (If not available, go to 3b)

OD________________________
OS________________________

3b. Reading of glasses on lensometer: (If not available, go to 3c)

OD________________________
OS________________________

3c. Average of ten readings from the Topcon KR7000 autorefractor:

OD________________________
OS________________________
Chapter 5: General Discussion

This research has demonstrated that simultaneously reducing the demand of accommodation and convergence and thus their associated errors or bias (i.e. accommodation lag and near phoria) by means of combining a positive-lens addition and base-in prism at near can slow myopia progression. The results from the clinical trial also suggested that reducing the accommodative demand and lag alone by standard bifocals only controlled myopia progression for children with high lags of accommodation. For children with low lags of accommodation, adding base-in prisms to the standard bifocals improved the myopia control effect. The base-in prisms could reduce the convergence demand and enhance oculomotor equilibrium by reducing the lens-induced near exophoria of standard bifocals. Issues related to prescribing bifocals and prismatic bifocals for myopia control in children and future directions of the bifocal treatment study are discussed.

The study on the prevalence of myopia in Chinese-Canadian children indicates that many ethnic Chinese children living in Canada are myopic and that high levels of myopia are common. The prevalence of myopia was 22.4% at age 6 increased to 64.1% at age 12. The average annual refractive shift was –0.52 D for this group of Chinese children and –0.90 D for just the myopic ones. Chinese-Canadian children, like their South East Asian counterparts, have comparable myopia development and their myopia progresses rapidly.

The greater availability of myopic subjects in this population allowed the bifocal lens trial to recruit children whose myopia was clearly progressing (at more than 0.50 D/yr). The average progression rate for the children enrolled at the baseline of the trial was about 1 D/yr. The results of the wearer trial support the conclusion of other studies that bifocals are more effective in children with high myopia progression. Since prescribing bifocal spectacles to children usually requires a higher cost than prescribing single vision lenses and bifocal lenses are less cosmetically appealing than single vision lenses, a further conclusion is that bifocal spectacles should not be prescribed for all myopic children (only those with high progression).
The investigation of the effect of positive-lens addition and base-in prism on accommodation accuracy and near horizontal phoria provides a systematic approach to the determination of the positive-lens addition and base-in prism combination most suitable for myopia treatment. This approach also demonstrates how the accommodation and convergence of myopic children can be modified to reduce the accommodation lag and lens-induced exophoria. The use of a positive-lens addition alone was shown to induce a large amount of exophoria (for example, about 9 \( \Delta \) exophoria with +3 D). This large exophoric shift is likely to cause an oculomotor imbalance and that may explain why standard bifocals or multifocals are not effective in all myopic individuals.

For the myopic children in this study, a lens addition of +2.25 D combined with a 6 \( \Delta \) base-in prism was found to minimize both the lag of accommodation and lens-induced exophoria (−0.33 D and −2.4 \( \Delta \)). However, this lens and prism combination was not used for the bifocal lens trial because the lone use of the +2.25 D addition in the standard bifocal group would induce a large amount of exophoria (−6.9 \( \Delta \)). As an alternative, a lens addition of +1.50 D combined with a 6 \( \Delta \) base-in prism was chosen. The 6 \( \Delta \) base-in prism totally controlled the exophoria (−0.3 \( \Delta \)) induced by the +1.50 D addition and the +1.50 D addition alone produced a modest degree of accommodative lag (−0.69 D). Were it not for the fact that the standard bifocal group limited the choice of add power, the use of +2.25 D combined with the 6 \( \Delta \) base-in prism should have shown a stronger myopia control effect. It is apparent that the graphical analysis of the lag of accommodation and near phoria provides valuable information for choosing suitable lens and prism power combinations for myopic individuals, and for that reason it is a highly recommended procedure whenever bifocals or prismatic bifocals are prescribed for myopia control. In an ideal bifocal lens trial, the bifocal lens and prism powers should be customized for all individuals such that the bifocals will provide an optimal state of oculomotor equilibrium whenever near-work is to be performed.

The bifocal clinical trial clearly shows that bifocals and prismatic bifocals can control myopia in children with high rates of myopia progression. The incorporation of base-in prisms to the near additions of the standard bifocals improves the myopia control effect, especially for children with low lags of accommodation (from 0.28 D
to 0.77 D reduction in myopia). For children with high lags of accommodation, reducing the accommodative demands and the lags by standard bifocals was adequate to control myopia (0.88 D reduction). A similar result has been shown in the COMET study (Gwiazda et al., 2003) in which multifocal lenses were reported to control myopia better for children with higher lags than those with lower lags (0.33 D vs 0.07 D in 3 years). In contrast, the baseline near phoria alone was not a strong determinant of the success of the bifocal treatment. Though children with esophoria are expected to benefit more from bifocal wear, it is important to point out that a large portion of the esophoric children will still have lens-induced exophoria with the bifocals in place, because AC/A ratio is usually high in this group of children (Gwiazda et. al., 1999). This explains why previous studies of bifocals on esophoric children do not always show a strong myopia control effect (Goss 1986; Goss and Grosvenor, 1990; Fulk et al., 2000). Therefore, in prescribing bifocals for myopia control, it is the state of lens-induced near phoria instead of baseline near phoria that plays a role in determining success; because it is this uncontrolled phoria that causes oculomotor imbalance.

Nearpoint esophoria has also been identified as a risk factor for progression of myopia in retrospective studies (Goss, 1990; 1991). Goss (1990) adopted Morgan’s (1944) norms to group children with different near phoria and found that children with habitual nearpoint esophoria had greater rates of myopia progression than children with orthophoria and exophoria. However, our trial showed that children with esophoria had less myopia progression than children with other phoria types in the single vision group. Yet, direct comparison could not be made because the near phoria in the trial was measured at 33 cm (3 D) instead of the 40 cm (2.5 D) required by the Morgan’s norms; a 0.5 D difference in the accommodation demand would point to a phoria measurement error of 3-4 Δ for this group of children. In addition, prospective studies (Drobe and de Saint-Andre, 1995; Goss and Jackson 1996) have been unable to demonstrate nearpoint esophoria has a significant effect on myopia progression. Instead, Goss and Jackson (1996) identified high exophoria as a risk factor; the number of children who became myopic was the greatest in their exophoric group. The children in our trial showed a similar effect in which a greater number of children with exophoria had myopia and the exophoric group had a greater myopia progression. In a recent prospective study of myopia progression
(Gwiazda et al., 2005), children who became myopic also showed a small average exophoria (range: 12 Δ exophoria to 15 Δ esophoria) instead of esophoria. More importantly, the COMET study (Gwiazda et al., 2003) which enrolled 469 children, using the same near phoria measurement method and phoria categorization as in the current study, did not show children with nearpoint esophoria had a greater myopia progression than children with orthophoria and exophoria in the single vision group. Therefore, baseline nearpoint esophoria should not be considered as a strong determinant of myopia progression in children.

At present, there is no known effective treatment for myopia. Among all the randomized controlled trials on myopia interventions, only atropine eye drop (Yen et al., 1989; Shih et al., 1999), and bifocal/multifocal lenses (Fulk et al., 2000; Gwiazda et al., 2003) are found to have some beneficial effects. However the routine use of atropine is not recommended because of photophobia, difficulties in reading and its possible adverse reaction to long term use. Conversely, bifocal/multifocal lenses have limited safety concerns and are quite effective in children with high lags of accommodation (Gwiazda et al., 2004). The results of the current study also support that bifocal/multifocal lenses can control myopia in children with high lags of accommodation. For children with low lags, addition of base-in prism to the bifocal lenses will enhance the myopia treatment effect. So, with a proper selection of myopic children and a systematic approach to determine the lens/prism combination, bifocal/multifocal lenses should be considered as a practical and reliable measure to prevent myopia development in children.

The wearer trial will continue for another year and then the children will revert to either single vision, contact lens or standard bifocal lens wear (the prismatic bifocal will cease to be available). Future work will determine if the effect of bifocals and prismatic bifocals and the myopia reduction are sustained; in some studies the myopia control effect of bifocals and multifocals has been shown to weaken over time (Fulk et al., 2002; Gwiazda et al., 2003). For that reason, the work in experiment 2 has to be expanded to study whether young progressing myopes could adapt to the lens and prism (prism adaptation) over time and the beneficial effect of the lens on the accommodation and oculomotor systems may reduce. Experiment 3 used a median method to differentiate children with high and low lags of
accommodation. A further analysis will be undertaken to determine at what actual level of accommodation lag should prismatic bifocals instead of standard bifocals be prescribed to control myopia. The lag of accommodation and near phoria of the individuals with the bifocal lens in place will be reported on, as this data has been collected, such that the direct effect of bifocal on myopia progression can be established. Other ocular component data such as anterior chamber depth, lens thickness, vitreous chamber depth and keratometry have also been measured and will be analyzed for their contributions to myopia progression. Lastly, the short and long term effects of bifocal wear on the oculomotor characteristics may provide a clue for determining when bifocal treatment should be initiated and ended. Perhaps only when the demand on accommodation and convergence and their bias are all minimized, will the effect of near-work on myopia be eliminated.

References


