CONTACT LENSES AND SPORT

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Doctor of Philosophy

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Summary

Contact lenses seem to be the ideal method of vision correction for ametropic people who participate in sporting activities.

This thesis sets out to evaluate the viewpoint of the optometric professional and that of the patient on the use of contact lenses in sport and to establish if education is needed within this area. It also aims to provide some scientific evidence on the effect of exercise on the physiology of the cornea with and without contact lenses.

Silicone hydrogel contact lenses have previously been suggested to impede heat dissipation from the cornea compared to mid water hydrogels. This was further demonstrated with exercise.

The physiological integrity of the cornea is dependant on the amount of oxygen available to its surfaces. Contact lenses can disrupt the diffusion of oxygen to the cornea. Previous methods of measuring the oxygen consumption of the cornea have been limited by their invasive nature and assessment of only a small surface area of the cornea. They are not suitable to measure corneal oxygen consumption during exercise with and without contact lenses. A new method needed to be established. This was achieved by designing a novel method by the use of an oxygen sensor inside an airtight goggle using dynamic quenching of luminescence method. This established a non-contact way of measuring the effect oxygen uptake with and without contact lenses *in vivo*, allowing the contact lens to be undisturbed in their natural environment.

The new method differentiated between the closed-eye and the open-eye condition with a good within-visit repeatability. It also illustrated that the cornea utilises oxygen at a faster rate during controlled aerobic exercise at moderate intensity.

New contact lenses are available specifically for sport, these claim to reduce glare and increase contrast for daylight outdoor sports. However, visual benefits of these types of contact lenses cannot be measured easily in an indoor clinical environment, such as the optometric practice. To demonstrate any potential benefits of these lenses emulation of them should be conducted outdoors.

Key words: Corneal, Oxygen, Temperature, Exercise, Ocular

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This thesis is dedicated to my amazing partner Josie, and my wonderful family and friends

- Your support during such times has been invaluable.

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CONTENTS

FIGURES

TABLES

CHAPTER ONE

INTRODUCTION

1.1 EXPLANATION OF LITERATURE REVIEW

1.2 PART ONE: CONTACT LENSES IN SPORTS; A GENERAL OVERVIEW

1.3 PART TWO: OXYGEN AND THE EYE

1.4 AIM OF THESIS

1.1 EXPLANATION OF LITERATURE REVIEW

The literature review in this thesis has been divided into two parts. The first part of the literature review will illustrate a general overview of contact lenses in sport, whilst the second part will review corneal oxygen. As oxygen plays an important role in exercise, it was important to review literature on corneal oxygen as it was quickly apparent that to measure oxygen during sport a novel non-contact method needed to be established. To do this the understanding of previous techniques was essential.

PART ONE: CONTACT LENSES IN SPORTS; AN GENERAL OVERVIEW

1.2.1 Participation in Sports

For many people exercise and sports are everyday activities and the sports market is now considered as the second largest industry worldwide (Loran, 2003). An audit by The Leisure Database Company, (2007), the online database company, has revealed that more Britons than ever have been signing up to get fit by joining a gym. An estimated 12% of the total United Kingdom (UK) population were members of these facilities, a rise of 3% on January 2006 (The-Leisure-Database-Company, 2007).

According to the National Statistic (NS) survey carried out in Great Britain in 2002, 75% of all adults had taken part in a sport, game or physical activity in the twelve months prior to the survey and 59% of adults had participated in sports four weeks prior to the survey. Sports and exercise accounted for only 3.4% of total free time activity on a week day and 3.3% at the weekend day in the UK for full time workers, with male respondents spending approximately 1.5 times more on sporting activities than females. The most popular physical activity in the UK was walking, which just over a third of males and females participated (Table 1.1). The Mintel report in 1993 illustrated swimming was the most popular recreational activity with ten million participants, followed by rambling / hiking (Table 1.2). Sports England, the sporting association for the UK, has a mission to increase participation in sports by a minimum of 1% annually (Sports England, 2005).

MEN PARTICIPATION (%)		WOMEN PARTICIPATION (%)	
Walking	36	Walking	34
Snooker/pool/billiards	15	Keep fit/yoga	16
Cycling	12	Swimming	15
Swimming	12	Cycling	6
Soccer	10	Snooker/pool/billiards	4
Golf	9	Weight training	3
Weight training	9	Running	3
Keep fit/yoga	7	Tenpin bowling	3
Running	7	Horse riding	2
Tenpin Bowling	4	Tennis	2

Table 1.1
The 'top ten' sports, games and physical activities for men and women: rank order for participation in the four weeks before interview: Great Britain 2002 (adapted from National-Statistic, 2005)

SPORT	MEN (Millions)	WOMEN (Millions)	TOTAL (Millions)
Swimming	4.4	5.6	10.0
Rambling/hiking	2.6	1.8	4.3
Snooker	3.5	0.05	3.9
Keep fit/ dance	N/A	3.9	3.9
Jogging/ training	2.7	0.9	3.6
Badminton	1.8	1.6	3.4
Golf	2.9	0.05	3.4
Cycling	1.9	1.2	3.1
Darts	2.2	0.8	3.1
Weight training	2.1	0.7	2.8
Tennis	1.5	1.1	2.7
Football	2.2	0.1	2.4
Squash	1.5	0.6	2.1
Cricket	1.2	0.1	1.4
Table Tennis	1.1	0.6	1.7
Bowls	0.9	0.4	1.4
Skiing	0.8	0.5	1.2
Climbing	0.5	0.2	0.7
Athletics	0.5	0.2	0.7
Rugby Union	0.6		0.7
Wind Surfing	0.3		0.3
n = 5,328. Data may not sum due to roundings. Source: Mintel, 1993			

Table 1.2
Sports participation in the UK in 1993 (adapted from Mintel, 1993).

1.2.2 Age and Sports

In general, participation in a sport, game or physical activity decreases with age, particularly over 30 years, as demonstrated in the 2002 National Statistics survey, of which 72% of 16 to 19 year olds participated, compared to 14% in the 70s and over group (Figure 1.1). This trend was also seen in a survey by Bowden and Harknett, 2005 (Figure 1.2).

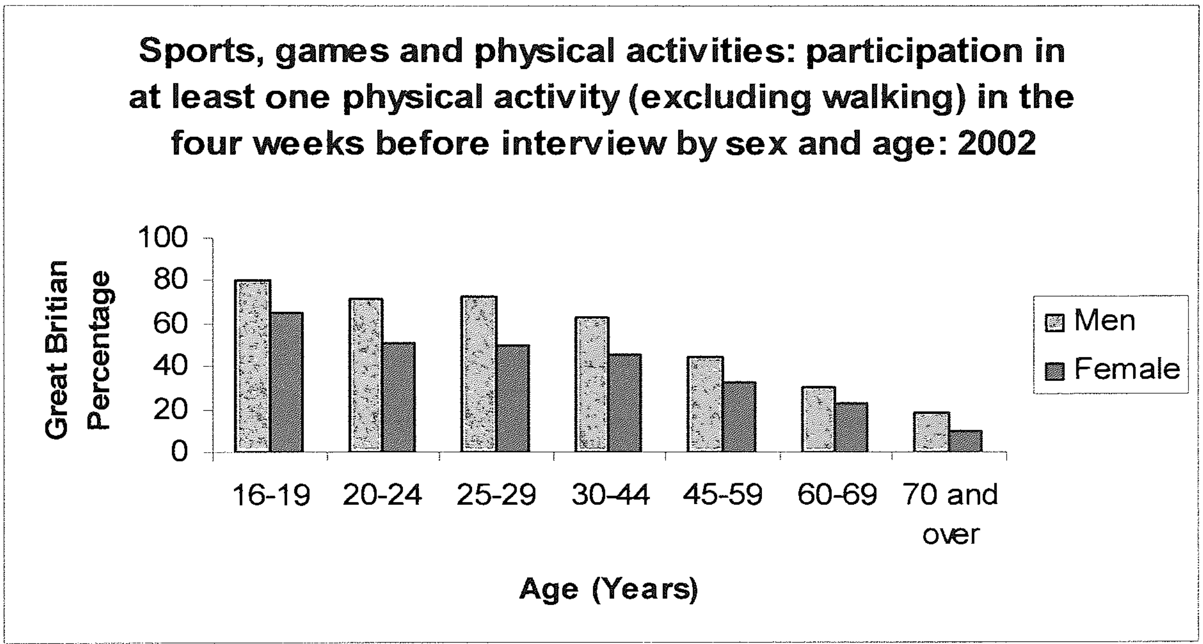


Figure 1.1
Sporting activity with age (redrawn from National Statistics, 2002)

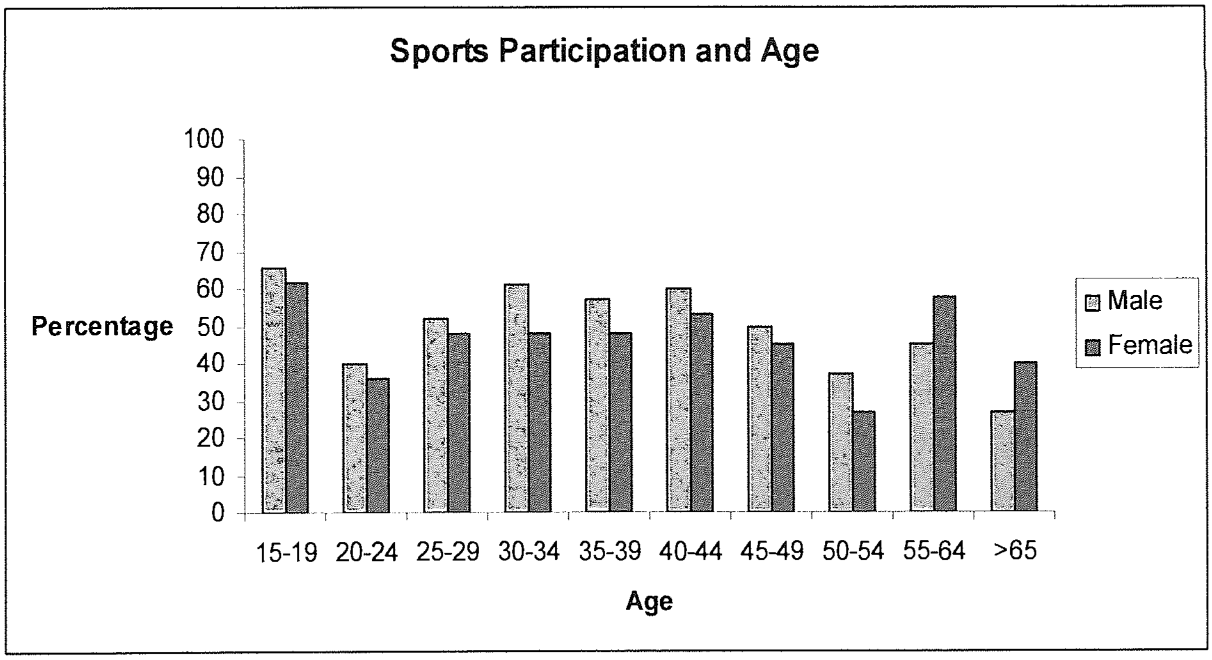


Figure 1.2
Sporting activity with age (redrawn from Bowden and Harknett, 2005)

1.2.3 The Contact Lens Industry

The UK market for eyeglasses and contact lenses has grown by around 8% since 2002 to reach a value of £3.2 billion in 2003, of which spectacles constituted the largest sector, accounting for over 77.4% of total sales (Euromonitor-international, 2005). Disposable contact lenses accounted for 44% of the total market of which around 85% were daily disposables (Table 1.3). These data demonstrate a decline in traditional soft lens market (conventional yearly planned replacement soft contact lenses).

Lens type	Volume '000	% Increase	Value £'000	% increase
Daily Disposable	186,359	35.6	42,939	24.4
Multi Use Disposable	28,197	4.2	35,999	-0.7
Continuous Wear	1,316	No 1999 Report	2,979	No 1999 Report
Traditional Soft	1,072	-39.4	10,045	-30.3
RGP*/PMMA**	273	-18.5	4,576	-7
Overall	217,217	30.3	96,536	7.2

*Rigid gas permeable. **Polymethyl -methacrylate

Table 1.3
Sales of contact lenses in the UK (redrawn from ACLM, 2001)

Contact lens wearers had risen to 2.95 million in the year of 2003 which represented an 11% increase in the past year (ACLM, 2004). The Association of Contact Lens Manufactures (ACLM) statistics showed that there had been a 10% growth in the overall contact lens market since 2001. In 2004 the number of contact lens wearers was over 3 million (ACLM, 2005), but the ACLM suggested this growth was showing signs of slowing down (ACLM, 2005).

The twelfth annual survey of the UK contact lens prescribing trends was conducted in early 2007 and demonstrated that 97% of all new contact lens fits between January and March of that year were soft contact lenses. Thirty nine percent of all new soft contact lens fits and 30% of soft contact lens refits were daily disposables (Morgan, 2007). This data showed that the percentage of new daily soft contact lens fits and refits has almost remained constant for the past several years (Morgan and Efron, 2004; Morgan 2007) and the amount of Monthly contact lenses accounted for just under half of all new fits and refits (44% and 46% respectively). Bowden and Harknett (2005) also demonstrated that monthly disposables contact lenses (34%) still remain the most popular modality; this was closely followed by daily disposables contact lenses (24%).

1.2.4 Contact Lens Wearers and Participation in Sport

Although spectacles have the stability of vision, for some people, they may present as an inconvenience for their sporting and leisure pursuits (IACLE, 1998). Due to the limitations and problems spectacles can impose (Table 1.4), contact lenses are an alternative for vision correction for sporting activities (Zagelbaum, 1996) and this has led to many practitioners prescribing contact lenses for such activities.

With the increased number of people participating in exercise, contact lenses are not just useful for the elite athlete, but also for the recreational casual sport participant. Thus, sports participation by the ametropic athlete has successfully been revolutionised by the use of contact lenses (Legerton, 1993; Loran, 2005).

Recent studies established that over a quarter of patients who choose contact lenses reported sports as a primary motivating factor (Gupta and Naroo, 2006; Naroo *et al.,* 1999) and Bowden and Harknett (2005) demonstrated that 45% of females and 65% of males contact lens patients participated in sports, of which over 94% of the participants wore their contact lenses for sports.

BENEFIT OF CONTACT LENSES OVER SPECTACLES	REASON
Wider field of view	Limitation on edge of spectacle lens design, restricted visual field
Less magnification	Object size is more constant "real-world"
Contact lens stability	Contact lenses do not slip down the nose
Enhances depth perception	They allow more stable vision and enhanced depth perception due to less magnification difference between the eyes
Less aberrations	Lenses move with the eyes
Less reflections	Lenses in contact with tears
Do not fog up or become covered in rain	Contact lenses in contact with tears and not exposed
Reduced ocular injury	Reduced risk of ocular injury from broken frames or lens (exclude protective spectacles and RGP contact lenses)
Wearing protective glasses	The bulk of the frame frequently interferes with the wearing of protective goggles

Table 1.4
The benefits of contact lenses over spectacles (adapted from IACLE, 1998; Loran, 1995; Weis, 1981; Zagelbaum , 1996)

A survey investigating the optometric trends in sports vision in the United States (US) in 1993 reported that 94% of optometrists favoured the use of contact lenses over spectacles for athletes (Zieman *et al.*, 1993). They reported that 85% of the optometrists preferred fitting soft contact lenses over rigid (5%) whilst 10% had no preference and 21% used extended wear contact lenses for these athletes. They compared their data to an unpublished survey in 1983 in which only 84% of optometrist preferred contact lenses over spectacles for athletes, thus the survey demonstrated a 10% increase between these two years.

As seen from Table 1.5, contact lenses wearers actively participate in many different sporting activities (Bowden and Harknett, 2005), ranging from swimming to dancing.

SPORT	FEMALE	MALE	OVERALL PERCENTAGE
Swimming/ Water sports / Scuba / Water Skiing	24	13	20
Tennis/Squash/badminton/racquetball	13	25	18
Athletics/jogging/running/hiking/cricket	11	15	13
Gym/gymnastics/aerobics/yoga/pilates	27	10	21
Football/rugby/hockey/rounders	3	22	10
Cycling/horse riding/skateboarding	5	4	5
Basketball/Netball	6	1	4
Snow sports	2	3	3
Golf	2	5	3
Dancing	3	1	2
Kick boxing/boxing/martial arts/wrestling	2	0	2
Fishing	0	1	1
Bowls	0	1	1

Table 1.5
Sports that are carried out whilst wearing contact lenses (redrawn from Bowden and Harknett, 2005).

1.2.5 The Eye and Exercise

Exercise increases the metabolic demand of muscle tissue and a number of respiratory and cardiovascular adjustments take place (Figure 1.3, Hilton, 2003).

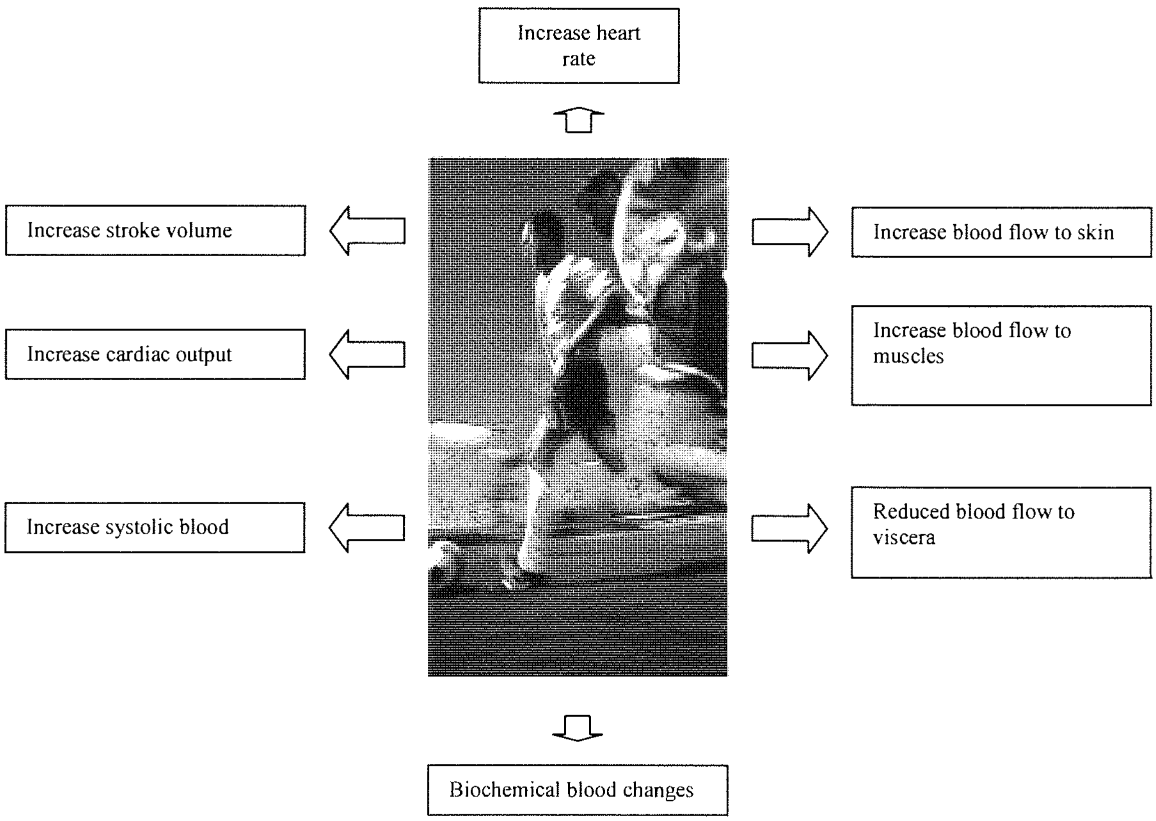


Figure 1.3
Systemic effects of exercise (adapted from Hilton, 2003)

There are two main primary responses that have been reported in the literature which occur in the eye as a result of exercise (Hilton, 2003). These are a decrease in intraocular pressure (IOP) and alteration to ocular blood flow, although visual acuity and contrast sensitivity have been known to increase during exercise (see Chapter 4) (Koskela, 1998; Woods and Thomson, 1995).

The reduction in IOP during exercise has been demonstrated in a number of studies (Avunduk *et al.*, 1999; Brody *et al.*, 1999; Chromiak *et al.*, 2003; Gungor *et al.*, 2002; Karabatakis *et al.*, 2004; Kiuchi *et al.*, 1994; McDaniel *et al.* 1983; Passo *et al.*, 1991; Price *et al.*, 2003; Qureshi, 1995a; Qureshi, 1995b; Qureshi *et al.*, 1997). Avunduk *et al.* (1999) reported that both isometric (exercises in which muscles are put under tension but do not allow them to contract) and isokinetic (muscle contracts and shortens at constant speed) exercise lowered IOP in ophthalmologically normal subjects, and that dynamic resistance exercises (leg press and chest press) induced modest post-exercise decreases in IOP (Chromiak, 2003). Regular aerobic exercise has been associated with a reduction in elevated IOP and has been suggested as an effective non-pharmacological intervention for patients suspected of having glaucoma (Passo *et al.*, 1991; Price *et al.*, 2003). Karabatakis *et al.* (2004) also demonstrated that jogging decreased IOP. This was supported by Qureshi *et al.* (1995a) who concluded that all forms of physical exertion, walking, jogging and running decrease IOP. Other studies had illustrated that the amount of reduction in IOP after short term exercise seemed to depend on the intensity of exercise and not the duration (Kiuchi *et al.*, 1994; Price *et al.*, 2003). In contrast Erb *et al.*, (1998) reported no effect of acute bicycle ergonomerty on the IOP of healthy eyes. Although exercise is known to reduce IOP, the full understanding of how exercise reduces IOP is not understood.

The autoregulatory capacity of the human eye during exercise is well documented (Fuchsjager-Mayrl *et al.*, 2003; Harris *et al.*, 1996; Kiss *et al.*, 2001; Lovasik *et al.*, 2003; Luksch *et al.*, 2003; Martin *et al.*, 1999; Movaffaghy *et al.*, 1998; Movaffaghy *et al.*, 2002; Nemeth *et al.*, 2002; Polska *et al.*, 2003; Riva *et al.*, 1997; Wimpissinger *et al.*, 2003). An increase in systolic blood pressure and decrease in IOP are influenced by the autonomic nervous system (ANS). This response leads to an increase in ocular perfusion pressure (Hilton, 2003; Riva *et al.*, 1997). Using laser doppler flowmeters to measure choroidal blood flow, it has been indicated that the choriod has some auto-regulatory potential (Kiss *et al.*, 2001). The presence of an effective compensatory autoregulation for the retinal circulation, in connection with an increased ocular perfusion pressure induced by exercise was confirmed by Németh *et al.* (2002). In general, the decrease in IOP during and after dynamic exercise helps to maintain constant blood flow in the central retinal artery by increasing the ocular perfusion pressure (Németh *et al.*, 2000).

Higher levels of oxygen are required during exercise and in many types of exercise. Oxygen uptake increases linearly with an increased rate of exercise (Åstrand and Rodahl, 1986). There is a lack in the literature of studies looking at the oxygen uptake of the eye during exercise, but a paper by Bomholt and Schnell (2000) stated that in sports such as running, a high level of lactic acid can occur along with decreased levels of glucose in the blood vessels and in the anterior chamber of the eye, which can, in turn, lead to corneal oedema. They frequently observed corneal oedema underneath contact lenses which quickly disappeared during rest. The authors also commented that this oedema was true for endurance sports which involved high rates of aerobic metabolic turnover (such as triathlon and road-cycling). The research also observed inflammatory responses, especially prostaglandins, under the contact lenses in athletes which could lead to corneal pannus. They concluded that unlike spectacles, contact lenses impede the metabolic process of the eye during exercise.

A rare neuro-ophthalmological condition called Uhthoff's sign/symptom was first investigated in the 19^{th} century by a clinician called Wilhelm Uhthoff (Cited by Selhorst and Saul, 1995). It described a link between a temporary visual loss or blurred vision with exercise, heat, fatigue and anxiety (Ariel, 2005). Uhthoff's symptom of visual loss with exercise was most frequently associated with optic neuritis and had been linked to multiple sclerosis (Selhorst and Saul, 1995). A study by Van Diemen *et al.* (1992), demonstrated Uhthoff symptom after exercise were seen in two multiple sclerosis patients.

1.2.6 The History of Contact Lenses in Sport

The first documented contact lenses to be used for sporting activities were moulded polymethyl-methacrylate (PMMA) hard scleral lenses following the introduction of plastics in the 1930s (Weis, 1981). Obrig Laboratories of New York began manufacturing these lenses in around 1944 (Goodlaw, 2000) and the PMMA material was used for many years as the standard hard contact lens (Gregg, 1987). This was followed by the major advance of PMMA corneal contact lenses in 1947 which was introduced by Kevin Tuohy (Weis, 1981). In the 1950s an Oregon optometrist, Dr George Butterfield, designed a corneal contact lens that followed the corneal curve instead of sitting flat.

A PMMA micro-scleral contact lens was designed by Levey in 1964 for sports fitting (Levey, 1964). The lens had limited wearing time and was supplied in addition to the normal corneal lens for sports-wear. As PMMA material properties were far from ideal, the development of hydroxyethylmethacrylate (HEMA) in the 1950s by Czechoslovakian polymer chemist Otto Wichterle and colleague Drahoslav Lima became a serious competitor. In the 1970s polyHEMA became fashionable (Gregg, 1987) and in 1971 the soft lens became available for commercial distribution in the US.

The introduction of soft contact lenses in the early 1970s was one of the greatest optical advances for athletes. While hard lenses had worked successfully for decades, there were still many individuals whose ocular sensitivity made it impossible for them to adapt to the foreign body sensation of hard contact lenses (Weis, 1981). In 1979, the first rigid gas permeable (RGP) contact lens made of co-polymers PMMA and silicone became available for commercial distribution (Sweeney, 2000).

The first disposable soft contact lenses were available in 1987. A new formulation of fluorosilicone acrylate material for RGP lenses became available in 1997 for commercial distribution. Silicone rubber into hydrogels produced a dramatic increase of oxygen transmission in soft contact lenses (Sweeney, 2000).

These lenses, termed silicone-hydrogels, passed Food and Drug Administration (FDA) approval for continuous wear (up to 30 days) in October 2001 (FDA, 2005).

Soft contact lenses are mainly the lens of choice for many sports (IACLE, 1998; Spinnell, 1993; Stein, 2002; Werner, 2000) and are manufactured mainly from materials known as hydrogels that usually contain a water content ranging from 38% to 80% (Loran, 1995).

1.2.7 Contact Lenses for Different Sports

Many factors influence the type of contact lenses that may be chosen for a given sport. With a vast array of contact lenses on the market today, careful consideration is needed when fitting the athlete. The main advantages of wearing soft contact lenses for athletes are that they rarely get dislodged from the eye compared to RGP contact lenses (Spinnell, 1993).

1.2.7.1 Swimming and Water Sports

There are approximately 10 million people who participate in swimming in the UK; it is regarded as one of the most popular recreational activities (Loran, 2003). Sharp visual acuity may not seem important in swimming. However, Spinnell (1993) suggested that, whilst it may seem unnecessary for swimmers to have sharp acuity, but during high speed turns, knowing exactly when to begin the turn can save fraction of seconds for competitive swimmers.

Generally, contact lens manufacturers do not recommend contact lens wear for water sports (IACLE, 1989), as chlorine and other pool contaminants may remain in the contact lens and cause complications, including punctuate keratitis (Zagelbaum, 1996). Acanthamoebal infections have also been associated with swimming (Rivera *et al.*, 1993; Vesaluoma *et al.*, 1995).

A review article by Brown and Siegel (1997) on the cornea-contact lens interaction in the aquatic environment, discussed that underwater images appear nearer and larger, thus requiring greater accommodation. The authors suggested that presbyopic contact lens corrected myopes required greater near adds underwater in scuba diving than viewing the same object in air when wearing contact lenses.

Contact lens wear is a risk factor for bacterial keratitis (Bourcier *et al.*, 2003). The evidence of amoeba isolation from swimming pool water was supported by research carried out in Poland by Górnik and Kuźna-Grygiel (2004), who concluded that the risk of contracting virulent strains of free-living amoebae by humans was higher in the open-air bathing pools compared to indoor swimming pools. A study on the microbiological quality in Finnish public swimming pools demonstrated that there was a theoretical risk of amoebic and bacterial keratitis associated with swimming (Vesaluoma *et al.*, 1995).

Research investigating whether hydrophilic contact lenses worn whilst swimming accumulated bacteria present in water reported that swimming increased micro-organisms present on the contact lenses (Choo *et al.,* 2005). A multicentre survey carried out in England between 1992-1996 (Radford *et al.*, 1998) investigating acanthamoeba keratitis concluded that 91% of the soft contact lens wearers who presented with acanthamoeba keratitis could have prevented the risk of the disease by effective disinfection and/or refraining from swimming whilst wearing lenses. Therefore swimming is still considered a contra-indication to soft contact lens wear (Schwartz, 1996). In contrast, studies carried out by Solomon (1977) and Solomon (1978) demonstrated no adverse effects of swimming in soft contact lenses and indicated that the soft contact lens may actually protect the cornea from irritation by chlorinated swimming pool water (Solomon, 1978; Soni *et al* 1986).

Salt water and chorine can impair the adhesion properties of soft contact lenses to the cornea (Werner, 2000). In a hypotonic environment, soft contact lenses can flatten and enlarge (Lergerton, 1993), whereas in a hypertonic environment lenses are more likely to tighten (Diefenbach *et al.*, 1988). However, it has been shown that in both environments soft contact lenses were more likely to adhere to the cornea (Diefenbach *et al.*, 1988).

A study of the characteristics of the tear-film by Quevedo *et al.* (2000) demonstrated that swimmers presented with a statistically significant reduction in tear film quality and quantity after aerobic training in an indoor swimming pool. The swimmers constantly wore protective goggles and because goggles prevented water evaporation, thus, reducing dehydration. They indicated that the reduction in tear volume may have been due to body dehydration.

Whether the practitioner decides to fit contact lenses for water sports and swimming, the use of water tight goggles should always be considered (Spinnell, 1993). A survey published by Loran (2003), reported that 76% of practitioners stocked swimming goggles which are available in plano or prescription lenses, clear, tinted or mirrored and with adjustable bridges. Goggles also helped the risk of rigid lenses going into the water, thus using a tight fitting goggle would prevent the loss of the contact lens (Spinnell, 1993).

1.2.7.2 Running / Track

Running is a dynamic sport that utilises a great amount of body movement and energy. During this sport an increase in lactic acid and a lack of glucose can develop causing corneal oedema, regardless of the running distance: short, medium or long (Bomholt and Schnell, 2000).

Quevedo *et al.* (2000) demonstrated that the quality and quantity of the tear film in track athletes did not significantly change from before to after training. They were surprised with the result as the track athletes were exposed to many environmental factors such as changes in air velocity and temperature, but this study only examined a small number of athletes (n=6) which may have affected their results and ability to conclude as indicated by the author. Due to running being a dynamic sport, IACLE (1998) recommended that contact lenses required extra stability on the eye, thus giving minimal movement on the eye when blinking. Ultra-violet protection is also an important consideration due to exposure to the sunlight if running outdoors (Schwartz, 1996) as the damage caused to the eye by long term exposure to ultra violet light is well documented (Classé, 1993b; McNeil, 2004).

1.2.7.3 Marksman / Precision Rifle Shooting

Marksmen require high levels of static visual acuity (Werner, 2000). Eye protection is essential due to flying debris from the gun and is advised over contact lenses (Breedlove, 1993; Gregg 1980). There are many myopic shooters who wear contact lenses as the advantage of contact lenses over spectacles is that good peripheral vision is obtained (Breedlove, 1993).

In this sport, Quevedo *et al.* (2000) demonstrated a statistically significant reduction in the quality and quantity of the tear-film with shooting training, believed to have arisen from a reduction in blinking rate. They suggested that high water contact lenses should be avoided and that the use of artificial tear substitutes would be advisable.

Although contact lenses have been suggested as the correction of choice for many sports, marksmen require intense concentration, meaning small movements of the contact lenses on blinking could be unacceptably off-putting and impede the performance of the shooter (Griffiths, 1999). RGP contact lenses however have a significantly better optical quality than soft contact lenses as they have been shown to produce a reduction in the eye's asymmetric aberrations and positive spherical aberration (Hong *et al.*, 2001).

1.2.7.4 Motor Sports

The Motor Sports Association UK is a division of The Royal Automobile Club and is responsible for Medical Standards in most UK motor sports. The association recommends that if contact lenses are worn, they should be of the 'soft' variety. They also state that contact lenses can be worn for motor cycling, but only under a full face visor or goggle (AOP, 2005).

1.2.7.5 Racket Sports

When looking at the tear-film of tennis players after training, Quevedo *et al.* (2000) showed a statistically significant difference in the meniscus test compared to non athletes. They assumed that environmental conditions played a major role with visual effort: general body dehydration and sympathetically-activated reduction in tear flow.

Soft contact lens for tennis have been recommended as they have better corneal coverage, less vertical and horizontal lag, thus better stability and centration when the player is looking up (Stein, 2002), compared to an RGP lens in which the lens frequently drops as the eye moves up. The author also suggested that, as contact lenses do not provide eye protection, eye protection is mandatory for squash and racquetball players because of the incidence of eye injuries. This statement was supported by a study carried out by Vinger and Tolpin (1978) in which they investigated injuries secondary to racket sports, concluding contact lenses provided no ocular protection.

1.2.7.6 Contact Sports

A study carried out by Giovinazzo (1987) on eye injuries and boxing concluded that after five losses in the ring, a boxer had a 20% chance of a retinal detachment and a 95% chance of a retinal tear after 75 bouts. The Association of Optometrists (AOP) Sport Vision Standards (AOP, 2007) stated that amateur boxing participants are not allowed to wear contact lenses or glasses; they also stated that if contact lenses are to be worn for karate, only soft contact lenses are advisable. IACLE (1998) also recommend fitting soft contact lenses that have good centration, good stability and minimal movement for contact sports. For sports such as football and rugby, impact to the head and body can occur frequently so they also recommend that RGP lenses should be avoided as they may be dislodged or damaged by such occurrences or cause trauma to the adnexa. Football has been demonstrated as the major contributor of sport eye injuries in the past (Capão *et al.*, 2003; MacEwen, 1989).

1.2.7.7 Altitudinal Sports e.g. Mountaineering / Skiing / Diving

The atmospheric pressure at sea level is about 760 mmHg comprising of 21% oxygen, thus the partial pressure of oxygen at sea level is 0.21 absolute atmospheres (ATA). As one ascends a mountain, the percentage of oxygen stays the same but there is a reduction in pressure (hypobarism), thus leading to a decrease in oxygen partial pressure. For example on the summit of Mount Everest (29,028 feet) the atmospheric pressure is 253 mmHg (0.33 ATA), equivalent to breathing just 7% oxygen at sea level (Butler, 1999).

It is well documented that the body responses to hypoxic stress by producing extra red blood cells, but with a reduction in plasma volume (Coote, 1995). If the reduction in atmospheric pressure is sudden, gas bubbles can occur in tissues in the body, including the eye and ocular adnexa. This condition is similar to bends in divers (Butler, 1999).

Simon and Bradley (1980) observed small bubbles in the pre-corneal tear-film beneath hard contact lenses following decompression. They demonstrated that these bubbles appeared as fine, punctate irregularities in the tear film and increased with time as decompression progressed. When the divers returned to the surface the bubbles decreased in number and size and after 30 minutes at sea level, no bubbles were seen under the contact lenses. They concluded that the use of PMMA contact lenses by individuals working in hyperbaric environments can cause injury to the cornea.

Flynn *et al.* (1987) examined the effects of soft and hard contact lenses at various altitudes, demonstrating bubble formation in approximately 24% of eyes tested and some were noted at altitudes of only 6,000 feet. They demonstrated that under soft contact lenses, the bubbles were seen at the limbus compared to RGP lenses in which the bubbles were located centrally, resulting in a potential reduction in vision.

Retinal blood flow has been shown to increase at high altitudes (Braun *et al.*, 1997). Frayser (1971) demonstrated that retinal blood flow increases by 128% at 17,384 feet after 4 days. It had been previously reported that this increase in blood flow resulted in an increase in diameter and tortuosity of retinal vessels, and optic disc hyperaemia (McFadden *et al.,* 1981).

High altitude retinopathy (HAR) is an increasingly known ocular condition in climbers who get above 16,000 feet (Wiedman and Tabin, 1999). Wiedman and Tabin (1999) demonstrated a prevalence of 74% of climbers who went above 16,000 feet in their study, had retinal haemorrhages, this increased to 91% who went above 25,000 feet. The retinal haemorrhages appeared in the inner retina. An investigation into HAR concluded that an inadequate auto-regulatory response of the retinal circulation under conditions of chronic hypoxia played an important role in the pathogenesis of HAR (Mullner-Eidenbock *et al.,* 2000).

Hypoxia can induce night blindness as it decreases retinal ganglion cell activity, both in photopic and scotopic vision (Vingrys and Garner 1987). Vingrys and Garner (1987) demonstrated a generalised colour vision loss affecting both red-green and blue-yellow discrimination at an altitude of 12,000 feet. This was also illustrated in a previous study in 1971 (Kobrick and Appleton, 1971).

As the cornea receives most of its oxygen from the atmosphere, it is important to consider the reduction in oxygen atmospheric pressure for mountaineers. As they ascend and that contact lenses can reduce the amount of oxygen available to the cornea, although cold weather, which usually increases as one ascends, depresses the basel metabolic rate of the corneal epithelium and oxygen demand is reduced. (Stein, 2002).

Hygiene has been demonstrated to be an important aspect of contact lens wear especially for long expeditions. Butler (1999) described how storing contact lenses in solution can freeze overnight in extreme cold temperatures. He suggested that the storage bottle containing the contact lenses should be kept in the sleeping bag at night.

Ultra-violet (UV) radiation exposure increases dramatically as elevation increases (Pitts *et al.*, 1977). This poses a problem for both mountaineers and skiers. In skiing, Classé (1993b) reported that photokeratitis can result from UV-B radiation reflecting from the snow. Socks (1982) concluded that this can be prevented by the use of goggles. It has also been suggested that contact lenses can be worn by skiers with no problems as long as protection from wind and glare is used (Holland, 1989).

Kolstad and Opsahl (1969) investigated the cause of blurred vision in cross-country skiers. It had been brought to their attention that cross-country skiers develop blurred vision when competing at very low temperatures. They examined 29 skiers after a 15 km race at temperatures of -16°C. Ninety per cent had epithelial damage shown by punctate staining (Rose-Bengal). One skier who wore contact lenses had no staining of the cornea. They found that the degenerated epithelium in the lower third of the cornea indicated insufficient protection by the lid due to impaired muscle contraction of the eye lids at such temperature. The damage was transitory and usually healed within 24 hours. They concluded a suitable solution would be the use of protective head gear, possibly combined with the use of contact lenses.

Socks (1982) investigated the use of contact lenses in rabbits in extreme cold temperatures. The author reported that previously reported instances of contact lenses sticking to the eye are more likely due to a dry eye problem as a result of low humidity and wind in cold climates rather than to freezing of the cornea. It has been reported that soft contact lenses can eliminate blepharospasm normally induced by falling snow that strikes the eyes when skiing fast (Weis, 1981).

1.2.7.8 Other Environmental Aspects of Contact Lens Wear and Sports

Athletic events can take place in hot and humid environments. As sweat can run into the eyes and cause blurring, Spinnell (1993) suggested a simple solution to wear fresh sweatband across the forehead or on the wrists to prevent this problem.

Wind has been demonstrated to cause lens dehydration by Legerton (1993). He suggested avoiding high water content thin lenses, followed by low-water content thin lenses.

1.2.7.9 Orthokeratology and the Athlete

Orthokeratology is "The reduction, modification or elimination of refractive error by the programmed application of contact lenses or other non-invasive procedures." as defined by the British Orthokeratology Society (BOKS, 2008).

It has been shown to effectively improve the myopic or astigmatic individual for a few hours by flattening the cornea with progressively flatter RGP contact lenses to achieve a reduction in myopia (Logan and Gilmartin, 2005), especially for refractive errors of myopia up to -5.00DS and astigmatism up to -1.50DC (BOKS, 2008). It has previously been suggested that this technique can be used for the athlete, enabling them to perform their sporting activity successfully without spectacles or contact lenses (Teig, 1980). However, microbial keratitis and corneal ulceration have been reported as an important risk factor during overnight orthokeratology (Hsiao, 2005; Hutchinson and Apel, 2002; Tseng *et al.*, 2005).

1.2.8 The Athletes Eye Exam

It has been reported that many sporting activities required a high level of visual skills (Table 1.6, Griffiths, 2005). The visual system provides sensorial information needed by athletes during competitive sporting activities (Gottin *et al.*, 1999). It has been suggested that 95% of all physical movements are controlled visually (Werner, 2000), and 70% of the information reaching the brain comes from the visual system (Spinnell, 1993), hence suitable visual correction is essential for the athlete (Werner, 2000).

SPORT	VISUAL SKILL
Cricket	Anticipation (batting) Hand eye response (fielding)
Football	Foot eye co-ordination Peripheral awareness
Archery	Visual acuity Glare recovery
Sailing	Glare recovery Motility Peripheral awareness
Table Tennis	Motility Hand eye reaction time
Snooker	Stereopsis Vergence facility
Netball	Depth judgement including stereopsis Peripheral awareness
Skiing	Contrast sensitivity Dynamic visual acuity
Hockey	Dynamic visual acuity Hand eye co-ordination
Athletics Track And Field	Visualisation Peripheral awareness
Tennis	Distance judgement Peripheral awareness Hand eye co-ordination
Clay Pigeon Shooting	Aiming Depth Judgement Eye tracking

Table 1.6
Visual skills required in different sports (adapted from Griffith, 2005)

The patient's 'History' taking is one of the most important aspects of the clinical eye examination for athletes (Berman, 1993). An adequate history must be taken to ensure that the clinician identifies the potential problems that the athlete may be experiencing, as an athlete may not associate their performance with a visual problem.

Griffiths (1999) stated that good vision is required in order to be successful at sport, but there are physiological limitations on the visual system. A study carried out by Christenson and Winkelstein (1988) demonstrated that athletes perform better than non-athletes in certain sports related to visual abilities, (e.g. eye-hand co-ordination). Analytical testing (Anticipation) has been proved to be an important aspect and helped the athlete to improve their reaction time (Griffith, 1999). Anticipation was interpreted by visual clues, (e.g. ball-spin and the speed of approach). Analytical tests and diagnostic tests (brock string, retinoscopy, dynamic fixation, vergence facility and accommodation facility) were carried out in a study by Griffiths (1999). The anticipation timing was measured using a Basin Anticipation Timer (a sequence row of light emitting diodes). The study found that those who anticipated later tended to be exophoric and those with poor anticipation were cross ocular dominant or totally left ocular dominant. Griffiths (1999) suggested that binocular vision and eye dominance were important to succeed in sport and therefore concluded that it was important that sports people were visually corrected, as seeing as clearly as possible helps to overcome the physiological limitation of the human nervous system. Applegate and Applegate (1992) investigated visual acuity on basketball shooting performance. They hypothesised that reduced visual acuity would lead to poor basketball shooting performance. The study ultimately found decreased visual acuity did not lead to significantly poorer shooting performance as the ring and board are large targets.

Beckerman and Hitzeman (2003) carried out a study to determine whether there was a need for specialist vision care services for athletes, and if there was any relationship between visual skills and athletic success. They investigated visual acuity, visual reaction time, motor reaction time, peripheral awareness and saccades at distance. They reported that, as athletes get older, their performance improved as a result of various vision care tests, concluding athletes would benefit from regular screening. The need for vision care was also demonstrated in the study carried out by Gottin *et al.* (1999), in which they discovered that 8.5% of athletes were unaware of a visual defect.

Although there are many factors relating to the success of athletes (e.g., coaching, training and attitudes), previous studies have agreed that visual skills contributed significantly to the performance of an athlete and further research is needed (Beckerman and Hitzeman , 2003; Gottin *et al.*, 1999; Griffiths, 1999).

Griffiths (1999) reported that it was important to understand that eye exercises are not the solution, and were only appropriate when there was a deficiency in visual performance after a full correction had been made.

The standard testing of visual acuity is the Snellen test, but only a small number of sports, such as archery and shooting, involve high contrast targets and backgrounds (Berman, 1993). Studies carried out by Coffey and Reichow (Coffey and Reichow, 1989; and Reichow and Coffey 1986) have demonstrated that when testing athletes' contrast sensitivity, athletes exhibit better acuity at higher spatial frequencies and achieve higher contrast sensitivity function overall than non-athletes.

Contrast sensitivity testing has been used in many studies to evaluate the performance of contact lenses (Bernstein and Brodrick, 1981; Cox and Holden, 1990; Kirkpatrick and Roggenkamp, 1985; Tomlinson and Mann, 1985; Wachler *et al.*, 1999). Briggs (1998) reported that contrast sensitivity testing is a more realistic measure of assessing contact lenses than LogMAR visual acuity, and a study carried out by Wachler *et al.* (1999), compared contrast sensitivity between different soft contact lenses and spectacles. They concluded that visual acuity appeared to be an insensitive method for evaluating soft contact lenses as there was no significant difference in visual acuity between any of the contact lenses tested. Contrast sensitivity testing has also been proven to be important for athletes wearing contact lenses, since it has been shown that if the lens performance was not optimal, it was not detectable when using a Snellen chart (Nowozyckyj *et al.,* 1988; Oxenberg and Carney, 1989; Grey, 1986).

1.2.9 Eye Protection in Sports

Griffiths (2005) reported that contact lenses, although the correction of choice for many sports, provide little or no eye protection during sporting activities concluding that, when prescribing contact lenses for such activities, they should often be combined with the protective advantages of a plano polycarbonate lenses in a sports appliance.

Sport has been identified as the most common cause of severe eye injury (MacEwen, 1989). Furthermore, eye injuries accounted for 2% of all sporting injuries (Medical Officer School Association). A survey carried out in Glasgow in 1988 (MacEwen, 1989) reported that 42% of all sport-related ocular injuries were due to football, indicating it as the major sport for sport-related ocular injuries. This was supported by a later study in Scotland (Barr *et al.,* 2000) reporting that the incidence of eye injury due to sport was 12.5%, with football being the most common cause. This sport also represents most sport injuries in Norway, Portugal and Britain (Capão *et al.,* 2003), although injury from racquet sports was also common in Britain (Barr *et al.,* 2000). In the US, baseball and basketball have been implicated as the cause of most sports eye injuries (Wong *et al.,* 2000). Research carried out in Portugal (Capão *et al.*, 2003) demonstrated that squash, paintball, bungee jumping and soccer injuries had resulted in an alarming number of severe ocular injuries. The prospective survey carried out by MacEwen (1989) demonstrated that, although sports injuries only accounted for 2% of all ocular trauma (Figure 1.4), 42% of all ocular trauma that required hospital admission were sports-related (Figure 1.5). MacEwen (1989) recorded a range of ocular injuries associated with different sports (Table 1.7).

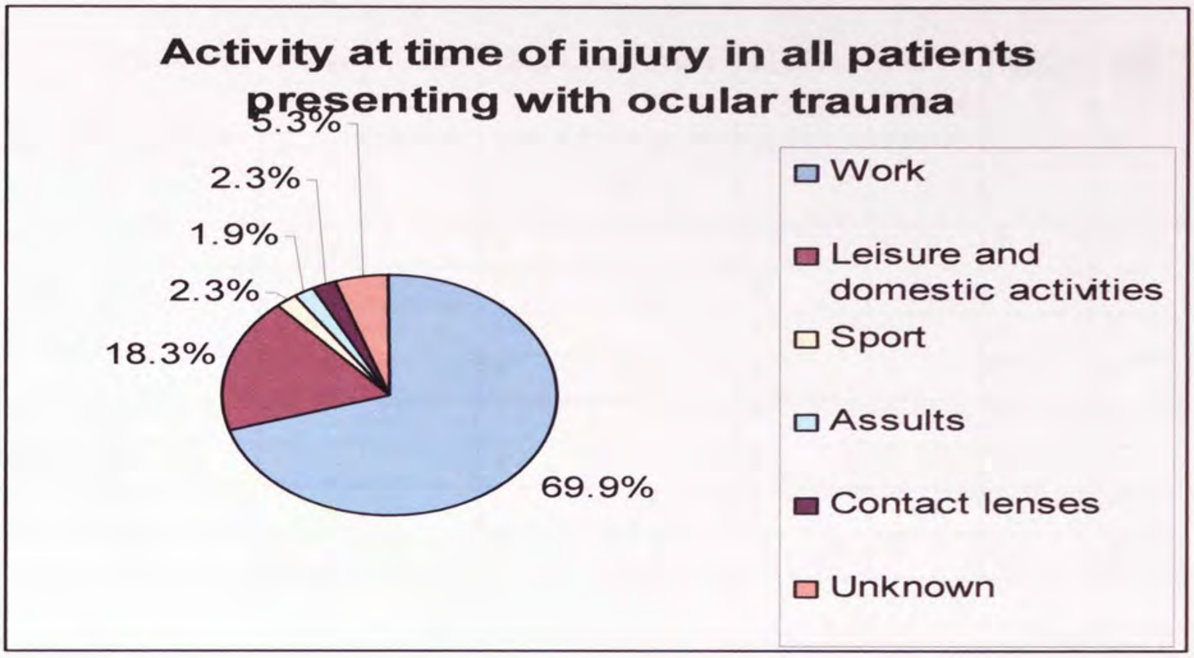


Figure 1.4
Type of activity that was carried out at the time of ocular trauma (redrawn from MacEwen 1989)

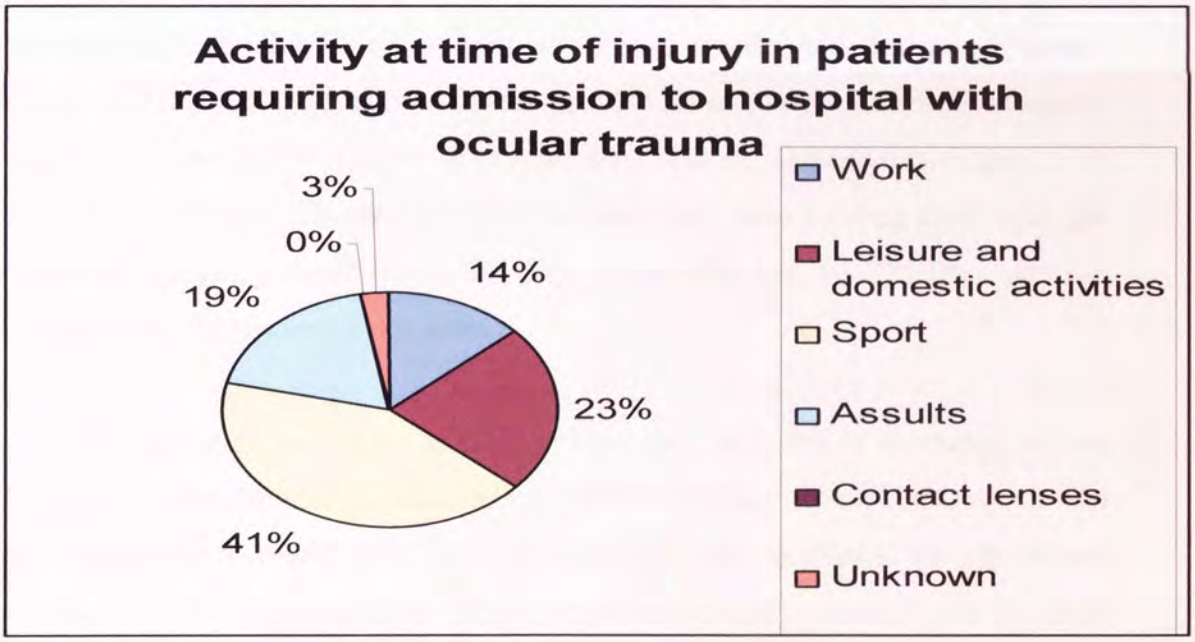


Figure 1.5
Activity required hospital admission (redrawn from MacEwen 1989)

Sport	Periorbital	Foreign Body	Corneal	Conjunctival	Uveitis	Hyphaema	Post Segment	Rupture	Total
Football	12	2	12	2	6	10	11	0	55
Squash	2	0	4	0	3	3	1	0	13
Badminton	0	0	1	0	1	6	1	0	9
Rugby	5	0	2	0	0	0	0	0	7
Golf	1	2	3	0	0	0	0	0	6
Cycling	0	2	2	1	0	0	0	0	5
Swimming	0	0	3	2	0	0	0	0	5
Other	8	1	11	3	3	2	2	1	31
Total	28	7	38	8	13	21	15	1	131

Table 1.7
Ocular injuries associated with different sports (adapted from MacEwen 1989)

The use of polycarbonate lenses for ocular protection is well documented and is clearly the lens of choice (Griffiths, 2005; Classe, 1993a; Davis, 1988), as it has been suggested that failure to prescribe this material could lead to negligence (Classe, 1993b). Although contact lenses provide no ocular protection from injury, Tang (2005) reported two cases of contact lens wearers that protected their eyes from serious foreign body-related injury because they were wearing their rigid gas permeable contact lenses. However, they concluded that RGP lenses are not recommended for protective purposes.

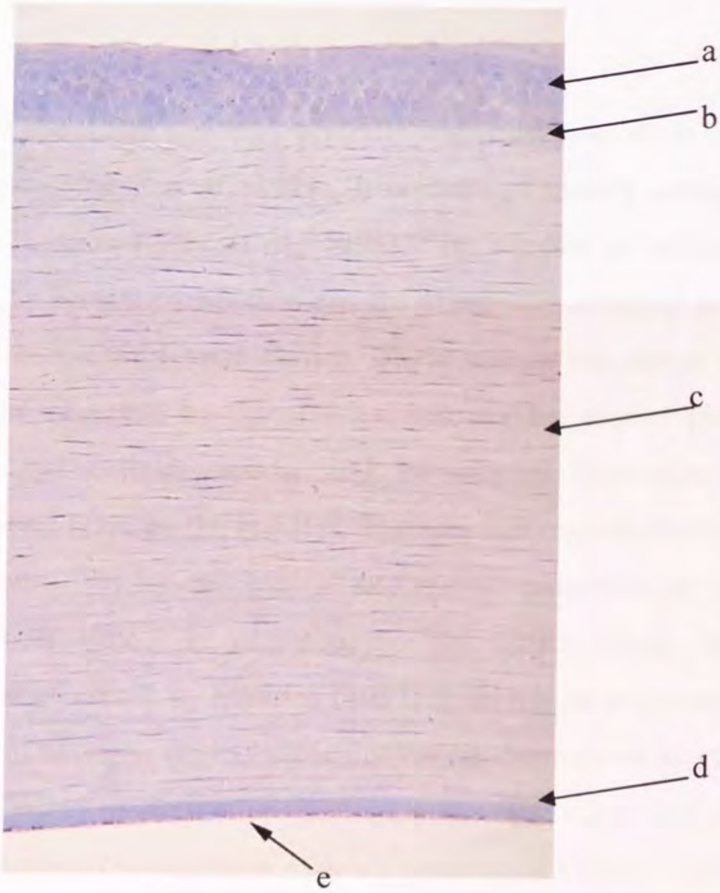
Ocular injury secondary to UV radiation can vary; this is dependant on the radiation wavelength and exposure (Sliney, 1988). Tomany *et al.* (2004) researched the relationship between sunlight exposure and the incidence of age-related maculopathy. They demonstrated that participants exposed to summer sun for more than five hours a day during their teens were at a higher risk of developing increased retinal pigment, concluding that the use of UV protection is essential.

It is evident that contact lenses are the ideal choice for vision correction during many sporting activities. There are many advantages and disadvantages of certain contact lens modalities for a given sport. As contact lenses can impede the passage of oxygen to the anterior surface of the cornea, it is essential that the physiology of contact lens wear during exercise is investigated to establish more evidential reasoning as to the most suitable type of contact lens to fit for sports.

PART 2: OXYGEN AND THE CORNEA

1.3.1 Anatomy and Physiology of the Cornea

The cornea is a transparent, avascular structure which has an average dimension of 11.7 mm horizontally and 10.6 mm vertically (Bron *et al.*, 1997). The central part of the cornea is thinner (approximately 0.56 mm) compared to the periphery (around 0.75 mm). It is made up of five layers, each layer providing a different function (Figure 1.6).



a=Epithelium, b=Bowman's layer, c=Stroma, d=Descemet's membrane, and e=Endothelium

Figure 1.6
A cross section of the five corneal layers, with the epithelium being the outmost layer (Reproduced from www.city.ac.uk, 02/02/06)

The epithelium is the outermost layer of the cornea and consists of primarily three types of cells; these are, from anterior to posterior, the superficial cells, wing cells and the basal cells (Bron *et al.*, 1997). The thinnest area is around 50-60 μm centrally and increases to about 70 μm near the limbus (Reinstein *et al.*, 1994). The main functions of the epithelium are to provide a mechanical barrier to micro-organisms, maintain the diffusion of water and solutes, and provide a smooth, transparent optical surface.

Beneath the epithelium is the Bowman's membrane, which is an anterior condensation of the superficial stroma (Stein, 2002). It is around 12 μm thick and terminates at the limbus (Gray *et al.*, 1995). It acts as a strengthening layer of the cornea.

The stroma is about 500 μm thick centrally and constitutes up to 90% of the total corneal thickness (Hogan *et al.*, 1971). It consists of mainly collagen fibres which are uniquely uniform (Gray *et al.*, 1995). The bundles of collagen fibres stretch from limbus to limbus of which there are about 233 arranged lamellae of collagen bundles in the central human cornea. Blood vessels are absent and nerve cells are occasionally observed in the anterior and middle stroma (Jalbert and Stapleton, 2005). Extracellular matrix and keratocytes (specialised corneal fibroblasts) are scattered between the bundles. The size and organisation of stromal collagen fibrils influence the bio-mechanical and optical properties of the cornea and hence its function (Boote *et al.*, 2003). The lattice theory of corneal transparency was first proposed by Maurice (1957) in which he suggested that the regular arrangement of collagen fibrils in a lattice causes destructive interference of light, behaving as a series of diffraction gratings permitting transmission through the liquid ground substance (extracellular matrix). Jester *et al.* (1999) suggested that the maintenance of cellular transparency was due to the water soluble proteins transketolase and aldehyde dehydrogenase found in the keratocyte bodies in the non traumatised cornea. The stroma is adherent to the Descemet's membrane, which is produced by the endothelium (Bron *et al.*, 1997). The Descemet's membrane grows throughout life; with a thickness of 5 μm at birth and increases to around 17 μm in the 9th decade (Gray *et al.*, 1995) and can regenerate readily after injury (Phillips and Speedwell, 1997).

The endothelium is the deepest layer of the cornea and its main function is to act as a permeability barrier for the passage of salt and metabolites in and out of the stroma. It also has a metabolic action pumping the bicarbonate ions out of the stroma into the aqueous (Hodson and Miller, 1976). These two actions are responsible for maintaining the corneal stroma free from oedema (Bron *et al.*, 1997). The endothelium consists of a single layer of flat and hexagonal cells that are in direct contact with the aqueous humor and is around 3-5 μm in adult life (Bron *et al.*, 1997). These cells do not regenerate throughout life but increase in size during the growth of the eye and spread to cover damaged areas when injured (Murphy *et al.*, 1984).

1.3.2 Oxygen Supply to the Cornea

In 1974, Fatt *et al.* indicated that oxygen (O_2) does not diffuse through the total thickness of the cornea, suggesting oxygen enters from both the anterior (epithelium) and posterior (endothelium) surfaces of the cornea with a minimum oxygen tension in the stroma (Figure 1.7) (Fatt *et al.*, 1974). The oxygen flux (rate of movement) into the cornea is dependant on the corneal metabolic rate and, providing there is no change in O_2 supply, then a steady state is maintained (IACLE, 1998).

It has been suggested that all of the oxygen supply to the corneal epithelium comes from the atmosphere in the open-eye condition and from the palpebral conjunctival blood vessels in the closed-eye (Galvin *et al.*, 2000), whereas, the endothelium is supplied by the aqueous humour (Weissman *et al.*, 1982).

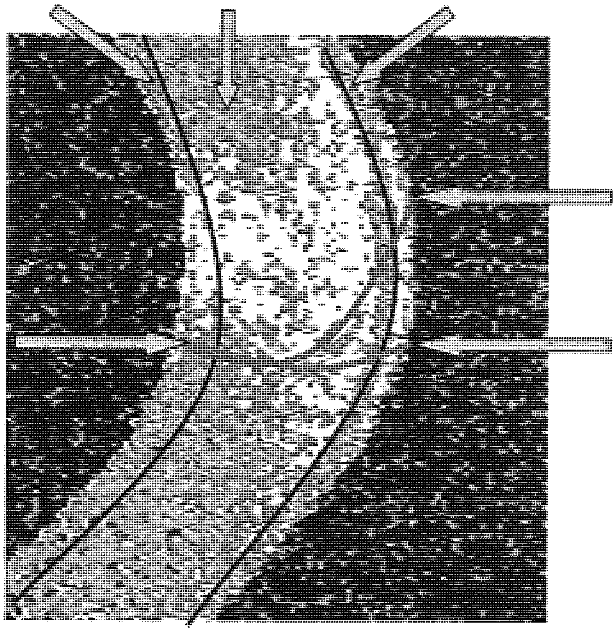


Figure 1.7
Schematic diagram of oxygen tension across the cornea. The blue line represents the open-eye condition, whereas the red line illustrates the closed-eye condition (adapted from Benjamin and Hill, 1986)

1.3.2.1 Supply to the Corneal Epithelium

1.3.2.1.1 Open-eye condition

Oxygen from the atmosphere diffuses across the tear film to supply the anterior cornea in the open-eye condition, being composed of 20.9% O_2 or 155 mmHg partial pressure (ranges from 151-159 mmHg) at sea level. Research has demonstrated that oxygen flux into the human cornea is around 4.8 μl / cm^2 / hr (Hill and Fatt, 1963), although Larke *et al.* (1981) reported flux to be between 3 and 9 μl / cm^2 / hr. Weissman (1984), mathematically estimated the oxygen consumption of the cornea to be 4.85 x 10^{-5} mlO_2/ml/s by assuming the corneal thickness was 0.5 mm. Limbal oxygen of the cornea comes from the blood of the ophthalmic artery diffusing a short distance from the radial capillaries (Ruben and Guillon, 1994). Benjamin and Hill, (1988a) demonstrated that the mean oxygenation in the open-eye state, at 1 mm below the superior limbus, was 10.7% atmospheric oxygen (79 mmHg). They also found that, on average, a 2.1mm vertical depth of the superior cornea (7% of the corneal area) is covered by the upper eyelid in the open-eye state.

1.3.2.1.2 Closed-eye condition

The anterior surface of the cornea in the closed-eye condition receives much less oxygen compared to the open-eye condition. Benjamin and Hill (1986) demonstrated that the effect of lid closure on oxygen demand to the cornea was almost immediate. At 1 minute after lid closure, by using a micropolarographic system (see section 1.3.4.1), the increase in oxygen demand was more than twice the average open-eye demand. They demonstrated an individual range from 2.10 to 2.82 times and suggested that this may have been due to difference in lid closure. In the closed-eye oxygen may enter the palpebral fissure from the atmosphere if the eye is not completely closed, identifying that lid flicker (very brief lid opening) when the eye was closed had a moderate effect in reducing the closed-eye oxygen demand. Holden and Sweeney (1985) measured the oxygen tension of the upper palpebral conjunctiva of 16 humans to be 61.4 ± 6.9 mmHg (8.2% atmospheric oxygen), whereas Efron and Carney (1979) found oxygen at the anterior corneal surface beneath the closed eyelid in 12 young adults to be 7.7 ± 3.8% atmospheric oxygen (56.7 mmHg). This is similar to measurements by Fatt and Beiber, (1968) in a single subject (55.5 ± 5.5 mmHg). It had been shown that the superior cornea in the closed-eye receives around 1.1% less oxygen compared to the central cornea in the closed-eye state (Benjamin and Hill, 1988b). Table 1.8 summarised average O_2% in the open and closed-eye condition.

CONDITION	O_2 (%)	O_2 TENSION (mmHg)
Open-eye, Central Cornea	20.9	159
Open-eye, Superior Cornea	10.4	79
Closed-eye, Central Cornea	7.7	59
Closed-eye, Superior Cornea	6.6	50

Table 1.8
Oxygen percentages and tensions at different corneal locations in open-eye (adapted from Ruben and Guillon, 1994)

1.3.2.2 Oxygen Supply to the Corneal Endothelium

The oxygen supply of the endothelium surface is supplied by the aqueous humour (Weissman *et al.*, 1981). Posterior surface oxygen diffuses in to the cornea from a reservoir of oxygen of approximately 55 mmHg partial pressure, equivalent to 7.4% O_2 in the atmosphere at sea level from the aqueous (Ruben and Guillon, 1994). This has been confirmed by a study carried out by Riley (1969) in which he demonstrated that a significant proportion of the oxygen supply comes from the aqueous even in the open-eye condition. This finding was further supported by Fatt *et al.* (1974) who showed that even for the open-eye the oxygen supply for the endothelium comes from the aqueous.

1.3.2.3 Oxygen Supply to the Corneal Stroma

Hamano (1986) illustrated that in a rabbit cornea the oxygen supply for the stroma of the cornea comes from the anterior chamber. They demonstrated this by investigating the effect of PMMA contact lenses on the cornea of a rabbit.

Table 1.9 gives and overview of the source of oxygen supply to the different layers in the human cornea.

STRUCTURE	**OPEN-EYE**	**CLOSED-EYE**
Epithelium	Atmosphere and aqueous	Palpebral conjunctiva
Stroma	Aqueous	Aqueous
Endothelium	Aqueous	Aqueous

Table 1.9
Oxygen supply to the cornea

1.3.3 Oxygen Supply to the Cornea with Contact Lenses

When wearing contact lenses, the physiological integrity of the cornea is dependant on the amount of oxygen available beneath the contact lens (Brennan *et al.*, 1987) and it is known that contact lens wear disrupts the diffusion of oxygen to the cornea (Brennan, 2005). Anterior corneal oxygenation is dependant upon the diffusion of atmospheric oxygen through the contact lens and the tears beneath the contact lens (Benjamin, 1994).

The flow of oxygen to the cornea though a contact lens is given by Fick's law (Equation 1.1).

j = (Dk/t)(P1-P2)
j = Oxygen flux (amount of O_2 that flows through a unit area of a substance in a unit time (IACLE, 1998))
Dk/t = Oxygen transmissibility
P1 = Partial Pressure at the anterior surface of the contact lens
P2 = Partial pressure at the posterior surface of the contact lens

Equation 1.1

Fick's Law (Brennan *et al.*, 1987)

During open-eye conditions, the partial pressure of oxygen at the anterior surface of the contact lens is around 155 mmHg surface of the lens and 55 mmHg in a closed-eye, equivalent to 7.7% oxygen (Efron and Carney, 1979). It has been suggested that the partial pressure at the posterior surface of the contact lens is dependent on the contact lens oxygen transmissibility (Dk/t) and the oxygen consumption of the cornea (Brennan *et al.*, 1987). In a review article by Brennan *et al.* (1987), the flow of oxygen through the contact lens can also be hindered by the tear film, thus the tear film on the anterior and posterior surface of the cornea affects the oxygen transmissibility and thus a new equation was derived (Equation 1.2). However, Brennan commented that this effect needed to be verified.

$$1/(Dk/L)m = Rt1 + L/(Dk)1 + Rt2$$

Rt1 = resistances due to the anterior tear layer

Rt2 = resistances due to the posterior tear layer

Equation 1.2
The adjustment for tear film

1.3.4 Measuring Corneal Oxygen Demand with and without Contact Lenses

To determine the effect of a contact lens on the oxygen supply to the cornea, many studies have been carried out measuring the oxygen uptake rate of the cornea with and without contact lenses (Benjamin and Hill, 1985; Fink and Hill, 2006; Gardner *et al.*, 2005). The most common method being the use of a polarographic sensor on the naked cornea and after a short period of time wearing a contact lens (Benjamin and Hill, 1985; Fink and Hill, 2006; Gardner *et al.,* 2005: Hill and Fatt, 1963).

1.3.4.1 Polarographic Technique

In 1963, Hill and Fatt (Hill and Fatt, 1963) were the first to make *in vivo* measurements of oxygen uptake of the cornea in the open-eye state from the atmosphere by humans. They used a Clark type polarographic electrode covered with a polyethylene membrane fixed to a scleral contact lens, which allowed a known oxygen tension solution to be flushed under the lens. This technique was subsequently applied to the closed-eye condition (Hill and Fatt, 1964).

The polarographic sensor was calibrated with normal levels of atmospheric levels of oxygen (around 155 mmHg). The sensor was then applanated onto the bare cornea and the reservoir of oxygen diffused into the epithelial cells at the rate of their metabolic process (Figure 1.8).

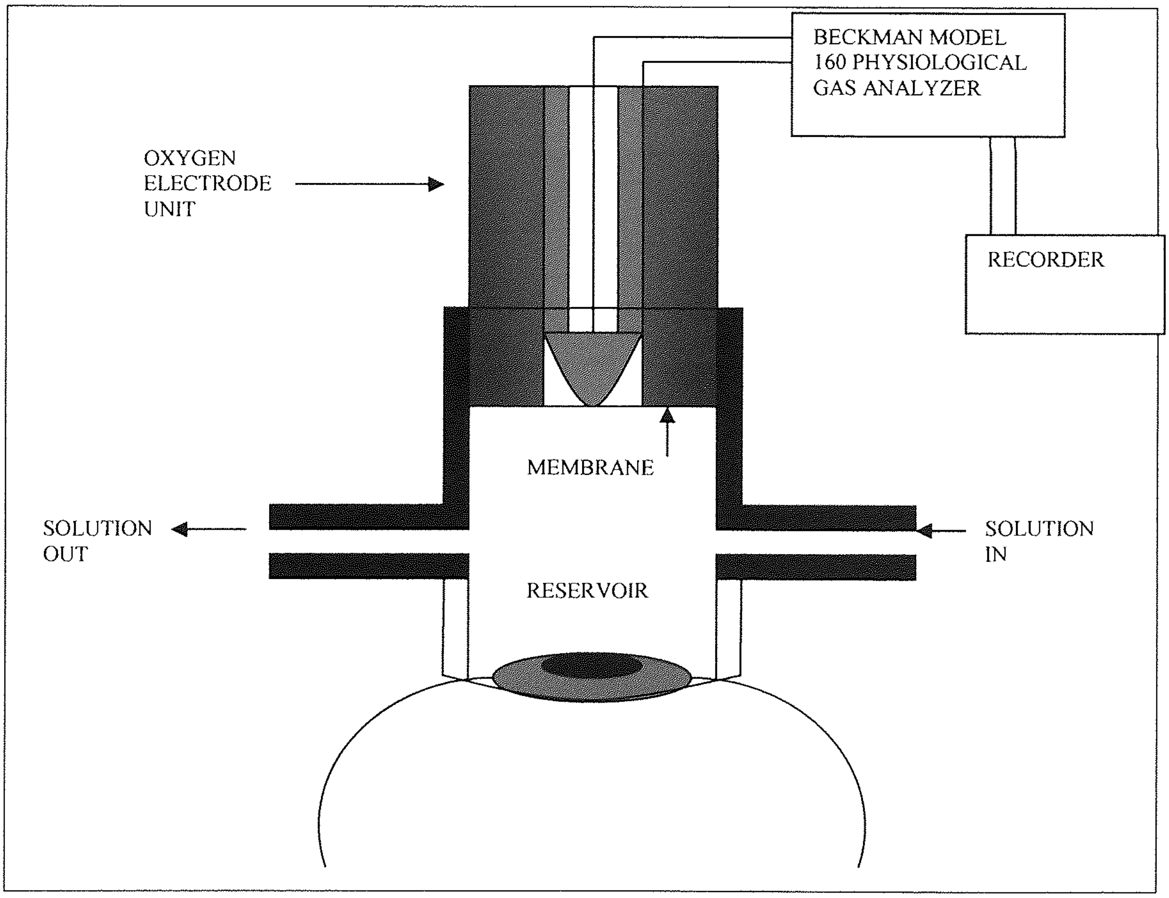


Figure 1.8
Schematic diagram of the electrode and lens assemblies used to obtain data for calculating the rate of oxygen consumption by the cornea *in vivo*. The reservoir volume may be changed as desired by moving the electrode assembly. (redrawn from Hill and Fatt, 1963)

Different membrane materials have been used in the past. Larke *et al.* (1980) described the polarographic sensor covered by a sheath of Delrin, whereas Quinn, (1981) used Teflon™ (Quinn, 1981, cited in IACLE, 1998). There have been four methods described in the literature to record the corneas response to oxygen using the polarographic technique (Fink and Hill, 2006).

1- Absolute units (mmHg) oxygen tension.
2- Oxygen uptake rate, a ratio of the corneal response under test conditions to the corneal response in air.
3- Percentage of the corneal response to hypoxia (change in corneal thickness)
4- Oxygen shortfall units (OSUs)

The oxygen shortfall units (OSUs) were used to assess the oxygen performance of the contact lens on the cornea, on a relative scale from 0 to 100. Zero is representative of the oxygen uptake rate for an eye in normal open conditions without a contact lens, in contrast to 100 OSU which represents the oxygen uptake rate associated with extreme hypoxia (Fink *et al.*, 1994; Hill and Szczotka, 1991).

Adaptations of the polarographic technique have been used in many studies to measure corneal oxygen consumption (Benjamin and Hill, 1986; Fink *et al.*, 1991a; Gardner *et al.*, 2005; Kwok, 1986). A study by Fink *et al.* (1991a) investigated the variability of human corneal oxygen uptake using a micro-polarographic electrode (25 μm diameter cathode, fitted with a 12.5 μm-thick polyethylene membrane) on the right cornea. A total of 24 measurements from 6 healthy subject were collected on the open-eye condition and hypoxic conditions (use of a PMMA contact lens), identifying a difference among the oxygen uptake rates of individual corneas.

1.3.4.1.1 The polarographic technique in contact lens wear

Contact lens oxygen transmissibility is an important aspect of corneal integrity during contact lens wear (Fatt and Ruben, 1994). Over the years many researchers have investigated the effect of contact lenses on the eye and tried to establish a contact lens material that will not alter corneal metabolism.

Many experiments have been carried out *in vivo* measuring Equivalent Oxygen Percentage (EOP) which gives a quantity that is related to the oxygen tension at the cornea-contact lens interface (Figure 1.9) (Fatt and Ruben, 1994; Hill and Fatt, 1963; Holden *et al.*, 1990; Ichijima *et al.*, 1998). The method for measuring the EOP was developed by Hill and Fatt (1963). EOP is a technique used to determine the level of oxygen at the surface of the cornea beneath the contact lens *in situ* (Benjamin, 1995). It is described as equivalent oxygen percentage because it is not measuring the oxygen beneath the contact lens directly. The technique involves the placement of the test contact lens onto the cornea for a period of about 300s. The contact lens is them removed, followed by the placement of a polarographic sensor in direct apposition with the surface of the cornea (Figure 1.9). The oxygen will then transfuse from the O_2 containing membrane of the polarographic sensor into the cornea. This depletion rate of the oxygen is dependant upon the oxygen depletion of the cornea caused by the test contact lens. The technique requires two stages (Efron, 1991), firstly the 'calibration' in which the cornea is subjected to several oxygen concentrations (ranging from 0% to 21%) and recordings are made. Then, secondly, a test contact lens is placed over the eye for a test period and then removed, the depletion rate being compared to the calibration to give an EOP result (Efron, 1991). Extensive research with this technique on the human cornea has indicated variations between individuals and techniques with the mean 4.8 $\mu l / cm^2 / hr$ for oxygen consumption by the cornea.

Others have placed the sensor directly on top of hydrogel lenses that have been worn on the eye to calculated oxygen flux (Fatt, 1978). However, the diffusivity and solubility of oxygen in the contact lens material is required. This has been reported to work best on hydrogels lenses with water percentages of around 40% (Fatt, 1978).

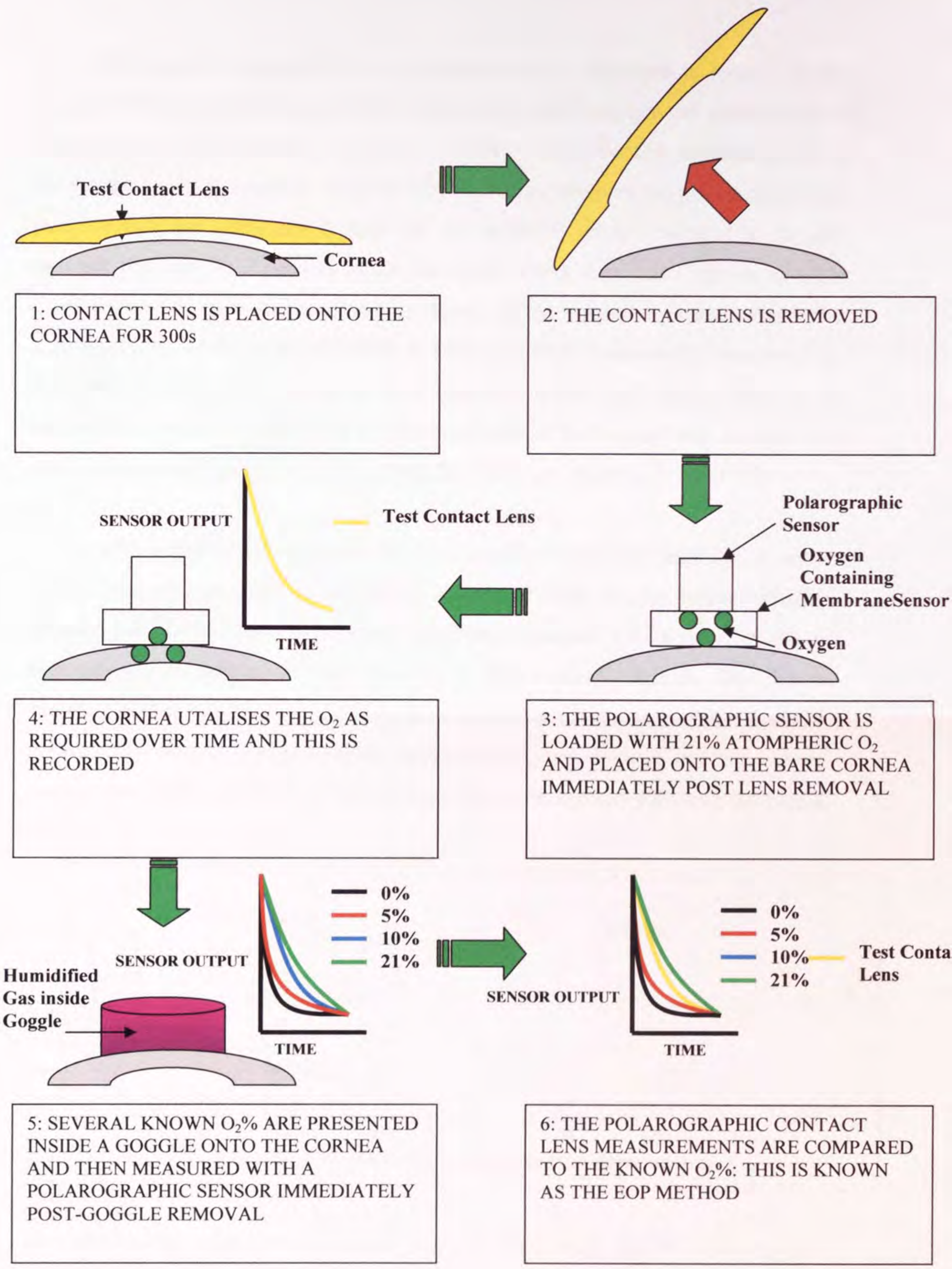


Figure 1.9
EOP method for measuring the effects of contact lenses on corneal oxygen uptake

The oxygen transmissibility of a contact lens is important in relation to the oxygen available to cornea and refers to the ease at which oxygen can pass through a contact lens of known thickness (Efron, 1991). The term Dk refers to permeability of the material, with D standing for diffusivity (speed at which an oxygen molecule can pass through the lens), and k signifies the solubility of the material to oxygen (oxygen that can be dissolved in the material). The t term (also known in older literature as L) refers to the centre thickness of the contact lens and affects the transmissibility of the material, which is known as Dk/t. Some researchers, such as Fatt, prefer to use flux instead of Dk/t (Brennan 2005). The oxygen flux in the contact lens system is influenced by characteristics of the contact lens material and design, the tear-film, and the cornea (IACLE, 1998) (see equation 1.1 and 1.2).

Although the EOP technique does not assess oxygen transmissibility directly it has been demonstrated to be highly correlated with oxygen transmissibility (Holden and Mertz, 1984) in the static condition, especially over a range of 4% to 19% oxygen (Benjamin, 1993) (Figure 1.10). In a review article in 1991, Efron commented that this is not necessarily the case because factors other than material permeability or lens transmissibility may affect oxygen passage into the cornea during wear (Efron, 1991). The EOP method had been applied with both hydrogels and RGP lenses.

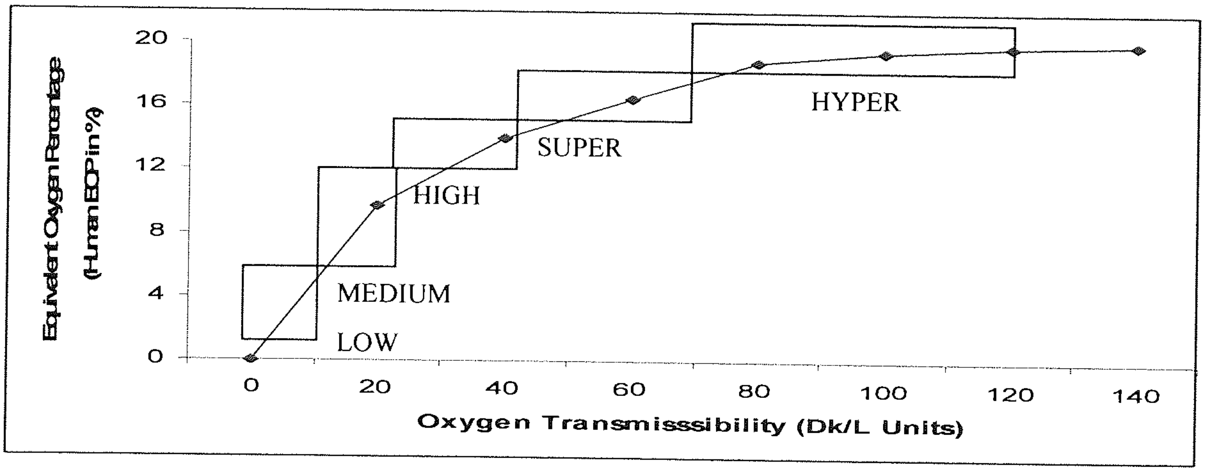


Figure 1.10
The relationship between equivalent oxygen percentage (EOP) and oxygen transmissibility (Dk/t), demonstrating a non-linear curve showing the slope of the curve being higher below 6% oxygen progressively flattening over a range of Dk/t until around 18% (redrawn from Benjamin, 1993)

1.3.4.2 Pachymetry Method

Changes in corneal thickness have previously been suggested as an exceptional indicator for measuring normal corneal physiology with and without contact lenses (Mandell *et al.*, 1970). The pachymetry method measures the change in corneal thickness from a baseline in response to the test environment, for example the change in response to eyelid closure compared to the open-eye. In 1984, Holden and Mertz explored the critical oxygen to avoid corneal oedema during daily and extended contact lens wear (Holden and Mertz, 1984). They concluded that to prevent corneal swelling in the open-eye (Daily lens wear) the minimum Dk/t contact lens would need to be $24.1 \pm 2.7 \times 10^{-9}$ (cm x ml O_2)/(sec x ml x mmHg) or an EOP of 9.9%.

Holden *et al.* monitored corneal thickness over 36 hours without contact lens wear (Holden *et al.*, 1983). They found that the mean overnight swelling of the cornea on awakening was 3.0% ± 1.2%, but with contact lenses they found an increase in overnight corneal swelling of between 9.7% and 15.1%, with the cornea showing gross stromal oedema. They suggested that 8% overnight swelling was the desirable maximum overnight swelling with extended wear contact lenses because this amount of swelling allowed the cornea to regain normal thickness during the day. Later in 1984, Holden and Mertz hypothesized that to avoid overnight contact lens induced corneal swelling, the critical oxygen transmissibility (Dk/t) of a contact lens should exceed $87 \pm 3.3 \times 10^{-9}$ (cm x mLO_2) (sec x mL x mmHg) (Holden and Mertz, 1984). Previous studies on the value of overnight swelling without contact lenses has ranged from 1.8 to 4.3% (Fonn *et al.*, 2005). More recently, in 1999, Harvitt and Bonanno calculated from a mathematical model that a contact lens Dk/t required to avoid swelling during the closed-eye condition was 125×10^{-9} Dk/t which was higher than that previously proposed by Holden and Mertz in 1984 (Harvitt and Bonanno, 1999).

1.3.4.3 Goggle Experiments

The use of an air-tight goggle to change the pre-corneal environment has been used in many experiments (Holden *et al.*, 1984; Holden *et al.*, 1985b; Mandell and Farrell, 1980; Polse and Mandell, 1970). The change in corneal thickness is measured in response to a known O_2% within the goggle placed over the cornea. Polse and Mandell (1970) investigated human corneal hydration by measuring changes in corneal thickness of three subjects. They subjected the cornea to various atmospheric oxygen percentages under an air-tight goggle for 8 hours, concluding that, to maintain normal central corneal thickness, the critical level of atmospheric oxygen was 1.5% to 2.5% (11.4 – 19.0 mmHg). Mandell and Farrell (1980) exposed 28 human corneas to different levels of oxygen partial pressures in a gas goggle for 4 hours. Their results showed that the average oxygen threshold to prevent corneal swelling was between 23 and 37 mmHg as it varied among individuals. Holden *et al.* (1984) also investigated the effect of various oxygen concentrations on eight subjects. They used concentrations of 1.0% to 21.4% (oxygen partial pressure 8 – 158 mmHg) oxygen which was supplied under a modified swimming goggle for eight hours. They measured corneal oedema through the goggle using pachymetry to measure corneal thickness. Central corneal thickness was measured both before and immediately after the goggle was placed on the subject, and at intervals of 1, 2, 4, 6, and 8 hours of gas flow. The mean results demonstrated that the minimum oxygen tension to prevent corneal swelling was 10.1% oxygen (74 mmHg), although there was a considerable individual variation.

1.3.4.4 Phosphorescence Method

An oxygen-sensitive phosphorescent dye has previously been used within a contact lens or tear film, allowing the oxygen beneath the contact lens to be measured. By this method Harvitt and Bonanno investigated the tear oxygen tension beneath gas permeable contact lenses in rabbits (Harvitt and Bonanno 1996). They used an oxygen-sensitive phosphorescent dye Pd mesotetra porphine which was added to the tears of New Zealand white rabbits. A contact lens was inserted and phosphorescence measurements were taken for 15 minutes. They concluded that phosphorescence-based measurements allowed direct non-invasive assessment of oxygen availability beneath a contact lens. More recently Bonanno *et al.* (2002) investigated a non-invasive measurement of tear oxygen tension while wearing hydrogel lenses to estimate human corneal oxygen. The procedure used an oxygen-sensitive dye which had been soaked in two standard hydrogel contact lenses (38% water) and a Silicone Hydrogel (SiH) contact lens overnight. The lenses were then placed onto the subject's eye and the tear oxygen tension (pO_2) was measured. They demonstrated that the tear oxygen tension in the SiH contact lens was 97.6 ± 22.9 torr (unit of pressure), 30.6 ± 3.1 torr for the thin hydrogel (0.06 mm), and 8.1 ± 3.1 torr for the thick hydrogel (0.2 mm) lens. The study therefore concluded that tear pO_2 behind hydrogel lenses could be measured in humans with this simple method. However, changes in the concentration of the dye through lens dehydration and diffusion into the tears will affect the results, as will the thickness of the lens, and it is not known whether the dye is toxic to the eye, so the technique may not be as non-invasive as suggested.

Phosphorescence had also been used by McLaren *et al.* (1998), in which they investigated oxygen tension in the anterior chamber of rabbits by injecting a phosphorescent dye (Pd-uroporphyrin) into the aqueous. They demonstrated that this technique allowed them to determine oxygen concentration *in vivo*.

1.3.5 Variations of Measurements Corneal Oxygen in the Open-Eye*

**Polarographic technique used unless stated otherwise*

1.3.5.1 Patient Variability

The oxygen uptake rate of the human cornea is some what variable, with estimations of between 1 and 10 $\mu l/cm^2/hr$ (Fink and Hill, 2006). Hill and Fatt (1963) first reported the human corneal oxygen uptake rate on humans as 4.8 $\mu l/cm^2/hr$ at sea level atmospheric pressure, whereas Jauregui and Fatt (1972) reported the average rate to be 2.8 $\mu l/cm^2/hr$. The variation in results may have been due to the number of epithelial cells in the cornea as suggested by Larke *et al.* (1981). Ocular health of the individual cornea is important when measuring oxygen uptake rate as Hill, (1979) showed that the health of the eye could influence the uptake rate.

1.3.5.2 Effect of Position on the Cornea

Generally previous experiments measuring corneal oxygen uptake rate have been limited to the central cornea (Benjamin and Hill, 1986; Hill and Fatt, 1963; Larke *et al.*, 1980). In 1993, Szczotka *et al.* (1993) investigated the oxygen uptake rate of the human cornea along the central-to-inferior vertical hemi-meridian, under the open-eye condition. Measurements were taken from the central cornea and 2 mm above the inferior limbus at the 6 o'clock position, concluding that the inferior corneal oxygen uptake rate is significantly greater (1.14x) than the central cornea. The authors hypothesised that the result may be due to the thicker layer of epithelial cells at the inferior point compared to the central area. In comparison, Brunstetter *et al.* (1999) demonstrated a similar oxygen uptake of the inferior compared to the central cornea.

1.3.5.3 Environmental O_2

In 1985, Benjamin and Hill (1985) reported the effects of seven healthy young adults following exposure of their anterior corneal surfaces to oxygen levels ranging from 0% to 20.9% for a period of 300 seconds. They concluded that there were two primary factors that influenced the flow rate of oxygen across the anterior surface of the cornea. The first was dependent on the demand of local metabolic processes and the second was dependant on the relative availability of the oxygen to meet those demands. The results showed a linear increase in post-exposure oxygen uptake rate for atmospheres from 20.9% to around 1.5%. When this fell below 1.5% there was a marked increase in the oxygen uptake rate suggesting that the oxygen tension in the stroma fell to zero.

Studies have investigated the minimal amount of oxygen required under the contact lens to prevent corneal oedema. In 1970, Mandell *et al.* demonstrated that corneal oedema was detected by pachymetry if the cornea was exposed to less than 2% oxygen (15 mmHg) (Mandell *et al.*, 1970). However, later studies by Uniacke *et* *al.* (1972) using a scleral contact chamber in rabbits, and Fatt *et al.* (1974), showed corneal oedema was present with atmospheres of oxygen less than 5% (40 mmHg) and 7% (60 mmHg), respectively. In 1975 it was suggested by Hill and Jeppe that 10% oxygen would be a more realistic value (Hill and Jeppe, 1975).

1.3.5.4 Hard Contact (PMMA and RGP)

Corneal oxygen uptake rate has been shown to significantly increase immediately after wearing contact lenses (Fink *et al.*, 1991b; Ostrem *et al.*, 1996; Paugh, 1992). Ostrem *et al.* (1996) carried out a study to determine the effects of rigid contact lens materials of various permeabilities and identical designs on the oxygen shortfall of the human cornea. They recruited six subjects and measured corneal oxygen uptake under three conditions (normal open-eye, after 5 minutes static (not blinking) wear of the six materials, and after 5 minutes dynamic (blinking every 5 seconds) wear of the same six materials). The six materials had Dk values ranging from 0.02 to 127 (cm^2/s)(ml O_2/ml x mmHg). The oxygen uptake rate was measured using a Clark-type polarographic electrode. They demonstrated that the oxygen shortfall of the cornea decreased with increasing lens transmissibility under both static and dynamic conditions. Ostrem *et al.* (1996) concluded that the PMMA lens gave the greatest oxygen shortfall (89.62 OSUs) compared to the material with the Dk of 127 x 10^{-11}(cm^2/s)(ml O_2/ml x mmHg) with an associated corneal oxygen shortfall of 5.4 OSUs.

Fink *et al.* (1991a) investigated the variation in responses to oxygen deprivation among 6 healthy corneas that had no history of contact lens wear. Parallel measurements were made following immediate removal of a custom made PMMA contact lens after 300 seconds coverage. They concluded that, in the normal open-eye, the thickness of the stroma was most closely related to the oxygen uptake rate, rather than to the epithelium, which was more closely related to rates obtained after deprivation of oxygen to the cornea.

The effect of overall diameter of PMMA lenses on oxygen uptake was demonstrated by Fink *et al.* (1991b) by using six diameters ranging from 7.6 to 10.6 mm (0.6 mm steps), with the optic zone diameter being set 1.4 mm smaller than the total diameter. The Oxygen uptake rate was measured in 6 corneas using a Clark type polarographic electrode in the normal open-eye and after the 6 contact lenses were worn after a period of five minutes. The study indicated that by increasing the overall lens diameter it resulted in an increased oxygen uptake rate, concluding that covering more of the cornea by a contact lens produces a higher oxygen demand by the central cornea, thus highlighting the physiological advantages of smaller RGP lenses. This study confirmed similar findings of earlier studies by Fink and colleagues (Fink *et al.*, 1990c; Fink *et al.*, 1991c). The effect of oxygen uptake rates was also investigated in relation to patients' palpebral aperture. Fink *et al.* (1990b) demonstrated that a small palpebral aperture can hinder lens movement thus decreasing oxygenated tears to the surface under the contact lens.

Fink *et al.* (1995) investigated the effect of different oxygen deprivation intervals in 12 young individuals using (static wear) PMMA lenses. The intervals ranged from 0 to 300 seconds. They found that the oxygen uptake rate with deprivations between 0 and 90 seconds increased more rapidly than that associated with deprivation intervals from 120 seconds and above.

Fatt and Hill in 1970 demonstrated that blink rate under hard contact lenses is important. It produces tear pumping under the contact lens allowing the level of oxygen to stay high compared to no blinking (Fatt and Hill, 1970). This was confirmed by Efron and Carney (1981) who obtained data from six rigid gas permeable contact lenses showing that blinking provided a significant ($p < 0.001$) increase in oxygen availability to the cornea with two different contact lens materials (Table 1.10).

Lens	Static (O_2%)	Blinking (O_2%)
CAB (Cellulose acetate butyrate)	3.1 ± 0.7	4.8 ± 0.6
Menicon O_2 (Methacryl methysiloxane)	2.9 ± 0.6	5.0 ± 0.5

Table 1.10
EOP under static and blinking conditions of two RGP lenses (redrawn from Efron and Carney, 1981)

1.3.5.5 Soft Contact Lenses

A method of measuring oxygen flux of the cornea through soft hydrogel contact lenses by the use of a polarographic oxygen sensor was described by Fatt (1978) and Morris and Ruben in 1981 (Morris and Ruben, 1981). They applied a polarographic oxygen sensor to a soft contact lens on the eye and recorded the decrease in oxygen content of the lens on the cornea.

It has been suggested that blinking has little effect on the oxygen underneath hydrogel contact lenses (Fink and Hill, 2006). However, Parrish and Larke (1981) found that, under dynamic conditions, flat-fitting hydrogel contact lenses resulted in lower corneal oxygen uptake rate compared to that of steeper fitting hydrogel contact lenses, supporting Kikkawa's (cited in Parrish and Larke, 1981) theory that a small tear pump operates in a soft contact lens.

Parrish and Larke (1982) looked at the relationship between corneal oxygen uptake rate before and after 48 hours wear of an extended-wear hydrogel soft contact lens (Sauflon 85) in 32 subjects. They demonstrated a wide variation of oxygen uptake rates between patients and found no correlation between apparent corneal oxygen uptake rate and the 'oxygen debt' generated subsequently from 48 hours of extended soft contact lens wear. They therefore concluded that the degree of 'oxygen debt' generated as a result of contact lens wear may be influenced by external factors.

All soft contact lenses dehydrate when on the eye (Efron, 2001). Paugh (1992) investigated the effect of hydrogel lens dehydration on the eye and its effect on EOP. A micro-polarographic system was used to measure the human corneal oxygen flux rates. He found that there was about a 7% decrease in absolute water content, with the steepest decrease in dehydration occurring during the first five minutes of wear, resulting in a significant loss in oxygen transmissibility of the contact lens (45%). A further study by Efron and Morgan, (1999) also concluded that dehydration of hygrogel contact lenses (Dk 7.5 to 26.9 x 10^{-11} (cm^2/secs)(mLO_2/mL x mmHg)) during wear can alter the oxygen transmissibility of hydrogel lenses.

1.3.6 Prediction Models of Contact Lens Transmissibility Ranges

Smith *et al.* (1997) investigated the relationship between oxygen shortfall units (OSUs) and Dk/t across a variety of contact lens transmissibility ranges (1.2 to 189 x 10^{-9} (cm/sec)(ml O_2/ml mmHg)) with the polarographic method, concluding that the quantitative models presented could provide a reasonably accurate and clinically adequate basis for predicting the human corneal response to different contact lens transmissibilities across a Dk/t range. Similarly, Glavin *et al.* (2000) measured the static oxygen uptake rate (polarographic technique) with six rigid contact lenses of various transmissibilities ranging from 0 to 91 x10^{-9} (cm/sec)(ml O_2/ml mmHg) in the open and closed-eye condition. From the results, they generated a predictive model for both closed and open-eye conditions in ten Dk/t steps.

1.3.7 Soft Contact Lens Oxygen Reservoir Theory

It has previously been suggested that hydrogel contact lenses can act as an oxygen reservoir thus supplying the cornea with oxygen when it is first deprived (Hill, 1981). Florkey *et al.* (Florkey *et al.*, 2003) demonstrated that this was also true for silicone hydrogel (SiH) contact lenses concluding that SiH lens materials may act as a short-term reservoir when oxygen tension across the lens is temporally reduced. This may be due to the contact lens absorbing more oxygen on its front surface that can be expelled from the lens back surface to the cornea.

1.3.8 The Effect of Local Anaesthetics on Oxygen Uptake

Occasionally the polarographic technique required local anaesthetics to allow applination of the sensor onto the cornea, but this may have affected the result as demonstrated by Herrmann *et al.* (1942). They investigated the influence of pontocaine hydrochloride and chlorobutanol on the respiration and glycolysis of bovine corneas. They reported that the oxygen uptake rate can be reduced after application of topical anaesthetics. The reduction in oxygen rate was also confirmed by Harvitt and Bonanno, (1995) after topical instillation of 0.5% proparacaine hydrochloride anaesthetic. They calculated a lower oxygen flux indicating reduced corneal oxygen consumption. Topical anaesthetic cocaine (1%), tetracaine (0.5%), and benoxinate (0.4%) have also been shown to depress oxygen flux of the cornea, by as much as 20% with cocaine (Augsburger and Hill, 1972).

1.4 CONCLUSION

This chapter has highlighted the advantages and disadvantages in the use of contact lenses during sport. Chapters 2 and 3 look at the practitioner habits when prescribing contact lenses and the patient experience of contact lens usage during sports, respectively. One concern of contact lens wear during sport may be the physiological changes, such as oxygen uptake, during the demanding physical activity of exercise. There are certainly limitations with the current methods of measuring oxygen uptake as mentioned in this chapter. Chapter 4 looks at physiological changes on the cornea during exercise. In chapter 5 the design of a novel technique for assessing oxygen uptake is discussed and its usage is demonstrated in chapter 6. Chapter 7 investigates the visual performance of a sport-specific contact lens available on the market today.

1.5 AIMS OF THE THESIS

The aim of the thesis is to investigate the use of contact lenses in sport, with emphasis on physiological changes of the cornea with and without contact lens wear. The specific aims are:

1: To establish the attitude of the eye care practitioner towards fitting contact lenses for sports.

2: To illustrate patients' experience whilst wearing contact lenses for sport, with emphasis on advice given by their eye care practitioner.

3: To investigate the physiological changes of the cornea with and without contact lens wear during exercise with emphasis on ocular thermography, corneal pachymetry, and bulbar hyperaemia.

4: To design a non-contact method of measuring corneal oxygen uptake

5: To attempt to establish the oxygen requirement of the cornea during exercise by a non-contact method.

6: To evaluate the optical performance of the Nike Maxsight™ contact lenses under indoor photopic lighting within the optometric practice, and to investigate the effect of wearing the lenses on colour discrimination.

CHAPTER TWO

CONTACT LENS FITTING TRENDS IN SPORTS: THE PRACTITIONER

2:1 INTRODUCTION

The literature has illustrated that contact lenses appear to be an ideal refractive correction for many sports when compared to spectacles. In the United Kingdom (UK), over the last few years, there has been an increase of 11% in contact lenses wearers since 2002 (ACLM, 2004). Research has demonstrated sport as a primary motivating factor for many patients opting for contact lenses (Gupta and Naroo, 2006), with almost all contact lens wearers using them when participating in sport (Bowden and Harknett., 2005). Zieman *et al.* (1993) carried out a survey investigating the optometric trends in sports vision in the US, demonstrating that most optometrists favoured fitting contact lenses over spectacles for athletes, with the soft variety being most popular. There are many different types of material and modality of contact lenses available on the current UK market. They all have their own merits, for example silicone hydrogel (SiH) contact lenses allow more oxygen to diffuse through the contact lens compared to a low oxygen transmissibility contact lenses. Where as daily disposable lenses have the added advantage over monthly replacement lenses on debris build up and convenience (Morgan, 2004). This chapter investigates the prescribing behaviour of optometrists and their views regarding the use of contact lenses for a variety of sports.

2.2 AIM

The aim of this study was to investigate the prescribing trends of optometrists for contact lenses when used for sport. They were asked about their choice of lens type for a variety of sporting activities. Emphasis was placed on their opinion of their patients' reason for choosing lenses, and the modality of contact lenses fitted for a given sport.

2.3 THE QUESTIONNAIRE

A simple one-page questionnaire was designed to try to establish the current prescribing trends of UK Optometrists in relation to contact lens wear for sport. The questions chosen in the questionnaire (Figure 2.1) were designed to ascertain information on the practitioners' experience of fitting contact lenses during sports and exercise. Demographic information on age and gender was extracted to illustrate the representation of the cohort. The type of contact lenses fitted for sports was to establish the optical practitioners' first choice recommendation when fitting contact lenses for a variety of sporting activities, as some lenses are not suggested for specific sports, e.g. RGP for contact sports. There are currently no validated questionnaires to assess the optical practitioners fitting trend of contact lenses for sports, however it ascertained some scrutiny by a panel of optometrists. The initial questions were reviewed by a focus panel of 4 optometrists and amended. A pilot questionnaire was administered to 25 subjects to establish the ease of interpretation of the questions chosen, from this the final edition of the questionnaire was constructed (Figure 2.1). The protocol required the forms to be completed by the individual optometrists. The questionnaire was designed to ensure the complete anonymity of the optometric practitioner.

Sport and Contact Lenses (Edition 5)

Thank you for taking a few moments to complete the following questionnaire.
Please note all answers are anonymous and for research purposes only.

Male ☐ **Female** ☐ **Your age:**____________ **Years in practice:** ____________

Q1: Do you fit Contact lenses? **Yes** ☐ **No** ☐
If **YES** please complete questions 2-5, if **NO** end of questionnaire.

Q2: Please tick the THREE main reasons for patients wanting contact lenses?

☐ Cosmetic reasons
☐ Advice from friends & relatives
☐ Sports and recreational
☐ Advertising / promotions / costs
☐ Inconvenience of spectacles
☐ Prescription related / professional advice
☐ Work or vocational reasons
☐ Other ________________________

Q3: Please indicate which lenses you fit in practice

Modality	**Please indicate if you fit on an average week (Yes/No)**
A. Daily soft	
B. Bi-monthly soft	
C. Monthly soft	
D. Yearly / conventional wear soft	
E. Extended wear soft/ Continuous	
F. Gas permeable	
G. Other (Sclerals, PMMA etc)	

Q4: Please circle your first lens of choice for the following sports:
The letter codes from question 3 are used here

Swimming	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**None**
Gym / Aerobics	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**None**
Outdoor athletics	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**None**
Football / Rugby	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**None**
Racquet sports	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**None**
Boxing / martial arts	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**None**

Q5: Are you on the General Optical Council voluntary contact lens list?
Yes ☐ **No** ☐

Figure 2.1
The questionnaire distributed to the optical practitioners

2.4 METHOD

The questionnaire was distributed among 116 optometrists at non-contact lens and non-sports vision related Continuing Education Training (CET) meetings in the UK in 2006. Data were collected from 3 separate events in the West Midlands, although some delegates were from outside the region. CET lectures are lectures for optometrists on any aspect of optometry to obtain compulsory points required to retain registration with the General Optical Council (GOC). Ethical approval was sought from the Aston University Ethics Committee and practitioner anonymity was maintained throughout.

2.5 RESULTS

A response rate of 90% was achieved, totalling 104 completed questionnaires. The respondents worked in a variety of practice environments from multiple optical practices to independent optical practices and the hospital eye service. The mean age of optometrists was 38.1 ± 11.3 years (range 22 to 72 years). The male to female ratio was approximately 2:1 (64%, male). The mean number years spent in practice by optometrists was 14.2 ± 11.0 years (range 1 to 47 years). The statistics were generated using Excel.

2.5.1 Optometrists Who Fit Contact Lenses

Ninety per cent (n=94) of optometrist who completed the questionnaire fitted contact lenses, of these, 48% (n=45) were currently on the GOC voluntary contact lens list. Of this group, 34% (n=32) were female. The mean age of optometrists who fitted contact lenses was lower than those optometrists who did not fit contact lenses and this was shown to be statistically significant (Figure 2.2; T-Test; $p < 0.05$).

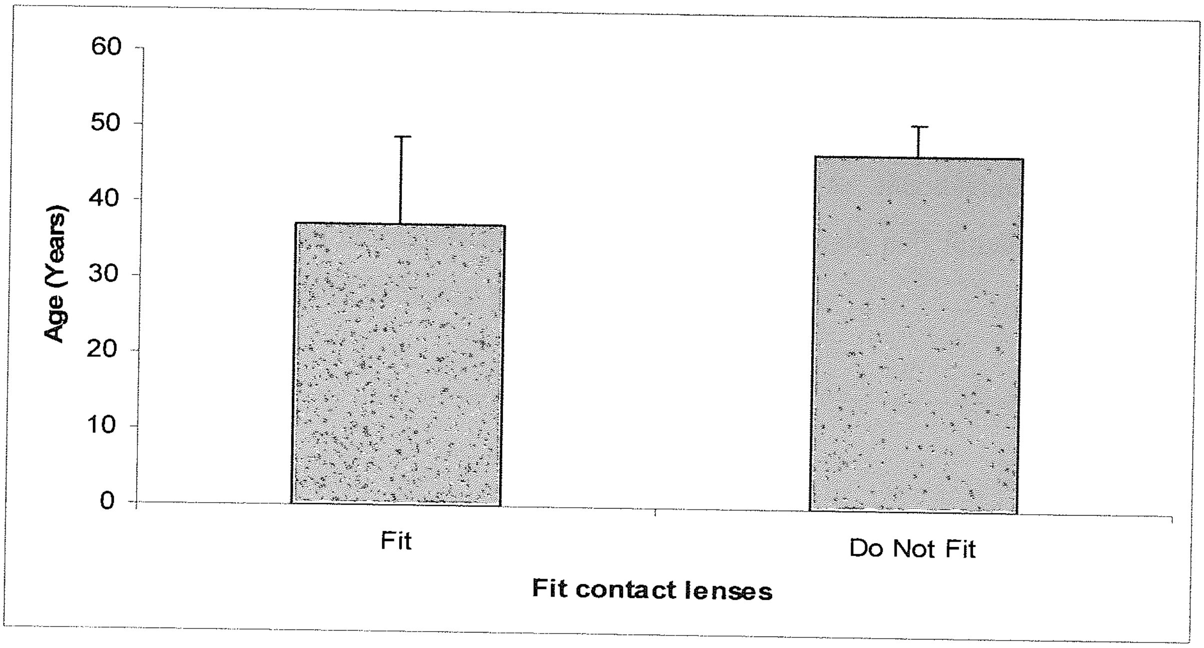


Figure 2.2
Average age of optometrists who fit and do not fit contact lenses, error bars = 1SD (n=104)

The mean number of years in practice for optometrists who fits contact lenses was 13.3 ± 11.1 years compared to 23.2 ± 5.6 years for those not fitting contact lenses. This was statistically significant (Figure 2.3; T-test; $p < 0.01$)

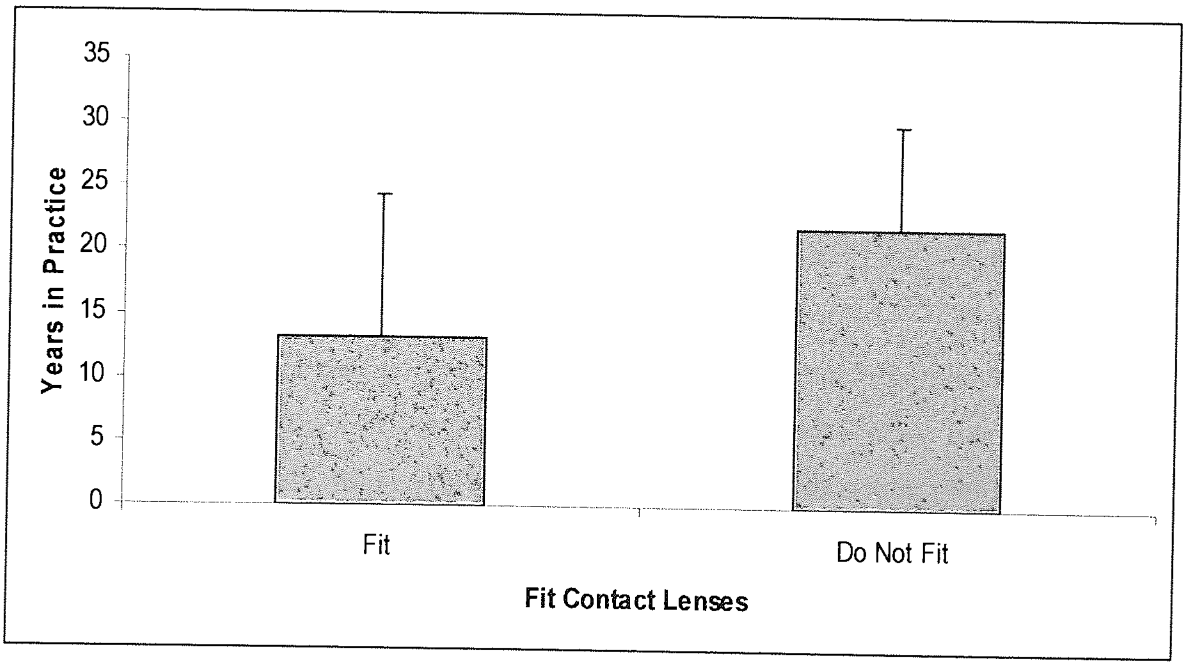


Figure 2.3
Average years in practice of optometrists who fitted contact lenses and who do not fit contact lenses, error bars = 1SD (n=104)

2.5.2 Main Reasons Patients Request Contact Lenses

A total of 91% of optometrists felt their patients requested contact lenses for cosmetic reasons, 80% indicated sports and 81% due to inconvenience of alternatives. There was no significant difference between male and females with these reasons (Figure 2.4; ChiSqu; p = 0.69).

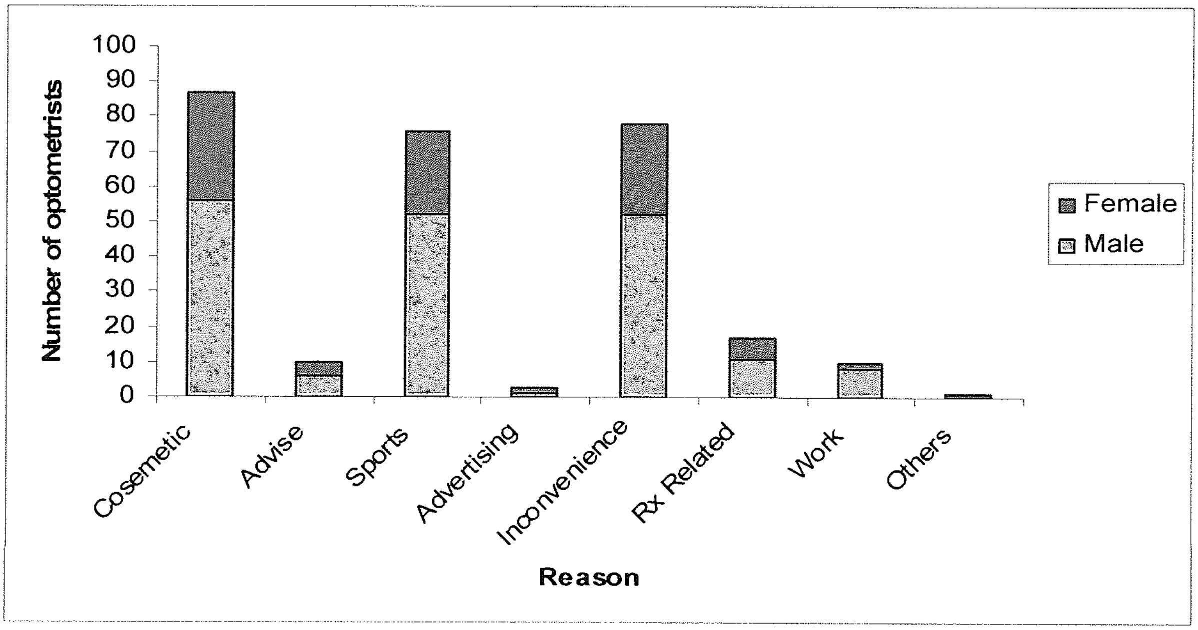


Figure 2.4
The reasons optometrists indicated why their patients chose to wear contact lenses. (Note: each optometrist chose 3 reasons each) (n=94)

2.5.3 Contact Lenses Practitioners Fitted in Practice

Ninety five per cent of optometrists fitted at least one daily soft lens in an average week, 46% fitted bi-monthly soft contact lenses, 90% fitted monthly soft contact lenses and 23% fitted yearly / conventional wear soft contact lenses. Over half the optometrists (59%) fitted extended wear soft contact lenses, 48% fitted RGP contact lenses and 5% (n=4) fitted other types of contact lenses. There was no significant difference between male and females in these fitting patterns (Figure 2.5; Chisqu p = 0.88).

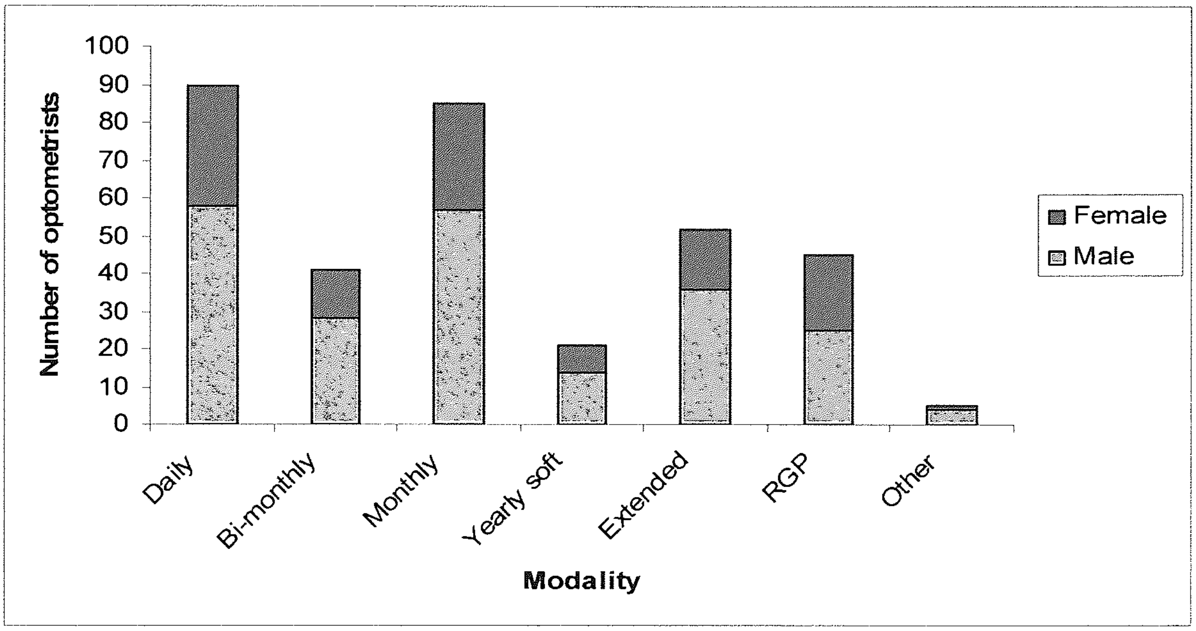


Figure 2.5
Modality type optometrists fitted in an average week. (Note: more than one modality could be chosen by each optometrist) (n=94)

2.5.4 First choice Contact Lens Type for Sports

Table 2.1 represents the overall percentage of first choice modality fitted for a given sport. There was no statistically significant difference between male and females for swimming, gym/aerobics, outdoor athletics, football/rugby, or racquet sports (Figure 2.6; Chisqu $p = 0.38, 0.17, 0.12, 0.16, 0.09$ respectively), however there was a statistically significant difference between the sexes for boxing (Figure 2.6; ChiSqu; $p < 0.05$).

Modality	Daily	Bi-monthly	Monthly	Yearly soft	Extended wear	RGP	Other	None
Swimming	59%	0%	0%	0%	2%	0%	1%	38%
Gym / Aerobics	75%	5%	18%	0%	2%	0%	0%	0%
Outdoor athletics	67%	9%	19%	1%	3%	1%	0%	0%
Football / Rugby	72%	7%	16%	0%	4%	0%	1%	0%
Racquet sport	72%	5%	18%	1%	4%	0%	0%	0%
Boxing/ Martial arts	64%	5%	14%	0%	4%	0%	1%	12%

Table 2.1
Percentage of first choice lens fitted for a given sport (n=94)

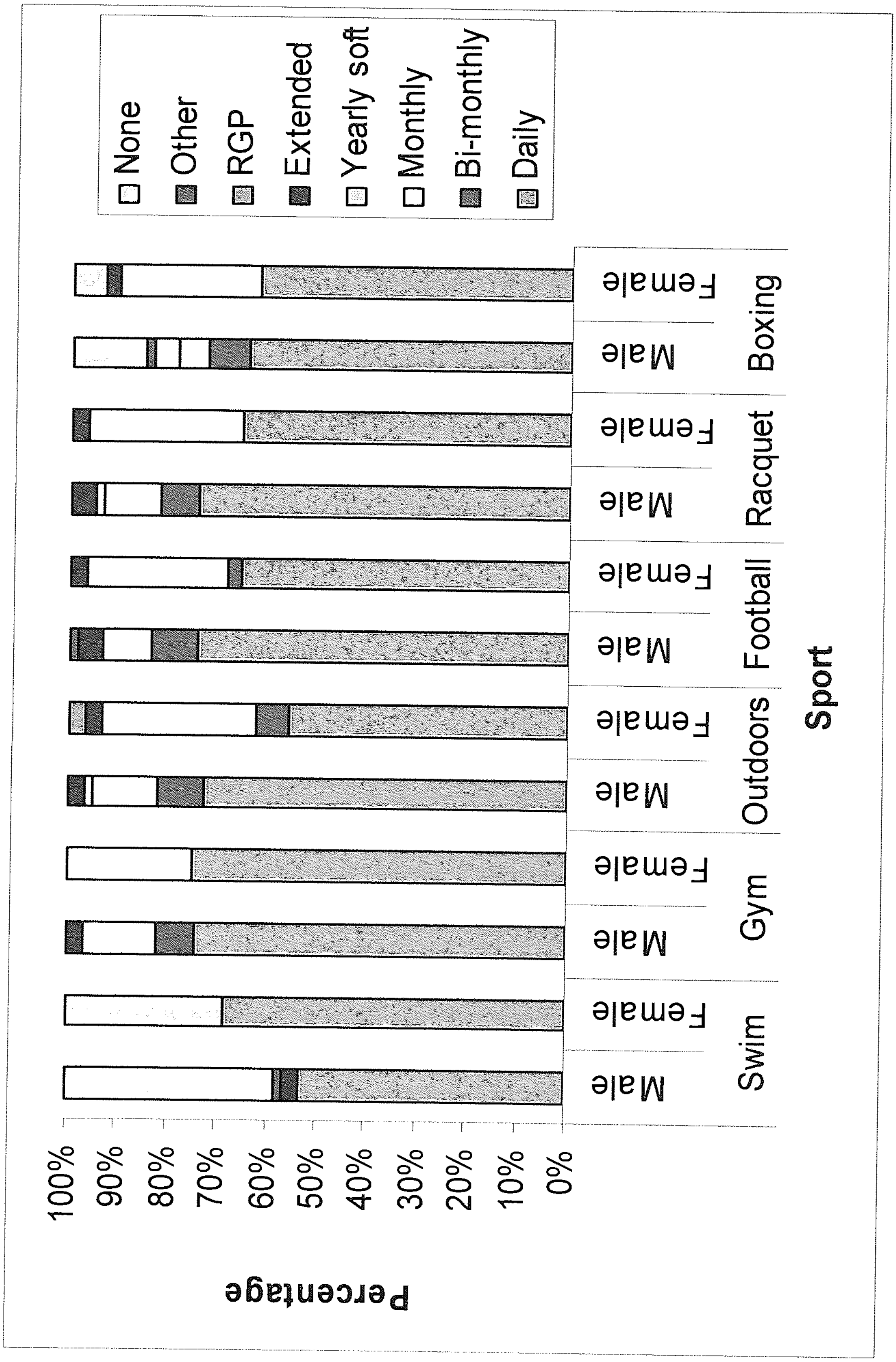


Figure 2.6
First choice contact lenses that optometrists would fit for a given sport (males n=62, females n=32)

2.6 DISCUSSION

The data gathered in this study do not identify whether the findings are representative of different practice environments. However, as CET points were compulsory at the time of this study and the optometric workforce is thought to be evenly spread over the UK, it is fair to assume the West Midlands cohort was representative of different types of optometric practitioners within the UK.

The average age of all the optometrist who fit contact lenses was significantly lower than optometrists who do not fit contact lenses. This was also true for average number of years optometrists were in practice between optometrists who fit and do not fit contact lenses. It would be interesting to see which working environment the non-fitters and fitters of contact lenses work in e.g. multiple companies or independents, but this was not further investigated in this study.

Sports, cosmetic reason and inconvenience to spectacles are the three main reasons why optometrists feel patients choose contact lenses, supporting recent research carried out by Gupta and Naroo (2006).

As far as the author is aware, this is the first study to investigate optometrist's attitude towards contact lens fitting for different sports. It is important to point out that when the optometrist was asked to fill out question four (Figure 2.1), they were to assume that the patient they would fit the contact lenses to had no ocular pathology, no previous contact lens-related problem, no dry eyes and the patient's prescription was available in all modality of lenses.

When asking the optometrist which first choice lens they would fit for swimming, they were advised that this could be with or without goggles. Generally most contact lens manufactures do not recommend contact lenses for swimming (IACLE, 1998) due to the increase risk of acanthamoeba (Rivera *et al.*, 1993; Vesaluoma *et al.*, 1995), punctate keratitis (Zagelbaum, 1996) and loss of contact lenses. It was clear from this study that optometrists are still unclear whether it is safe to fit contact lenses for swimming, as over 50% of all optometrists would fit daily disposable soft contact lenses as their first choice lens and 38% of all the optometrists questioned would refrain from fitting any contact lenses for swimming. It is often agreed that, as chlorine in swimming pools and salt water can impair the adhesion properties of soft contact lenses to the cornea (Werner, 2000) and due to the increase risk of acanthamoeba and punctuate keratitis, tight fitting waterproof goggles should always be worn on top of the patients contact lenses. Quevedo *et al.* (2000) demonstrated that swimmers present with a statistically significant reduction in tear film quality and quantity after exercise compared with non-athletes. As goggles prevent water evaporation and reduce dehydration, Quevedo *et al.* (2000) recommended that goggles should be worn and high-water content contact lenses should be used contrary to common practice.

Daily disposable contact lenses were chosen by over 50% of all optometrists as the first choice lens for all sports indicated in this study. This type of modality could have been chosen due to the potential benefits of daily disposable lenses (Morgan and Efron, 2004). This modality of choice has the advantage of reduction of lens surface deposits and lens ageing. The other benefit especially for sports are that they require no care system thus the athlete can insert and remove lenses almost anywhere and spare sets can be carried with them, eliminating problems of storage if the athlete is wearing them infrequently, for example just for sports. The next common modality of contact lenses to be chosen as optometrist first choice contact lens was monthly disposables ranging from 10% to 25% for different sports except swimming in which no optometrist would use. It is important to mention that the monthly soft disposable lenses could include silicone hydrogel contact lenses. With the potential risk of infection associated with swimming and contact lenses, it was surprising that one optometrist would choose an extended wear contact lens for such sport. This was surprising considering that Radford *et al.,* (1998a) concluded that almost of all acanthameabal infection (91%) presented in there study could had be prevented by either not swimming and or effective disinfecting their contact lenses.

It appears from this study that yearly conventional replacement soft contact lenses are obsolete form the first choice lens for fitting for all sporting activities. It was interesting to observe from this study that this lens is the least-fitted modality in practice today, which correlated with trends for fitting for 2006 in the UK as yearly/ conventional replacement soft contact lenses only accounted for 0% of all new fits.

However, this is much higher in some other countries, such as China, in which this was 27% of all lens fits (Morgan *et al*, 2008).

Due to the increased risk of lens facture in the eye with RGP contact lenses during contact sports, for example racket sports and boxing, it was not unexpected that RGP contact lenses were not indicated in any contact sports.

2.7 CONCLUSION

This study suggests that many optometrists believe sport to be a primary reason for patients' wearing contact lenses, with daily disposables being the most popular first choice contact lens for all sports emphasised in this study. This may be due to the reduced lens surface deposits, stability and reduced complications of this modality of contact lens wear. The other benefit especially for sports are that daily lenses require no care system thus the athlete can insert and remove lenses almost anywhere and spare sets can be readily available. As demonstrated from this study there appears to be a market for sports vision in the optometric practice. It is clear from this study that optometric professionals are aware that patient's motivation behind wearing contact lenses is the playing of sports. Due to this reason it would be interesting to examine patients experience and advice they receive from their optometrist and or contact lens fitter. This will be investigated in Chapter 3.

CHAPTER THREE

CONTACT LENS FITTING TRENDS IN SPORTS: THE PATIENTS' EXPERIENCE

3:1 INTRODUCTION

The previous chapters have established that contact lenses are a suitable form of vision correction for those involved in sport and have shown the prescribing trends of optometric practitioners. In this chapter the wearing habits of patients, especially in relation to sport, will be investigated.

Despite the obvious advantages of contact lenses in sport, there are some issues that need to be considered. Previous research has demonstrated that contact lens wearers report more ocular dry symptoms than non-wearers (Chalmers and Begley, 2006; Fonn *et al.*, 1999; Glasson *et al.*, 2006; Glasson *et al.*, 2003; Richdale *et al.*, 2007), and this has been attributed to be the primary reason for discontinuation of contact lens wear (Pritchard *et al.*, 1999) with one study reporting 51% of subjects giving up contact lenses due to ocular discomfort (Young *et al.*, 2002). It has previously been believed that the ocular dryness was due to contact lens dehydration, but Fonn *et al.* (1999) found no correlation between lens dehydration and subjective dryness and comfort, between contact lens wearers and non-wearers.

Different tasks and environments have been linked to an increase in ocular symptoms whilst wearing contact lenses, with air-conditioning and the use of visual display units being a significant problem (Gonzalez-Meijome *et al.*, 2007). Although little research has been carried out regarding ocular symptoms due to contact lenses and sport, a study on athletes in the US revealed the most common contact lens problems experienced was irritation and loss of the contact lens itself (Zieman *et al.*, 1993).

3.2 AIM

The aim of this study was to evaluate the patient's own experiences of wearing contact lenses for sport, level of participation in sport and recreational activity, any associated visual problems, and advice given by their optometrist or contact lens practitioner. In order to investigate the patient's own experiences of wearing contact lenses for sport, a questionnaire was designed.

3.3 THE QUESTIONNAIRE

The questions chosen in the questionnaire were designed to ascertain information on the patients' experience of wearing contact lenses during sports and exercise, with emphasis on the percentage of time they are used for such activities. Demographic information on age and gender was extracted to illustrate the representation of the cohort. As swimming with contact lenses is still a controversial area, specific questions were asked about this sport to establish patients' factual experience with contact lenses in such an environment.

There are currently no validated questionnaires to assess the use of contact lenses for sports vision, however, the initial questions were reviewed by a panel of 4 optometrists and amended. A pilot questionnaire was administered to 10 subjects to establish the ease of interpretation of the questions chosen; from this the final edition questionnaire was constructed. From analysis of the first return of questionnaires, additional questions were asked to subsequent undergraduates as it became clear these would benefit the study (Figure 3.1). Again these additional questions were reviewed by a panel of 4 optometrists. The protocol required the forms to be completed by the individual subjects. The questionnaire was designed to ensure the complete anonymity of the respondent.

Sport and Vision Correction

Thank you for taking a few moments to complete the following questionnaire.

Please note all answers are anonymous and for research purposes only.

Male ☐ **Female** ☐ **Age: ....**

Q1: On average, how many hours do you participate in sporting activity per week?

Hours:...................... (if you do not participate in sport indicate 0 hrs)

Q2: Which main sports do you play (maximum 3)?

....

....

Q3: At your last eye exam were you asked if you play sports?

☐ Yes ☐ No

If **YES** are you asked what type of sport?

☐ Yes ☐ No

Q4: Do you wear: (Please tick)

☐ Spectacles only answer section A&C ☐ Both (answer all Q)

☐ Contact lenses only answer section A&B ☐ None (end of questionnaire)

Section A (To be completed if you wear spectacles and or contact lenses)

Q5: What is your prescription?

☐ Longsighted (Hyperopic) below +3.00 ☐Short Sighted (Myopic) below -3.00

☐ Longsighted (Hyperopic) above +3.00 ☐ Short Sighted (Myopic) above-3.00

☐ Don't know

Section B (To be completed if you wear contact lenses)

Q6: Which type of contact lenses do you wear (if more than one type indicate by a cross ones you wear for sport) ?

☐ Daily disposable soft lenses ☐ Two weekly soft lenses

☐ Monthly soft lenses ☐ Extended wear lenses

☐ Gas permeable hard lenses ☐ Other........... (Please specify)

Q7: Why did you choose contact lenses?

☐ Cosmetic reasons ☐ Inconvenience of spectacles

☐ Advice from friends & relatives ☐ Prescription related / professional advice

☐ Sports and recreational ☐ Work or vocational reasons

☐ Advertising / promotions / costs ☐ Other............(Please Specify)

Q8: Did your optician/ contact lens fitter recommend you remove your contact lenses after sport?

☐ Yes ☐ No ☐ No advice given

If **YES** how often do you follow these recommendation _____%

Q9: Do you remove your contact lenses immediately after playing sport?

☐ Yes ☐ No

Q10: Have you ever experienced any problems with your contact lenses either during or after a sporting activity?

☐ Dry eyes ☐ Sore eyes ☐Red eyes

☐ Gritty feeling ☐ Ripped / Split lens ☐ Lost lens

☐Other.................. ☐ None

Q11: Do you wear your contact lenses whilst swimming?

☐ Yes with goggles ☐ Yes without goggles

☐ No ☐ Do Not Swim

If **YES** what advice did your optician/ contact lens fitter give you when swimming in contact lenses?

☐ None ☐ Remove after swimming and throw away

☐ Remove after swimming and clean with contact lenses solution

☐ Other (Please specify)..

Q12 How often do you wear your contact lenses for sport? (if you wear spectacles as well, Q12 and Q13 should not add up to over 100%)

☐ Most of the time (75 -100%) ☐ Frequently (50 - 74%)

☐ Occasionally (25 - 49%) ☐ Rarely (1 - 24%)

☐ Never

Section C (To be completed if you wear spectacles)

Q13: How often do you wear your spectacles for sport? (if you wear contact lenses as well, Q12 and Q13 should not add up to over 100%)

☐ Most of the time (75 -100%) ☐ Frequently (50 - 74%)

☐ Occasionally (25 - 49%) ☐ Rarely (1 - 24%)

☐ Never

Q14: Have you ever experienced any problems with your spectacles either during or after a sporting activity?

☐ Dry eyes ☐ Sore eyes ☐ Red eyes

☐ Gritty feeling ☐ Broken lenses or frame ☐ Fell off

☐ Other.................. ☐ None

Figure 3.1

Questionnaire (note: highlighted questions are the additional questions given to the sub cohort)

3.4 METHOD

The questionnaire was distributed among 456 first year UK undergraduate optometry students during the first week of term at Aston University, Cardiff University and Manchester University at the beginning of the academic year between 2005 and 2007. In this way the students were not influenced by their experience of the Optometry undergraduate programme. Additional questions were asked to 231 undergraduates from the same cohort. Ethical approval was sought from the Aston University Ethics Committee.

In 2005 and 2006 data were collected from Aston University. To increase the numbers it was widened to include Cardiff and Manchester Universities in 2007. Although the data were collected from three different regions within the UK (West Midlands, South Wales, and the North West) the subjects were not necessary from the region they attended university, therefore their optometrist or contact lens practitioner in which they attended prior to the investigation were not necessarily from this region. For this reason all the data were analysed together and not regionalised for comparison

3.5 RESULTS

A total of 456 questionnaires were collected. The response rate was 100%. The mean age of all subjects was 19.9 ± 3.1 years (range 18 to 51 years). The male to female ratio was approximately 1:3 (35.5% males). The demographics of the sub-cohort who completed additional questions were very similar to the total population sample, 20.0 ± 3.8 years (range 18 to 51 years). The male to female ratio was approximately 1:3 (32% males). The statistics were generated using Excel.

3.5.1 Visual Correction

Fifty-five percent of subjects wore a visual correction (n=251), of which 38% wore spectacles only, 7% wore contact lenses only, and 55% wore both forms of correction (Figure 3.2). There was a significant difference between males (Figure 3.3) and females (Figure 3.4) (ChiSqu; $p < 0.01$), with 38% of females wearing contact lenses compared to 26% of males and 28% of males wearing spectacles compared to 18% of females.

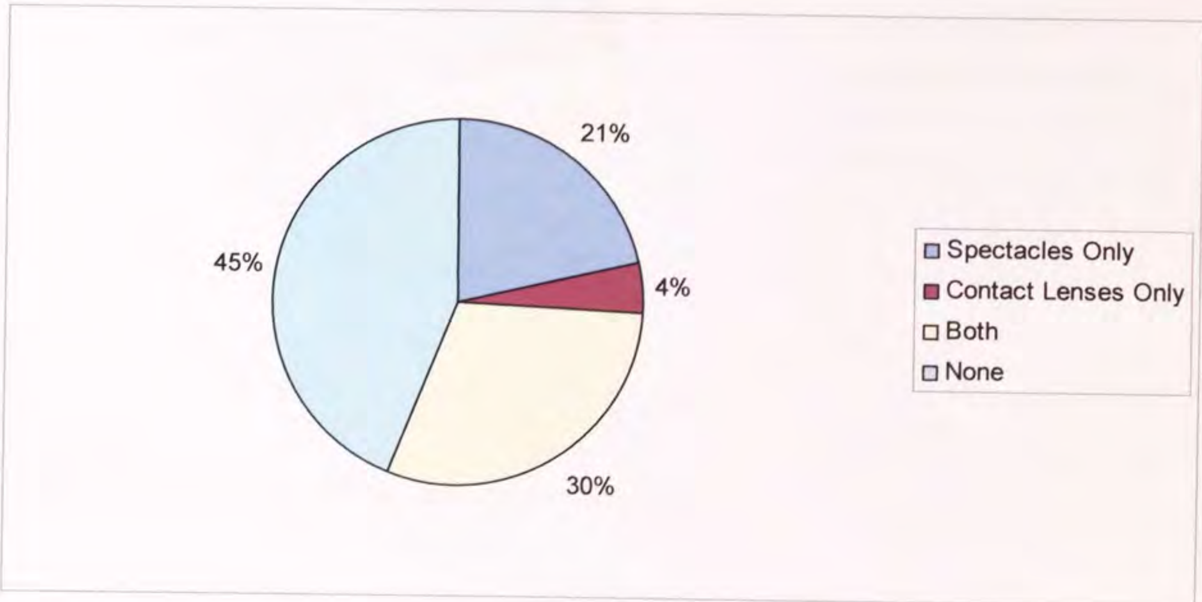


Figure 3.2
Method of visual correction (n=456)

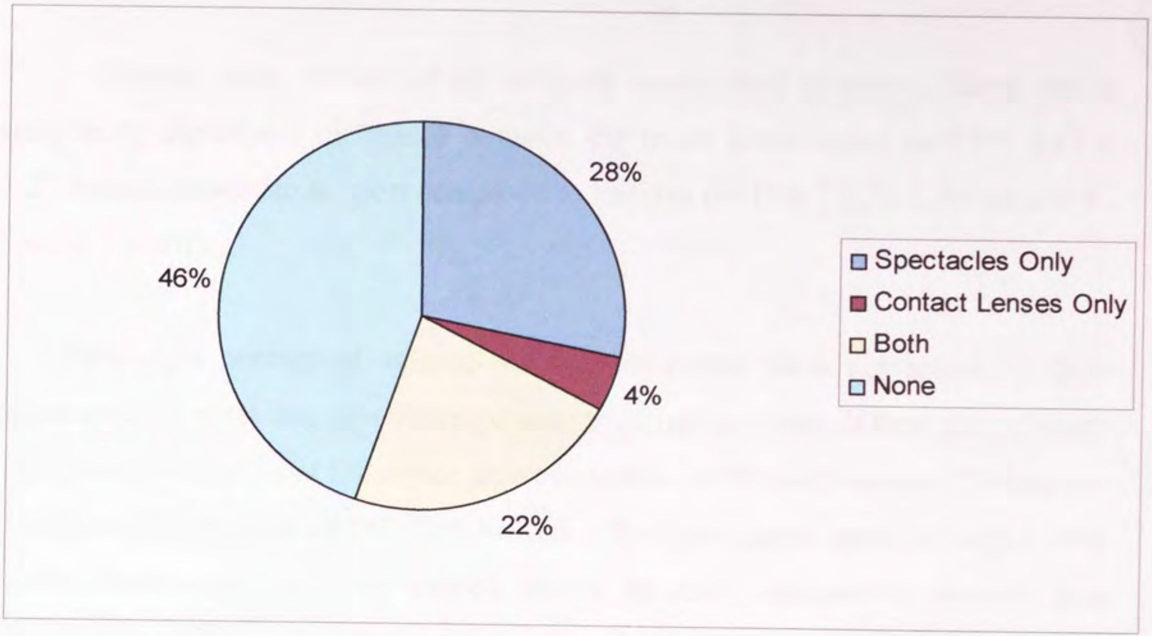


Figure 3.3
Method of visual correction for males (n=162)

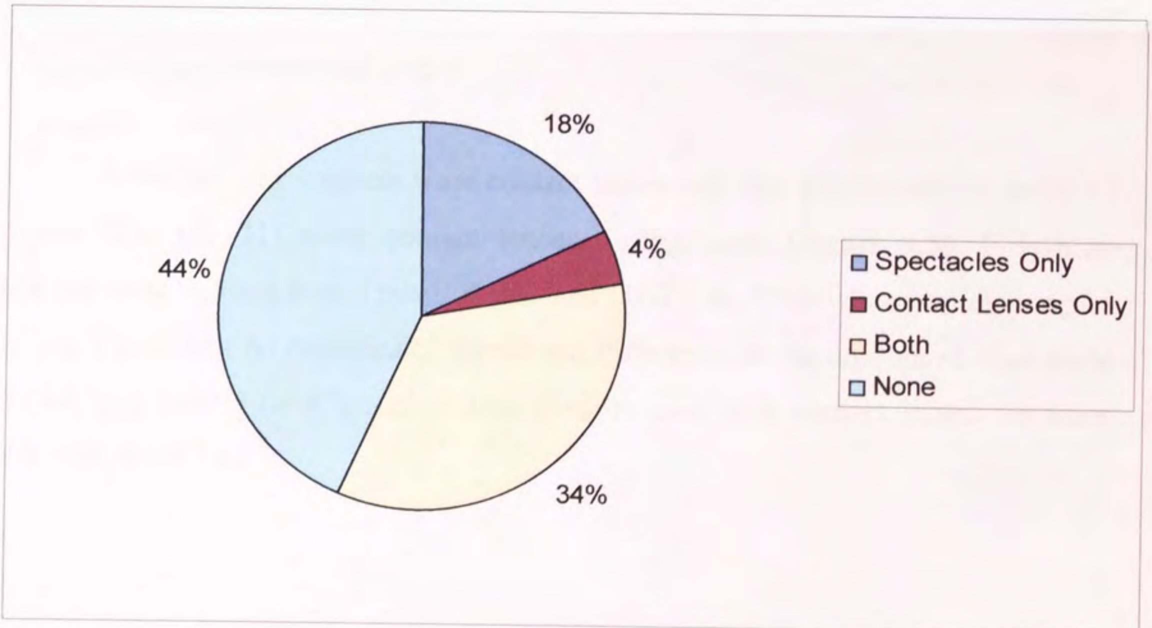


Figure 3.4
Method of visual correction for females (n=294)

3.5.2 Sports Participation

Seventy-three percent of the subjects participated in sports. There was a statistically significant difference between the mean hours males ($n=177$; 5.53 ± 3.27 hours) participate in sport compared to females ($n=158$; 3.12 ± 2.30 hours) (T-Test; $p < 0.001$).

Fifty-eight percent of subjects of the sub-cohort were not asked by their optometric / contact lens practitioner during their last eye exam if they played sport. There was no significant difference between males (n=74) and females (ChiSqu; $p = 0.85$) (n=157). A total of 158 (68%) of the sub-cohort played sports of which 45% (n=71) were asked if they played sports by their optometric/ contact lens practitioner. Of this group 85% (n=60) were asked what type of sports they played. There was no significant difference between males (n=30) and females (n=41) (ChiSqu; $p = 0.36$).

3.5.3 Contact Lenses and Sport

A total of 141 subjects wore contact lenses and also participated in sport, of which 93% (n=131) wore contact lenses during sport (Figure 3.5). Fifty-nine percent wore contact lenses most of the time (100% to 75%) when participating in sports. There was no statistically significant difference in the amount of time male (n=44) and female (n=87) contact lens wearers used their contact lenses for sport (ChiSqu; $p = 0.36$).

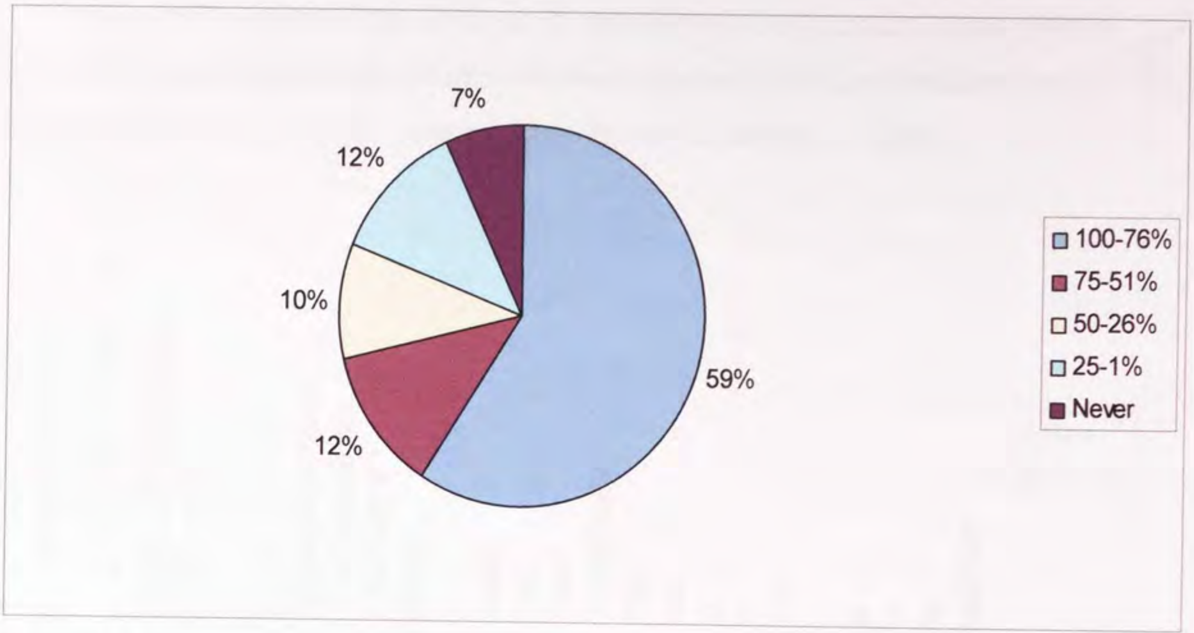


Figure 3.5
Amount of time subjects wear contact lenses when participating in sports (n=141)

Monthly disposable contact lenses accounted for the modality of 51% of the contact lenses used during sports (Figure 3.6). There was a statistical difference between modality of contact lenses worn for sport between males and females (ChiSqu; $p = 0.01$), in which 21% of males wore daily disposable contact lenses compared to 40% of females.

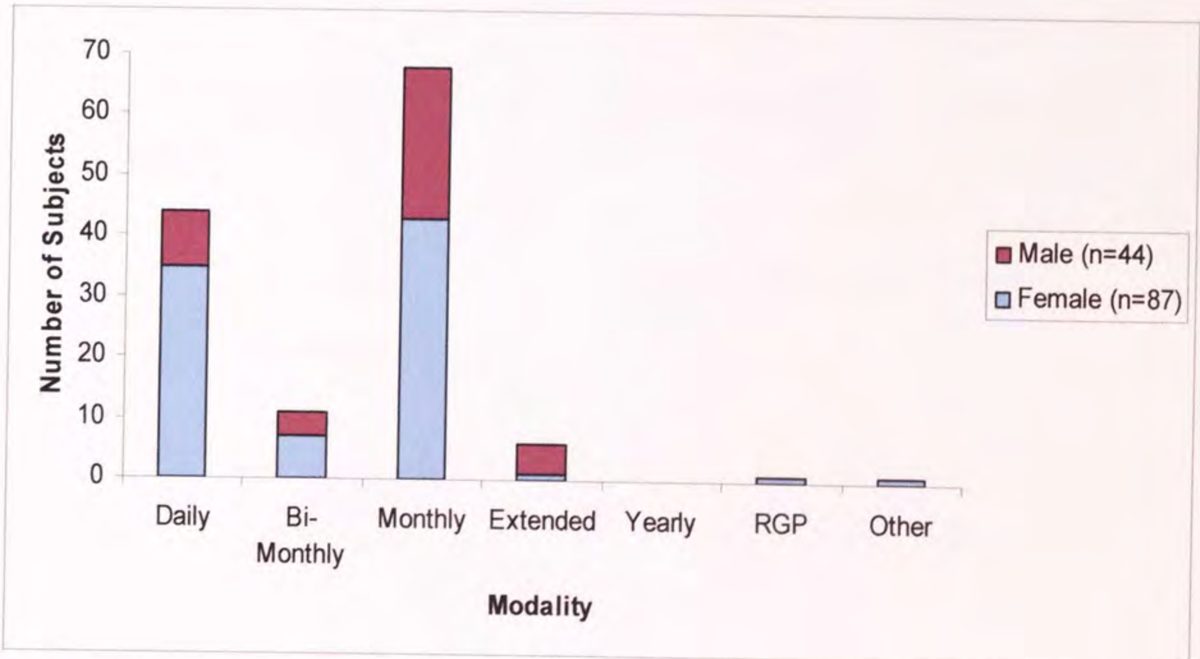


Figure 3.6
Contact lens modality used for sport (n=131)

Football accounted for 17% of all sports played in contact lenses (Figure 3.7). There was a significant difference between males (n=84) and females (n=131) for which sport they played wearing contact lenses (ChiSqu; p = <0.001).

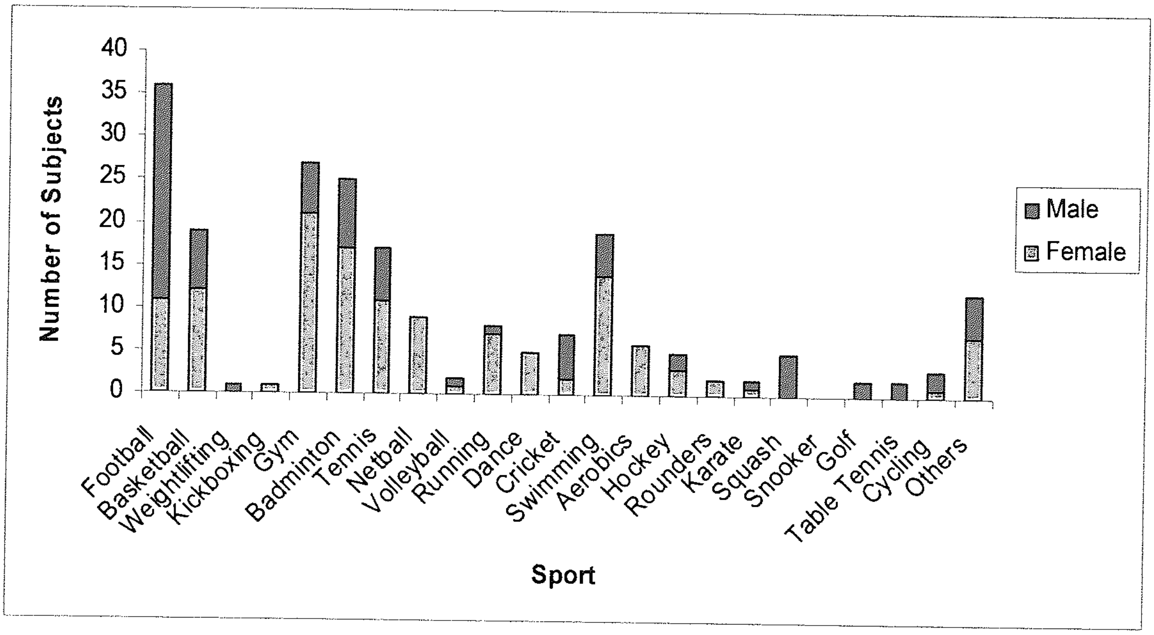


Figure 3.7
Sports played whilst wearing contact lenses. Note: many of the subjects participated in several sports (n=131)

3.5.4 Symptoms and Sport

In total, 113 reported symptoms were recorded when wearing contact lenses during sport, although 23% (30 out of 131) of all subjects who wore contact lenses during their sporting activity reported no adverse symptoms (Figure 3.8). There was no statistical difference in the reported symptoms between males and females (ChiSqu; $p = 0.58$).

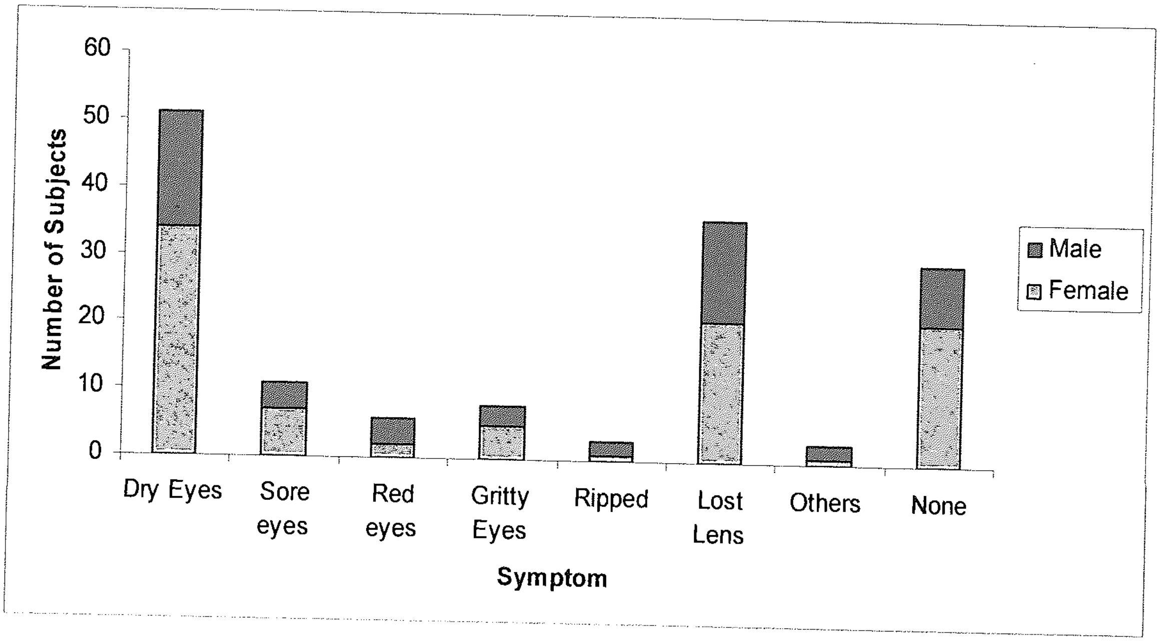


Figure 3.8
Symptoms reported when wearing contact lenses during sporting activities. Note: more than one answer was given by some subjects (n=131)

Ten percent of all subjects removed contact lenses immediately post-sports or exercise (Figure 3.9). There was no statistical difference between male and females (ChiSqu; p = 0.91).

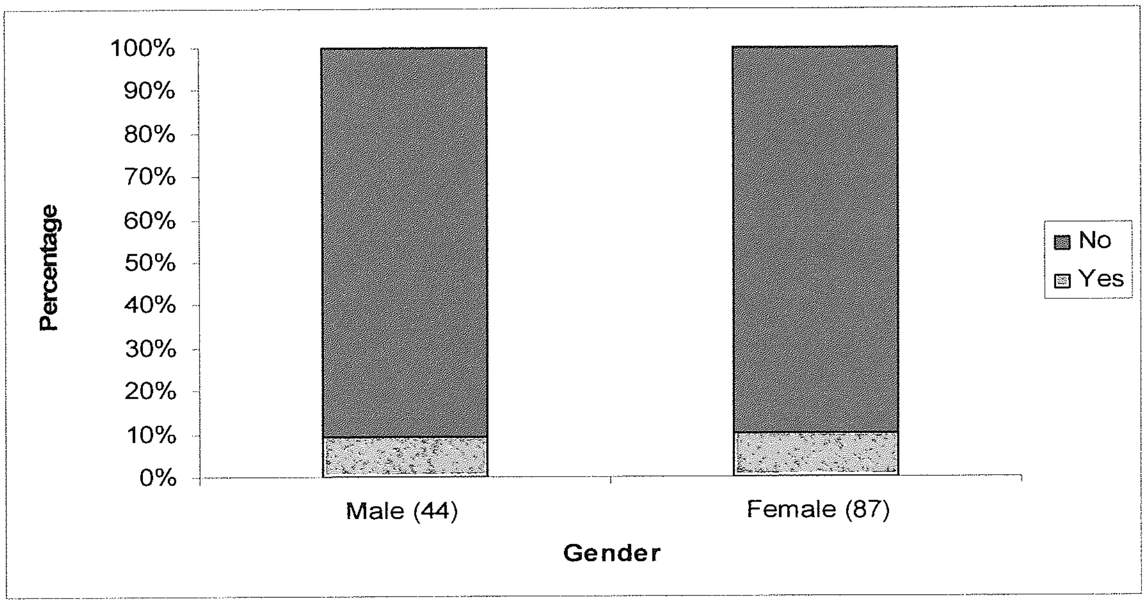


Figure 3.9
Percentage of Contact lens wearers who remove contact lenses immediately post sports (n=131)

3.5.5 Contact Lenses and Swimming

Fifty-one percent (n=24) of the participants who reported swimming in this study swam whilst wearing contact lenses, of which 61% wore their contact lenses without swimming goggles (Figure 3.10). There was no significant difference between male (n=17) and female (n=30) (ChiSqu; p = 0.99).

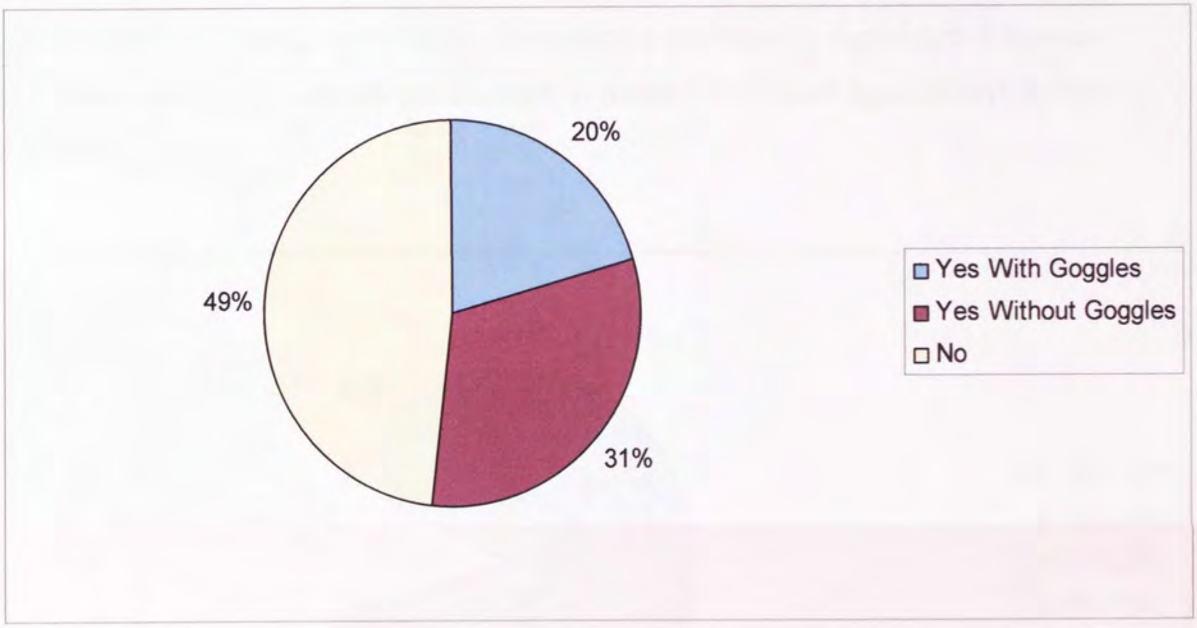


Figure 3.10
Subjects who swim whilst wearing contact lenses (n=47)

3.5.6 Contact Lenses versus Spectacles

A total of 45 subjects from the sub-cohort group who wore both contact lenses and spectacles played sport. Of these, 68% wore contact lenses nearly all the time (100% to 75% of the time) when playing sport (Figure 3.11). There was no significant difference between males (n=14) and females (n=31) (ChiSqu; $p = 0.25$). Eleven percent wore spectacles for 'most of the time' when participating in sport (Figure 3.12). There was no significant difference between males (n=14) and females (n=31) (ChiSqu; $p = 0.21$). There was a statistically significant difference in the amount of time subjects participated in contact lenses and spectacles (ChiSqu; $p < 0.001$).

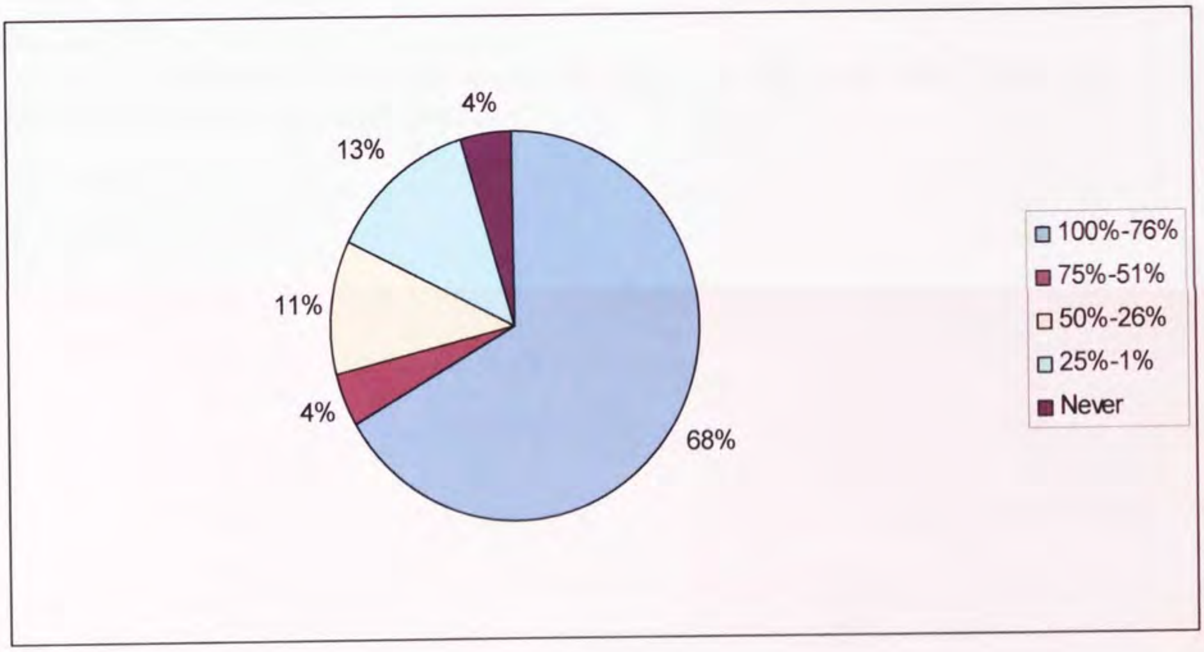


Figure 3.11
Amount of time subjects wear contact lenses when playing sport who wear both spectacles and contact lenses (n=45)

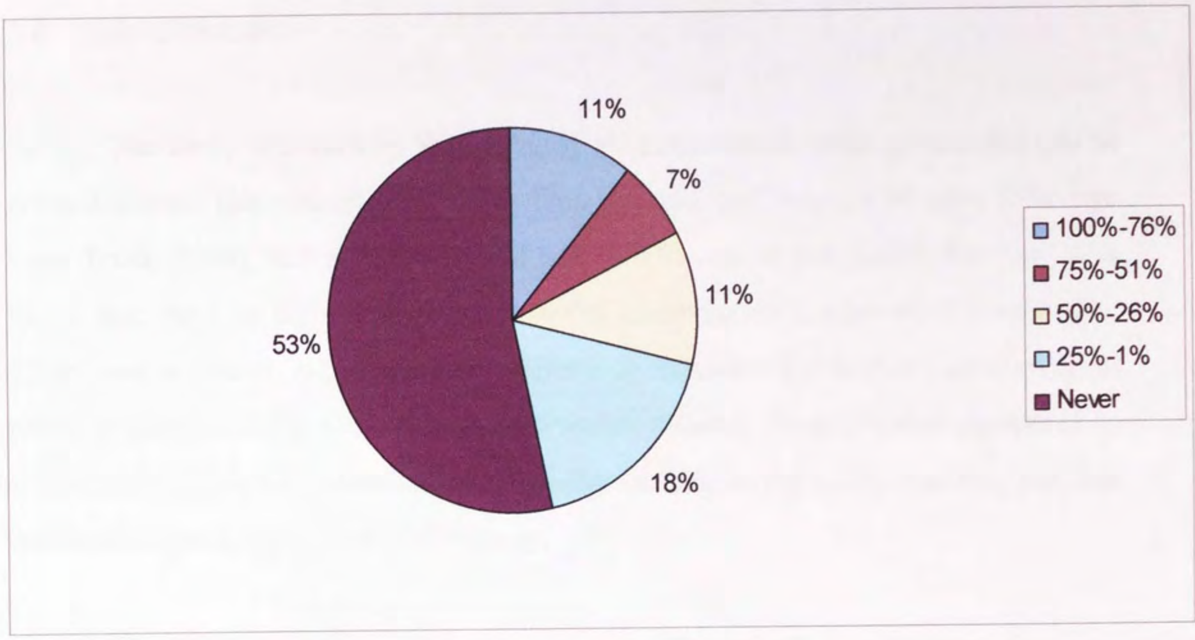


Figure 3.12
Amount of time subjects wear spectacles when playing sport who wear both spectacles and contact lenses (n=45)

3.6 DISCUSSION

The study highlighted that 55% of all respondents wore spectacles and/or contact lenses; this was slightly lower than the national average of 68% (The Eye Care Trust, 2006), although it was not possible to age or sex match the data. It is likely that the Eye Care Trust data includes many patients who were presbyopic. There was a statistically significant difference between the method of correction between males and females, with more females wearing contact lenses compared to males. This may have been due to cosmetic reasons or refractive reasons, but this was not further investigated in this study.

Sports participation in this study was 73% of all respondents; this was similar to the national average as demonstrated in the National Statistics data (National statistics, 2002) in which it concluded that 75% of respondents regularly participate in physical activity. Males participated in sports more than females in this population. A high percentage of contact lens wearers (93%) wore their contact lenses at some point during sports, which support the findings of Bowden and Harknett (2005).

There are many reasons why it is essential that a practitioners question their patients about sports in which they participate. One reason is the recommendation of appropriate eye protection as sports is regarded as the commonest cause of severe eye injury (MacEwan, 1989), and there is a legal requirement for the optometrist to recommend eye protection for certain sports (Classe, 1993b). For example, in squash it is mandatory for players under 19 years of age and when playing doubles, to use eye protection (England Squash, 2007). The type of vision correction appliance is also essential as, for example, it is not generally recommended that RGP contact lenses are used in contact sports (IACLE, 1998). Therefore, it was surprising to demonstrate in this study that less than half of the sub-cohort population (regardless of any vision correction needed) were asked about sports by their optometrist / contact lens practitioner, and the proportion was similar in those who actively undertook sporting activities, dismissing the possible argument that sporty individuals are easy to spot. A follow-up question was asked in the majority of those who said they used their contact lenses during sports, but there were still

15% where the type of sport, and hence appropriate contact lenses, was not investigated. The result is worse than those identified by Loran (2003), who established that only 60% of optometrist asked all patients if they participate in sports.

The study also illustrated that over half of all subjects who wear their contact lenses for some time during sports, wore their contact lenses most of the time (100 – 76%) when participating in sport. It was also demonstrated in the sub-cohort of subjects who wear both contact lenses and spectacles, that they statistically significantly favour contact lenses as opposed to spectacles as the choice of correction when undertaking sports. It is unsurprising that a high number of subjects wear contact lenses as a form of vision correction over spectacles for sport with the numerous advantages they hold, as highlighted in Table 1.4 in Chapter 1. It should be mentioned that this result may well vary according to the type of sport participated and the degree of visual correction required. Whilst males tend to participate in sport for more hours per week than females, there was no evidence to suggest a difference in the amount of time male and female contact lens wearers used their contact lenses for sport.

When fitting contact lenses for any sport or sporting activity it is important to consider both the type and modality of contact lens wear. It is generally not recommended to wear rigid gas permeable lenses for contact sports as these may fracture on impact (IACLE, 1998), nor lenses with low oxygen transmissibility for altitudinal sports such as skiing or snow boarding were partial pressure of oxygen is low (Efron, 2002). As ultra-violet (UV) light can cause ocular injury secondary to UV radiation e.g. age related maculopathy (Sliney, 1988; Tomany *et al,* 2004), and whilst sunglasses can shield against some UV light, Kwok, (2003) suggested that they may be unable to protect against oblique rays unless side shields are applied, concluding that this can be shielded with UV blocking contact lenses in addition to sunglasses, thus indicating the importance of UV blocking contact lenses for outdoor sports. This study demonstrated that many different contact lens wear modalities are worn for sports, the most common of these being that of monthly soft replacement contact lenses with 51%, whilst 34% of respondents wore daily disposable contact lenses to participate in sporting activity. These findings are very similar to the soft replacement data reported by (Morgan), 2007 in which 39% of all new soft, and 30% of all soft refits were daily disposable lenses and that 44% of all new soft fits and 46% of all refits soft were monthly soft replacement contact lenses (Morgan, 2007). However, it does not fit with the higher confidence of optometrists in daily disposables for sport as identified in chapter 2; however, the individual's visual correction and ocular findings may influence the choice of contact lens thus modality. It is interesting to note that none of the subjects questioned wore rigid gas permeable lenses for sports. This finding may be due to the increase risk of ocular trauma with RGP contact lenses compared to soft during contact sports (IACLE, 1998), as well as the general dominance of soft contact lenses over RGP contact lenses in the market today (Morgan, 2007).

A wide variety of sports are played whilst wearing contact lenses from football to karate. Amongst the different sports the most common sport, played by just under a quarter of the cohort were racquet sports (badminton, squash and tennis). This data had a similar trend to Bowden and Harknett, (2005) in which 18% used contact lenses for racquet sports activity.

Although just under a quarter of all subjects who wore contact lenses during their sporting activities did not report any adverse reactions, the most common complaint was dry eyes. This was similar to a study published in 1993 in the US in which the most common contact lens problems experienced by athletes (Zieman, 1993) was irritation and loss, which may have been linked to dry eyes. Despite the symptoms reported in this study, only 10% of the respondents removed their contact lenses immediately after sport. It is not surprising that over a third of the symptoms reported in this study were dry eyes when wearing contact lenses whilst playing sport, as a study by Quevedo *et al.* (2000) demonstrated a significant decrease in both tear film quality and quantity after swimming, tennis and shooting. Research conducted by Ridder *et al.* (2005) reported a benefit from using certain tear supplements on visual performance in those subjects with an evaporative dry eye condition. These findings may be one reason for subjects not wearing contact lenses full time for sports; however, Young *et al.* (2002) demonstrated that 77% of contact lens patients who discontinued contact lens wear could be refitted with a different contact lens with great success (Young *et al.*, 2002).

In general contact lens manufacturers do not recommend their contact lenses to be used in water sports due to the aforementioned potential problems that can arise with increased infection risk. Contact lens wear itself is regarded as a risk factor for bacterial keratitis (Bourcier *et al.*, 2003). In addition to this, a study conducted by Vesaluoma *et al.* (1995) on micro-biological quality in swimming pools, demonstrated a theoretical increased risk of amoebic and bacterial keratitis if contact lenses were worn for swimming. A multi-centre survey investigating the incidence of acanthamoeba keratitis in England between 1992 and 1996 (Radford *et al.*, 1998) concluded that 91% of those soft contact lens wearers who presented with acanthamoeba keratitis could have prevented their infection by either removing their contact lenses prior to swimming or by effective disinfection of the contact lenses. Consequently, swimming is still considered a contra-indication for successful soft contact lens wear (Radford *et al.*, 1998). Therefore it was surprising to discover that whilst there is clearly a risk of infection associated with contact lens wear and swimming, over half of subjects who swim and wear contact lenses do so with them in; furthermore over 60% of this group swam without the use of goggles over the contact lenses. This data represented a higher percentage of patients swimming in contact lenses compared to previous research by Bowden and Harknett (2005) in which only 20% of their subjects swim in contact lenses. This study demonstrated that either the respondent's optometrist or contact lens practitioner did not advise the patient or, that patients are not following the professionals' advice on contact lenses when swimming, which is apparently given to the patients as identified in chapter 2. Although the literature available on the use of contact lenses in swimming is often contradictory, the Vision CRC in Sydney has launched the *'Take care with contacts'* campaign in which they recommend if contact lenses are to be worn for swimming, tight fitting goggles should be mandatory and effective cleaning and disinfectant of lenses should be advised (Vision CRC, 2006). A possible safer alternative that should be considered is the use of prescription swimming goggles.

This study illustrates a need for optometric training in this area, highlighting the importance of patient questioning during the eye examination. Interestingly football has previously been reported as the commonest sport to cause ocular injury in the UK (MacEwen, 1989). However, it is not clear whether the increased risk of eye injury associated with football is simply because there are more people engaged in the sport (National Statistic, 2005).

3.7 CONCLUSION

Over half of the population in this study who wore contact lenses for sport used them *'most of the time'* for their sporting activities. These results certainly seem to highlight that contact lenses are the visual correction of choice for sports and sporting activity. This study highlighted that there is clearly a market for sports vision and contact lenses. Education for both the athlete and gym participant regarding when to wear their contact lenses for sporting activities needs to be addressed. This issue has arisen since over a third of subjects complained of dry eyes whilst playing sports whilst wearing their contact lenses; with the correct instruction and use of artificial tear substitutes this problem may be minimised. Also, the fitting of newer contact lenses with enhanced lubricating properties may be indicated. With such a high proportion of patients likely to be participating in sport it is essential that practitioners ask such questions not only to educate patients about their contact lenses and their application to the sports that they play, but also for the practitioner to advise the patient about suitable eye protection.

Just under two thirds of subjects who swim with contact lenses do not wear swimming goggles over the top. This raises the question whether patients are being given the correct advice, or if the risks are being emphasised enough to them, on swimming whilst wearing contact lenses by their optometrist or contact lens fitter. It is clear that swimming whilst wearing contact lenses is still an issue thus more investigation is needed into the adverse effects of such an activity. Due to this it appears that ametropes who do not wear their contact lenses for swimming may be using prescription swimming goggles as recommended by their optometrist.

As a result of this study, a simple educational poster to display in the ophthalmic practice was developed for patients to alert them to the benefits as well as the risks of wearing contact lenses for sport (Figure 3.13).

This study has highlighted that many contact lens patients are wearing their lenses whilst participating in sports. As this is the case, it is imperative that research is carried out onto the effect of contact lenses on the eye during sports. This will be investigated in subsequent chapters.

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Figure 3.13
The educational poster for safe use of contact lenses in sport (Devised by Martin Cardall)

CHAPTER FOUR

THE EYE AND EXERCISE: VISION, THERMOGRAPHY, OEDEMA, and BULBAR HYPERAEMIA

4.1 INTRODUCTION

Exercise or physical activity can have many potential physiological effects on the human body. Some of these effects may be evident on the cornea. As contact lenses seem to be an ideal vision correction for sports, many questions arise regarding the effect on the cornea due to exercise. For example, does the cornea swell as a result of exercise due to a possible increase oxygen demand the body may require? Furthermore, is there an oedematous effect due to anaerobic respiration? Also, does the temperature of the cornea increase, thus affecting heat dissipation, with contact lens wear during exercise?

Many studies have been carried out investigating exercise or strenuous physical activity on the effect of human visual function (Ishigaki *et al.*, 1991; Koskela, 1988; Millslagle, 2000; Millsiangle *et al.*, 2005; Woods and Thomson, 1995). Woods and Thompson (1995) demonstrated that in twenty university students aged between 18-25 visual acuity improved post-exercise ($p = 0.03$) compared to pre-exercise after either cycling for 20 minutes, stairs running (120 stairs, 10 times), or jogging 3 kilometres (km). In contrast, Ishigaki *et al.* (1991) showed a decrease in visual acuity after 15 minutes of bicycle ergometer in mesopic lighting condition and interestingly visual acuity also decreased with increase in work- load.

A study reported by Koskela in 1988 on 11 subjects investigating the effects of contrast sensitivity after jogging between 7 and 15 km demonstrated an increase in contrast sensitivity post-exercise (1 c/deg and 6c/deg $p < 0.01$). The improvement in contrast sensitivity after exercise was also confirmed by Woods and Thompson (1995) who demonstrated a significantly improved contrast sensitivity post-exercise, with cycling having the greatest effect.

Woods and Thompson (1995) also investigated the effect of exercise on accommodation in 20 young university students. They demonstrated that exercise (cycling, stair running and jogging) had no effect on accommodation.

Humans can generally maintain a very narrow core body temperature of around 37°C regardless of the changing surrounding temperature (Kosaka *et al.*, 2004). The body core consists of several large organs, including the brain, lungs, heart, kidneys, and liver (Wheeler, 2006). It is important to maintain a constant body core temperature for these organs to function effectively and prevent damage (Wheeler, 2006). It has been reported that the body is an effective machine at dissipating heat generated by stress such as exercise or hot environments, thus maintaining body core temperature (Kosaka *et al.*, 2004). The internal regulation of body temperature is controlled by heat-loss and heat-gain (Kakitsuba *et al.*, 2007). This temperature control mechanism for maintaining body temperature is known as homeostasis. Temperature-sensitive neurons in the great veins, spinal cord, abdominal viscera and the hypothalamus measures core body temperature (Wheeler, 2006), whilst the periphery (e.g. skin) temperature monitoring is performed by peripheral thermo-receptors.

Studies have shown that metabolic heat production is due to physical activity or non-shivering thermo-genesis (Weinert and Waterhouse, 2007). If the core body temperature increases it is essential the body loses heat to maintain function. Heat from the body is generally lost through vasodilation of the peripheral blood vessels in the skin through radiation and convection (Weinert and Waterhouse, 2007) and sweating (Weller, 2005) mediated from the sympathetic nervous system (Wheeler, 2006). Studies have measured either / and oesophageal temperature and rectal temperature to evaluate body core temperature (Jay *et al.*, 2007; Kakitsuba *et al.*, 2007; Kenny *et al,*. 1996a; Kenny *et al.*, 1996b; Kenny *et al.*, 1999; Kenny *et al.*, 2000). Kenny *et al.* (1996a) demonstrated a mean evaluation in oesophageal temperature from 36.74°C pre to 37.36°C post-exercise, thus body core temperature increased during exercise. Davies, (1979) investigated the thermoregulation during exercise in relation to age (range 18-65years) and gender, finding no differences. Interestingly, studies have shown that temperature regulation during swimming is different compared to out of water sports (Nielsen, 1978). Fujishima *et al.*, (2001) reported that if the water temperature is higher than that of the body, heat gain is greater than on land, similarly if the water temperature is cooler than the body, heat loss is greater than on land.

Body temperature is generally higher than ocular surface temperature (OST) (Purslow and Wolffsohn, 2005). A common way of measuring ocular temperature is through ocular thermography (Purslow, 2005). The term thermography refers to the measurement of the temperature or the temperature distribution of a body (Jones, 1998). When a body temperature is above absolute zero it will emit electromagnetic radiation known as thermal radiation. Thermography has been used in medicine for several decades (Jones, 1998). It has been use for diagnosis of any pathology that shows changes in temperature such as signs of inflammation, cancers, especially malignancies. It has been used as part of diagnostic method for ocular diseases. Mapstone (1968c) investigated the corneal thermal patterns in anterior uveitis, concluding that acute unilateral anterior uveitis produced a higher corneal temperature than that of the normal opposite eye. It has also been demonstrated that there is a decrease in corneal temperature in carotid artery disease (Morgan *et al.*, 1999). The relationship between glaucoma and corneal temperature had been investigated by Gugleta *et al.*, (1999) in which they demonstrated that the corneal temperature of 18 patients with open angle glaucoma was lower compared to healthy age matched controls.

In the 1870's, Dohnberg and Galezowski measured normal Ocular Surface Temperature (OST) to be between 36.4°C and 36.7°C (cited in Holmberg, 1952). Whereas Horven (1975) showed that the average central corneal temperature, with a thermistor probe in forty normal subjects, was 33.7°C (range 32.0 – 34.9 °C). Mapstone (1968a) identified the disadvantages with contact thermography, so therefore measured absolute temperature of the eye using non-invasive ocular thermography (a bolometer which measures radiation emitted from the surface of the eye). He measured a 10 mm area of the cornea and demonstrated the mean corneal temperature to be 34.8°C with a range between 33.2-36.0°C. The environmental temperature has been shown to influence OST (Freeman and Fatt, 1973; Kolstad, 1970; Mapstone, 1968b, Rysa and Sarvaranta, 1973; Schwartz, 1965;), with Mapstone (1968b) illustrating a decrease in corneal temperature (0.15°C per degree change) as environmental temperature fell. He concluded that convection and radiation were the main reason for heat loss, with conduction only playing a small part as air is a poor conductor of heat.

Lindahl (cited in Mapstone, 1968a) reported that the pre-corneal tear film will emit and absorb the same temperature as the cornea. Dry eyes have been associated with lower central corneal temperatures compared to those with normal tear circulation (Craig *et al.* 2000). However, Purslow and Wolffsohn (2007) demonstrated that subjects with poorer tear stability had a higher initial OST than those with 'good' tear films, concluding that the initial OST measured by infra-red thermography was that of the tear film and not the cornea. Fatt and Chaston, (1980) measured the temperature of the bare cornea and the temperature with a hard and soft contact lens in the eye using the bolometer method. When they measured the temperature with the hard contact lens *in situ*, the temperature was 0.5 to 1.5°C cooler than the bare cornea alone. Similarly a reduced temperature was seen in the soft lens condition although the reduction was much smaller (0.5°C). Hill and Leighton (1965) demonstrated a slight temperature reduction, although not statistically significant, in corneal tear temperature of 0.84°C with a scleral contact lens *in situ* compared to the bare cornea in 8 subjects. Furthermore they demonstrated no further temperature change with the contact lens *in situ* for 60 minutes. The OST under a soft hydrogel contact lens was measured by heat transfer by Martin and Fatt (1986). They concluded that the higher the water content of a soft contact lens, the smaller the rise in anterior corneal surface temperature than lenses with lower water content. Purslow *et al.*, (2005) examined the changes in OST with different contact lenses *in situ*. The results demonstrated that the silicone hydrogel (SiH) contact lenses lens produced a higher OST compared to the mid-water contact lenses and the bare cornea. Hamano *et al.* (1969) demonstrated that 80% of infra-red radiation was absorbed by the tear film on the cornea and the contact lens indicating that the temperature measured by a bolometer is close to the tear temperature. Table 4.1 summarises the research on OST and contact lens wear.

Author and year	Contact lens type	Temperature (°C)	Method	Subjects
Fatt and Chaston, 1980	Hard Soft	0.5 to 1.5°C below the bare cornea 0.5°C below the bare cornea		N=6
Hamano *et al.*, 1969	Hard	No more than 0.5°C than naked cornea		N=10
Hill and Leighton, 1965	Hard	0.85°C reduction than no contact lens		N=8
Martin and Fatt, 1986	Soft	higher the water content of a soft contact lens the smaller rise in anterior corneal surface	Heat Transfer	N=13
Purslow *et al.*, 2005	Soft (SiH and mid water)	35.3-37.1°C	Infra-red	N= 48 in total (8 for each condition)

Table 4.1
Summary of OST and contact lenses

A change in corneal thickness has previously been suggested as an excellent marker for measuring changes in normal corneal physiology with contact lenses (Mandell *et al.,* 1970). The cornea exhibits a diurnal variation in thickness, with the cornea being thickest in the morning due to normal overnight swelling due to lid closure. The mean overnight swelling of the cornea on awakening has been found to be 3.0% ± 1.2% (Holden *et al.,* 1983). The cornea returns to its original thickness 1 hour after eye opening (Holden *et al.,* 1983). It has been suggested that the change in corneal thickness is due to the disruption of oxygen and carbon dioxide transmissibility within the corneal stroma to prevent hypercapnia (increased carbon dioxide CO_2) and/or hypoxia (reduction in oxygen) (Ang and Efron 1990). The effect on the human cornea from deprivation of its normal oxygen supply was reported by Polse and Mandell in 1976 by studying ten human subjects using the goggle method (see section 1.3.4.3 in Chapter 1). They noted that vertical striae (fine white lines deep in the corneal stroma or Descemet's membrane) were first observed when the cornea swelled at about 5%, so therefore striae in the posterior stroma have been described as one of the first signs of oedema (Jalbert and Stapleton, 2005). A change in corneal thickness has also been shown to be present during exercise (Bomholt and Schnell, 2000).

As previously discussed in Chapter 1, contact lens wear can disrupt the diffusion of oxygen to the cornea (Brennan, 2005), and therefore, lead to an increase in stromal thickness within the cornea (Liesegang, 2002). Studies have demonstrated that if a contact lens is worn in one eye, a small amount of corneal swelling may exist in the non wearing contralateral eye (Fonn, *et al,*. 1999; Guzey, *et al,*. 2002; Harris and Mandell, 1969). Harris and Mandell, (1969) showed a 3% increase in corneal swelling in the contralateral eye of 3 patients wearing a PMMA contact lens in the other eye. This effect has also been seen with soft contact lenses (Fonn, *et al,*. 1999; Guzey, *et al,*. 2002). It is unclear why this occurs, however, Fonn *et al.,* (1999) suggests this may be a sympathetic physiological response rather than an unusual sampling coincidence.

As already discussed in Chapter 1, Holden and Mertz (1984) investigated the critical oxygen to avoid corneal oedema during daily and extended contact lens wear. They concluded that to prevent corneal swelling in the open-eye (daily lens wear) the minimum Dk/t contact lens would need to be $24.1 \pm 2{,}7 \times 10^{-9}$ (cm x ml O_2)/(sec x ml x mmHg) or Equivalent Oxygen Percentage (EOP, see section 1.3.4.1.1 in Chapter 1) of 9.9%, and to avoid overnight contact lens induced corneal swelling the critical oxygen transmissibility (Dk/t) of a contact lens should exceed $87 \pm 3.3 \times 10^{-9}$ (cm x mLO_2) (sec x mL x mmHg). Furthermore, in 1999 Harvitt and Bonanno calculated that a contact lens Dk/t required to avoid corneal swelling during the closed-eye condition was 125×10^{-9} Dk/t (Harvitt and Bonanno, 1999) which was higher than previously proposed by Holden and Mertz in 1984.

There is a lack in the literature of studies looking at corneal oedema during exercise. However, as previously mentioned, Bomholt and Schnell (2000) stated that contact lenses used during sports, such as running, can lead to corneal oedema due to a high level of lactic acid occurring and decreased levels of glucose in the anterior chamber of the eye, although this disappears quickly after cessation of exercise. The authors also commented that this oedema occurred for endurance sports which involved high rates of aerobic metabolic turnover (such as triathlon and road cycling). They concluded that unlike spectacles, contact lenses can impede the metabolic process of the eye during exercise but this was purely observational.

Ocular hyperaemia or redness has been suggested as an important indicator of ocular health (Papas, 2000) and has been associated with contact lens wear (Coles *et al.*, 2004; Riley *et al.*, 2006). Efron *et al.* (1988) studied temperature changes in the hyperaemic bulbar conjuctiva in 18 normal young adults. They commented that dilation of the capillary blood vessels increased bulbar hyperemia and, as the capillary blood temperature is higher than that of the intact bulbar conjunctiva, they expected temperature in bulbar hyperaemia to be higher than the undisturbed state. Using the bolometry technique they demonstrated that in hyperaemia (grade 3 Efron scale), a 0.5°C increase in temperature was seen, concluding that, as contact lenses can cover significant part of the conjunctiva resulting in a stressed physiological status of the tissue beneath the contact lens, this may be enhanced by an increase in temperature and also increase micro-organism activity. Once again there seems to be a lack of literature on ocular hyperaemia during sports.

The literature has established that the cornea, visual acuity, and contrast sensitivity are affected by exercise, and that many factors can influence ocular surface temperature, for example, the presence of ocular disease and the use of contact lenses, and to the authors knowledge there are no data in the literature investigating the OST effect, and very limited data on corneal oedema, during a period of exercise with and without contact lenses.

4.2 AIM

The aim of this study was to investigate the physiological effects on visual acuity, OST, corneal thickness, and bulbar hyperaemia with and without a variety of contact lenses during a controlled exercise period.

4.3 METHOD

4.3.1 Apparatus

Non-contact methods of measuring the corneal volume, ocular hyperaemia, and OST were chosen to prevent interference with the eye directly, as this would also prevent any disruption to the tear film either by the use of local anaesthetics or by direct applanation forces which may produce an inaccurate result (Mapstone, 1968a).

4.3.1.1 Thermal Camera

The camera used for this research was a commercially available thermo-camera (NEC San-ei Japan Thermo Tracer TH7102MX; Figure 4.1).

Figure 4.1
Thermo-camera NEC San-ei Japan Thermo Tracer TH7102MX

Radiation from the subject is transmitted and focused by the optical system of the thermo-camera. The Vanadium Oxide (VOx) detector used in this camera acts as a microbolometer (see section 4.1). The VOx detects the thermal radiation in a scene, and pixel intensities are developed from the varying degrees of thermal radiation (Purslow, 2005). The detector was compensated for ambient temperature and humidity by manual programming. This camera has been used and verified for repeatability and accuracy by Purslow (2005). The camera is self-calibrating, so there is no requirement for a separate black body radiator. The camera is sensitive to 8-14um, which is an appropriate emission for measuring OST (Lerman, 1980, cited in Purslow *et al.*, 2005). The camera has an accuracy of ± 2% and has a pixel size of 320 (H) x 240 (V), and a maximal temporal resolution of 0.08°C at 30Hz. To enable measurements of the OST at near, an additional close up lens was fitted to the camera to allow a 60mm close focus, with a spatial frequency of 100um, allowing a 34.5mm (H) x 26.0 mm (V) field of view (Figure 4.2).

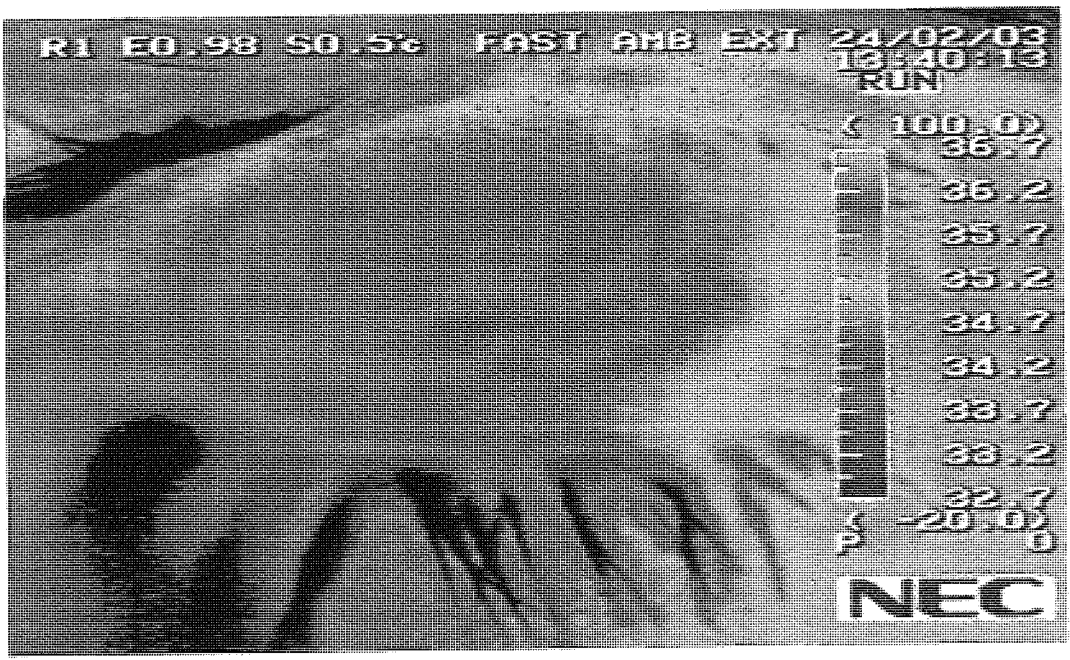

Figure 4.2
The colour image of the anterior eye (close up lens) with the Thermo-camera NEC San-ei Japan Thermo Tracer TH7102MX

4.3.1.2 Camera Configuration

Unlike Purslow *et al.* (2005), in which the camera was mounted on a slit-lamp base for stability, due to the subjects' set-up in this study, the camera was hand-held. A measurement was taken at around 58 mm from the anterior plain of the cornea. To minimise variations, the examiner took an OST image when the lashes of the eyelids were in focus as moving the focusing length can affect radiation source. Previous studies have suggested using an average of 3 measurements, as this improves accuracy, and repeatability does not significantly improve with further readings (Purslow, 2005). The average temperature was taken over a (5 mm^2) box generated by the camera from the centre of the cornea (Figure 4.3). To enable each measurements to taken from the same area, anatomical features such as the limbus were used to determine location.

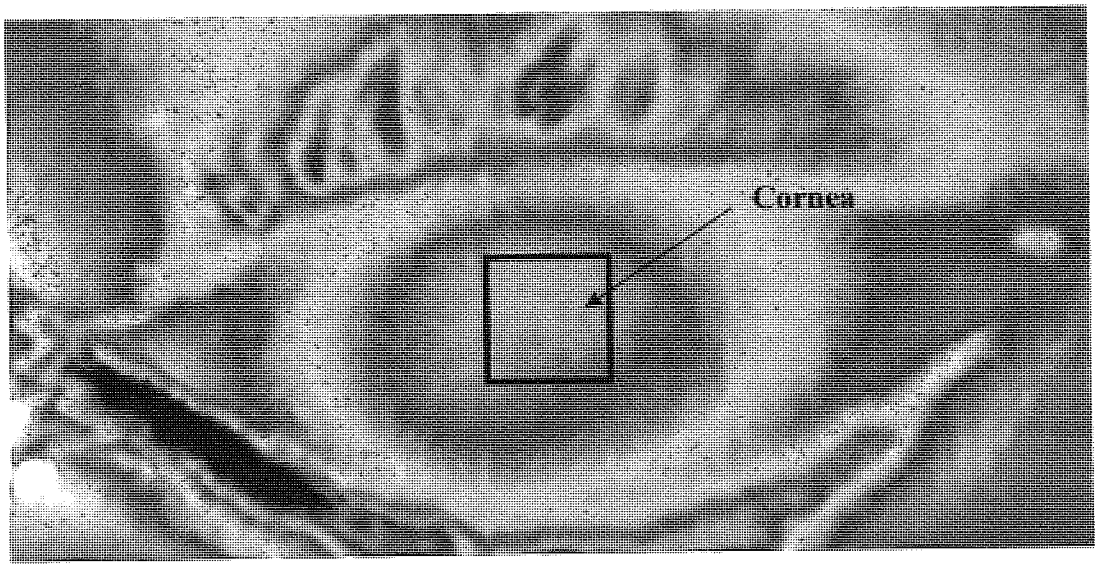

Figure 4.3
Area on cornea measured (black box) using the Thermo-camera NEC San-ei Japan Thermo Tracer TH7102MX

4.3.1.3 Measuring Corneal Thickness

The Oculus Pentacam (Oculus GmbH, Wetzlar, Germany) was used to measure corneal pachymetry (Figure 4.4). This device is a rotating Scheimpflug camera generating a three-dimensional, dot-matrix image of the anterior section of the eye (Figure 4.5). The instrument measures the corneal topography and corneal pachymetry of the whole anterior and posterior cornea from limbus to limbus. The Pentacam software gives data of corneal volume, thinnest pachymetry measurement of the cornea, as well as several other properties such as anterior chamber volume and chamber angle. For the purpose of the research, corneal volume was measured. The corneal volume measured with the Oculus Pentacam is (from epithelial surface to endothelial surface) calculate from a pupil-centred ring around the apex of diameter 10 mm. The corneal measurements were taken just prior to contact lens insertion and post-removal after the test period (2 hours adaptation and 35 minutes control or exercise). For the purpose of this study the control and exercise condition included a 2 hour adaptation period for the lens.

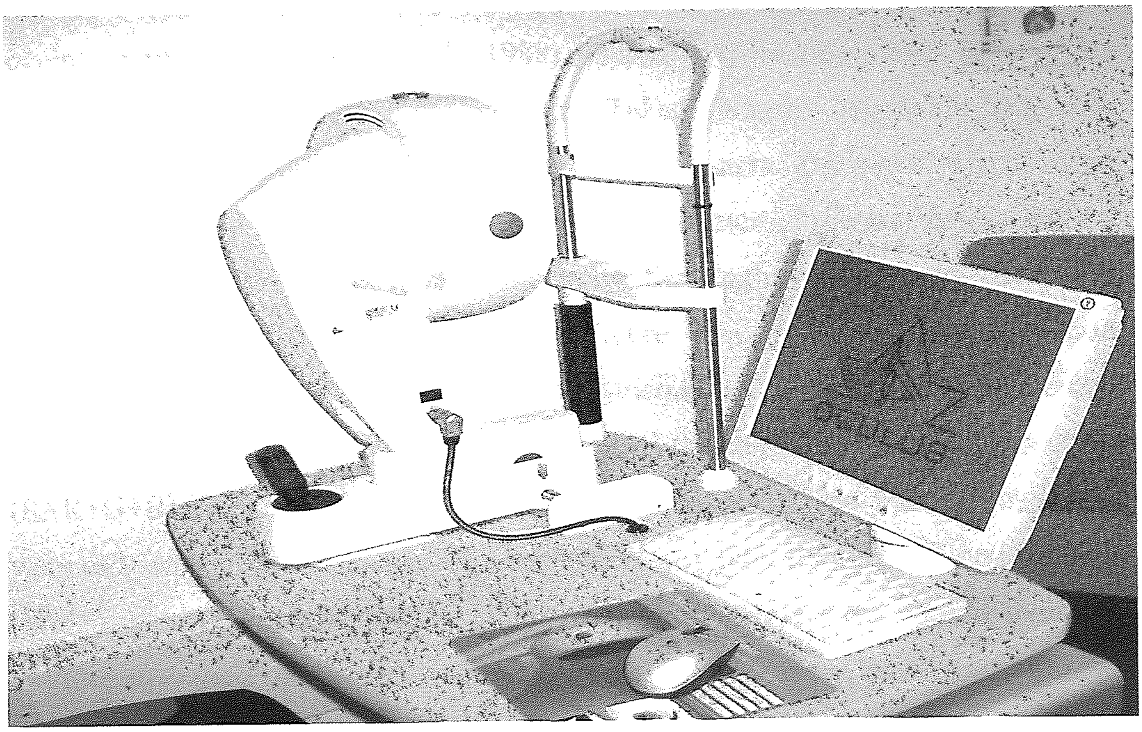

Figure 4.4
The Oculus Pentacam

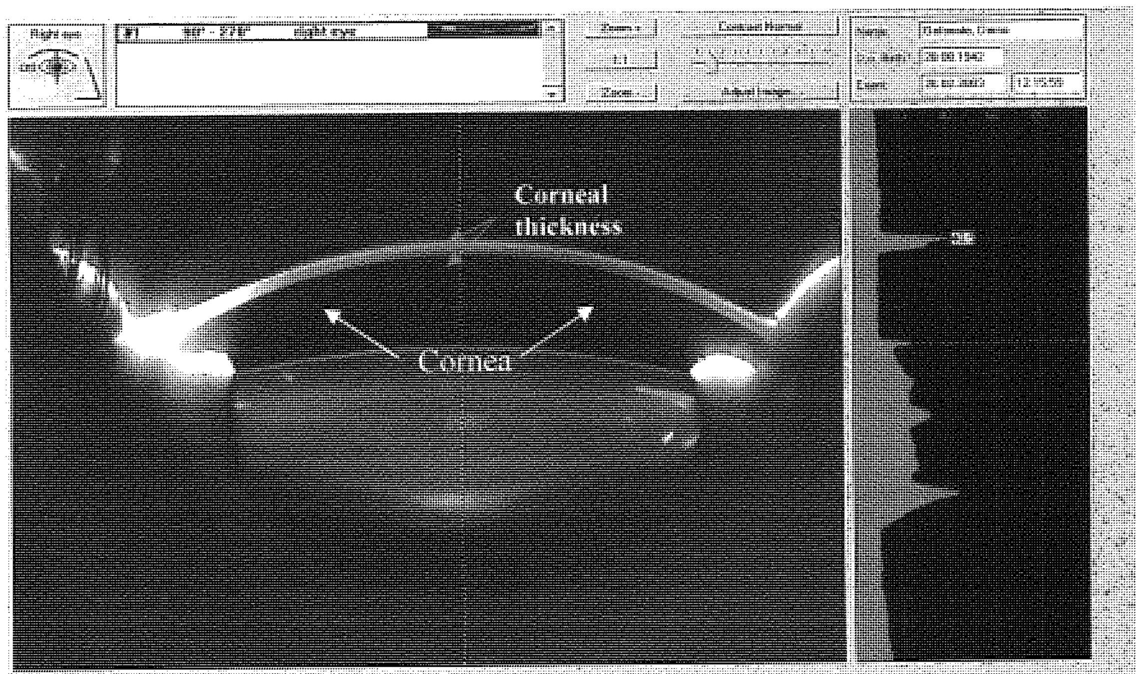

Figure 4.5
Scheimpflug image produced from the Oculus Pentacam

4.3.1.4 Bulbar Hyperaemia Measurements

The literature has suggested that body temperature increases with exercise (Kenny *et al.*, 1996a), and that bulbar hyperaemia is associated with an increase in ocular temperature (Efron *et al.*, 1988). Bulbar hyperaemia was assessed by capturing a temporal image of the eye with a Takagi (Nagano, Japan) slit-lamp with attached Jai CV-S3200 (Yokohama, Japan) digital camera. The percentage of blood vessel coverage was analysed using purpose-written software developed by Professor James Wolffsohn, (Aston University, Birmingham, UK) using Labview® software (National Instruments, USA) (Figure 4.6) by using edge detection (extraction of edges by pixel to pixel comparisons used to produce a sharpening effect on a feature boundary). This also measured the colour intensity of the redness (R/(R+G+B) by using relative colour extraction (red, green and blue colour planes were extracted from the image. This technique was fully investigated and verified (Wolffsohn and Purslow, 2003). Objective measurements were chosen over the traditionally used subjective method (e.g. Efron Grading Scale in which a practitioner would compare the bulbar hyperaemia to a series of pictures form grade 0 (normal) to grade 4 (severe)) as Peterson, (2007) demonstrated that the computer programme (objective method) used in this study was 20x more sensitive than subjective grading (0.01 of an Efron grade). The baseline ocular hyperaemia photo was taken after the 2 hours adaptation period, just prior to the investigative period (35 minutes control or exercise) and immediately post-investigative period. A square of 4 mm by 4 mm on the temporal bulbar conjunctiva was analysed. This area was chosen as it was the largest area of the conjunctiva that could be analysed without interference from the palpebral aperture (Peterson and Wolffsohn, 2007).

Figure 4.6
Screen View of the hyperaemia area analysing program

4.3.1.5 Visual Acuity (VA) and Contrast Sensitivity (CS)

Visual acuity was measured with a Bailey-Lovie LogMAR chart at 3m. Contrast sensitivity was assessed with a Pelli-Robson chart at 1m, with subjects encouraged to name each sequence of 3 letters in turn until less than 2 out of 3 could be identified correctly (Cho, 2000; Woods *et al.,* 1994).

4.3.1.6 Contact Lenses

Three types of soft contact lenses were chosen to be analysed in this study. The lenses chosen were used to demonstrate the effect of soft contact lenses of a variety of Dk/t and materials (Table 4.2). The subjects' own contact lens refractive data was used to establish best spherical refractive power of the test contact lens. The patients own spectacles were used to establish VA and CS during the no-lens condition. Contact lenses were inserted into the right and left eye (due to the influence of the potential sympathetic effect of the contralateral eye, see section 4.1), but measurements were only taken for the right eye.

Name	Polymacon	Lotrafilcon	Nelfilcon
Material	HEMA	SiH	HEMA
Oxygen permeability (Dk)	8.5	140	26
ISO Category (ACLM, 2007)	1	5	2
Water Content (%)	38	24	69
BOZR (mm)	8.7	8.6	8.6
Total Diameter (mm)	14	13.8	13.8
Power (Dioptre)	-3.00	-3.00	-3.00
Modality (Disposable)	Conventional	Monthly	Daily
Centre Thickness at -3.00D (mm)	0.06	0.08	0.10

Table 4.2
Contact lens materials and parameters, all lenses quoted at -3.00DS

4.3.1.7 Exercise Equipment

The Kettler Golf GT exercise bike was used (Figure 4.7) for the purpose of this research. An ergometric exercise cycle was chosen as the load of exercise can be controlled and the weight of the subject does not influence the exercise load (Åstrand and Rodahl, 1998).

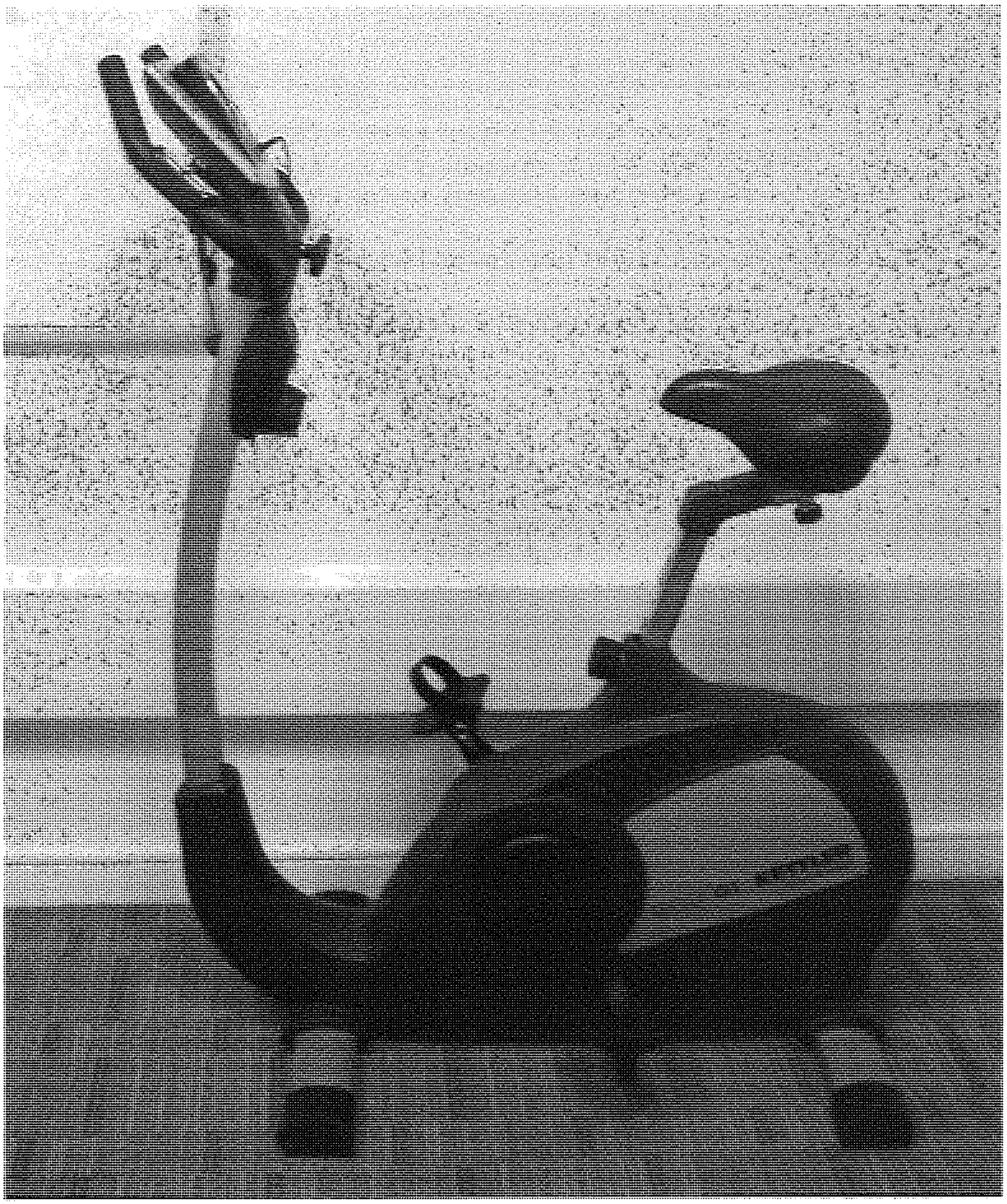

Figure 4.7
The Golf GT Kettler exercise bike (Kettler, GB Ltd, Redditch, UK)

4.3.1.8 Exercise Period and Load

A safe level of exercise was established on recommendation of the American College of Sports Medicine (ASCM), and the Centre of Disease and Control Prevention (ASCM, 2000; CDC, 2007). It is currently recommended for under 65years of age to actively participate in moderate exercise (around 60 – 70% of your maximum heart rate) (Figure 4.8) for a period of 30 minutes five days per week.

220 – Age (20) = A (200)
A (200)- Resting Heart Rate (70) = B(130)
B (130) x Low end of percentage work load (60%)= 78
B (130) x Top end of training zone (70%)= 91

So target Heart rate would be between 78-91 beats per minute

The above example is a 20 year old with a resting heart rate of 70 beats per minute.

Figure 4.8
Method used to calculate maximum heart rate (Karvonen method)

4.3.1.9 Laboratory Set-Up

To enable accurate readings, a temperature-monitored laboratory was used. The laboratory air temperature and humidity were monitored by use of a hygro-thermometer with a sampling rate every 10 seconds (accuracy ± 1%, sensitivity 0.1°C).

4.3.2 Design Procedure

The literature demonstrates that OST is dependant on the environmental temperature (Mapstone, 1968b; Schwartz, 1965), therefore for OST measurements to be taken accurately, the subjects must adapt to their surroundings. Previous research on OST has illustrated the adaptation time to be between 15 and 20 minutes (Mapstone, 1968a; Morgan *et al.*, 1995; Purslow *et al.*, 2005). Mapstone chose 15 minutes, whereas Morgan *et al.*, (1995) established an 18 minute adaptation time, and Purslow chose 20 minutes (Purslow *et al.*, 2005). In this study, a 20 minute adaptation time was chosen. Purslow has demonstrated that the OST with contact lenses is best taken 2 hours post-contact lens insertion (Purslow *et al.*, 2005), and this protocol was followed in this study. Diurnal changes and OST have also been shown to influence OST data (Du Toit *et al.*, 1998). To minimise this variation, all subjects were examined between 10am and 1pm. It has been previously demonstrated that OST measurements can vary according to post-blink time (Purslow, 2005). Therefore, the thermo-camera images were taken 5 seconds post blink as used by Morgan *et al.* (1993).

4.3.3 Experimental Protocol

The following protocol was constructed. To ensure a safe protocol was adhered too, an exercise period time at a maximum heart rate load was established as recommended in section 4.3.1.8. All subjects attended in the morning to minimise diurnal variations (between 10am-1pm). Each subject was required to read and complete a standard Ethical Committee consent form and a PAR-Q questionnaire (see Appendix). The study group attended four experimental sessions lasting up to 3 hours each, one session with no contact lens and three contact lens sessions, each with a different contact lens. The test contact lenses were randomised so neither the subject nor the examiner could identify the lens type until after the experiment had been completed. This was repeated for control data in which all protocol were followed without the exercise (Figure 4.9). The subjects adapted to the room environment for 20 minutes prior to measurements and the contact lens was inserted by the examiner 2 hours prior to OST measurements (Purslow *et al.*, 2005). All the subjects were required to have had a complete optometric exam prior to enrolment in order to assess their ocular health, refractive status (by their own optometrist) and they were also required to have had a recent contact lenses assessment (within past 12 months). Resting pulse rate was taken using a Pulse Oximeter (Nonin Model 8500, Minneapolis, US). The patient was required to sit for 20 minutes prior to this measurement for their resting pulse rate. The pulse rate was monitored continually during the exercise test. Measurement of visual acuity and contrast sensitivity, central OST corneal area, corneal volume/ thickness and bulbar hyperaemia were recorded as directed in Figure 4.9. The subjects were required to exercise for a period of 35 minutes on a static exercise bike. The exercise intensity was between 60% and 70% of their maximal heart rate. To prevent eye rubbing due to sweat, a sweatband was worn as eye rubbing can increase OST on average by +0.21 ^{o}C (Purslow, 2005). Patients were advised that the study did not replace the need for regular eye examinations and / or contact lens assessments. Patients were all previous soft contact lens wearers, but were instructed not to wear their contact lenses for at least 48 hours prior to the study.

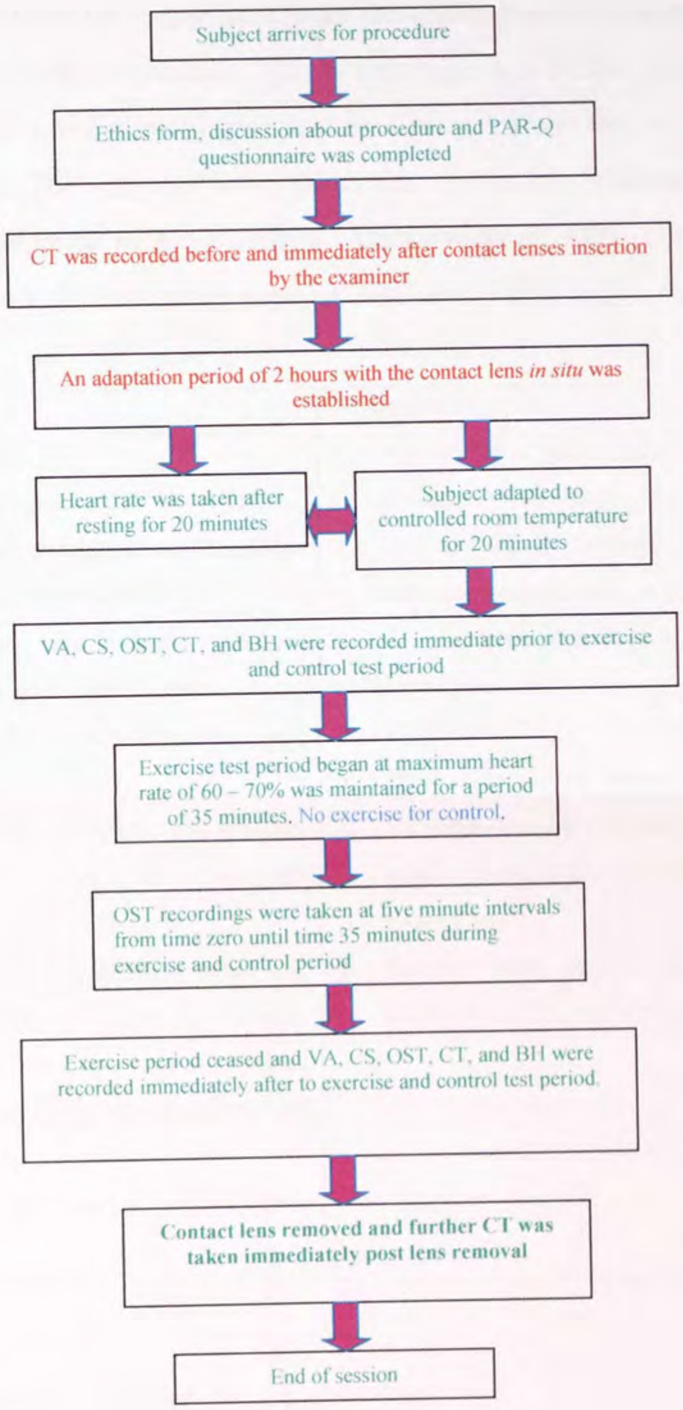

Figure 4.9
Flow diagram of study procedure on each visit. Text in green indicates both control and exercise no lens visits. The red text indicates additional measurements taken only during contact lens visit and the text in blue indicates control visit only. (VA= Visual Acuity; CS= Contrast sensitivity; OST= Ocular Surface Temperature; CT= Corneal Volume; BH= Bulbar Hyperaemia)

4.3.4 Subjects

Twelve subjects were recruited from the under-graduate, post-graduate and staff population of Aston University. The average age was 30.5 ± 5.02 years with a 3:2 male to female ratio. Ethical approval was sought from the Aston University Ethics Committee. The subjects were given the option of withdrawing from the experiment in accordance with the Helsinki Declaration of 2000. The requirements for the subjects to enrol in the study were as followed (Table 4.3):

Inclusion Criteria	Exclusion Criteria
1. Good general health. 2. Best corrected visual acuity of 6/6 or better. 3. No known cataract or opacities on the ocular lenses or other ocular problems. 4. Currently contact lens wearers with no history of contact lens complications. 5. Pass the PAR-Q questionnaire (see Appendix). 6. Actively participate in exercise (30 minutes 60-70% maximum heart rate 5 times per week). 7. Have had a recent eye exam and contact lens examination/ aftercare within 12 months. Subjects are aware that this does not replace the need for regular eye examinations and contact lens check. 8. Aged between 18 and 45 years (pre-presbyopic).	1. Known active ocular pathology. 2. Cataract or opacities on the ocular lenses. 3. Any history of problems with contact lens induced complications in the past. 4. Any systemic condition e.g. diabetes, high blood pressure. 5. Amblyopia. 6. Previous refractive surgery. 7. Subjects who do not actively participate in sports (defined as 30 minutes exercise 5 times a week). 8. Subjects who answer yes to any of the questions to the PAR-Q questionnaire.

Table 4.3
Inclusion and exclusion criterion used in the study

All patients were interviewed with respect to their ability to adhere to the study protocol.

4.3.5 Subject Set-Up

The subject was instructed to cycle for 35 minutes (5 minute warm up) as the examiner recorded the thermography of the cornea every 5 minutes (Figure 4.10).

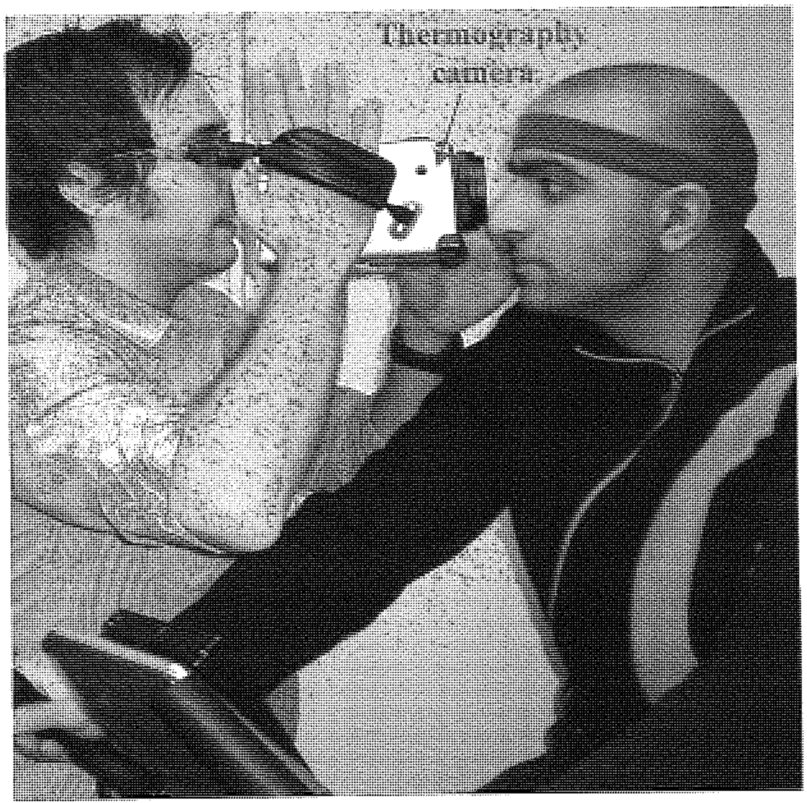

Figure 4.10
The subject set-up

4.4 RESULTS

The mean contact lens Rx correction was -1.17DS ± 2.50 DS. The room temperature was 21.3 ± 2.5°C, and the humidity was 41 ± 5%. The statistics were generated by SPSS version 15, Excel, and SigmaPlot 2000.

4.4.1 Visual Acuity

Visual Acuity decreased after exercise with no contact lens on the eye although this was not statistically significant ($p = 0.59$). The visual acuity increased after exercise with Nelfilcon, Lotraficon, and Polymacon contact lens materials, but again this was not statistically significant (Figure 4.11; T-Test; $p = 0.08$, $p = 0.48$, and $p = 0.59$ respectively).

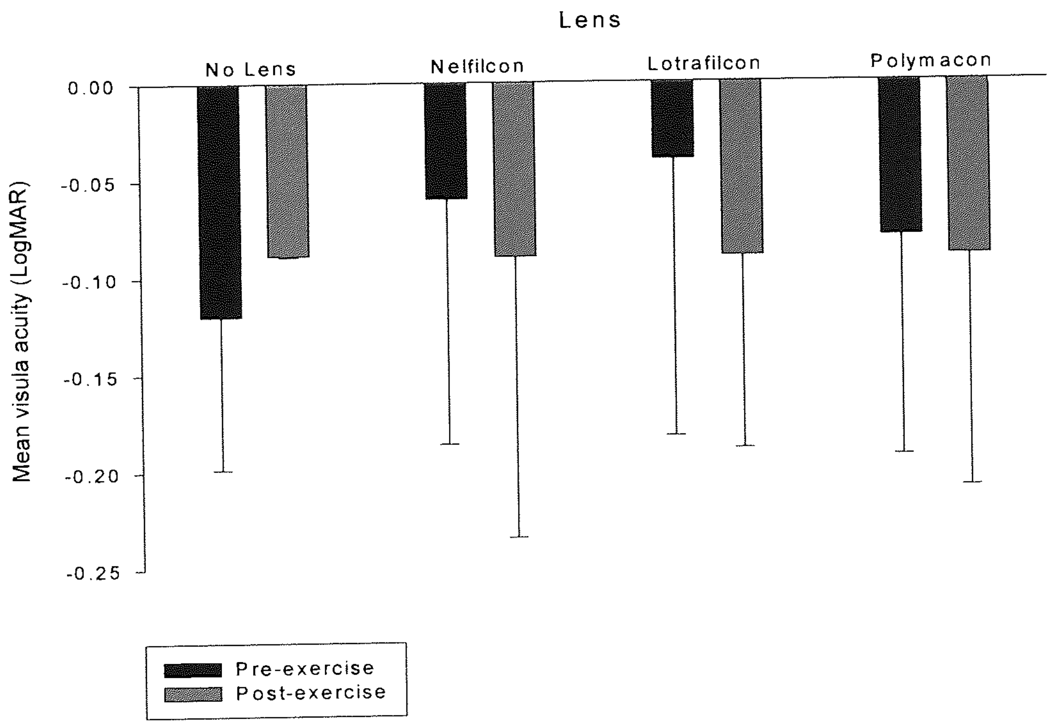

Figure 4.11
Mean visual acuity (LogMAR) pre and post 35 minutes exercise. Error bars = 1SD (n=12)

4.4.2 Contrast Sensitivity

Contrast sensitivity decreased after exercise with no contact lens on the eye although this was not statistically significant (Figure 4.12; T-Test p = 0.56). The contrast sensitivity increased after exercise with Nelfilcon, and Polymacon material contact lenses, but again this was not statistically significant (T-Test; p = 0.06 and p = 0.08, respectively). No change was seen after exercise whilst wearing Lotrafilcon contact lens material (T-Test; p = 1.00).

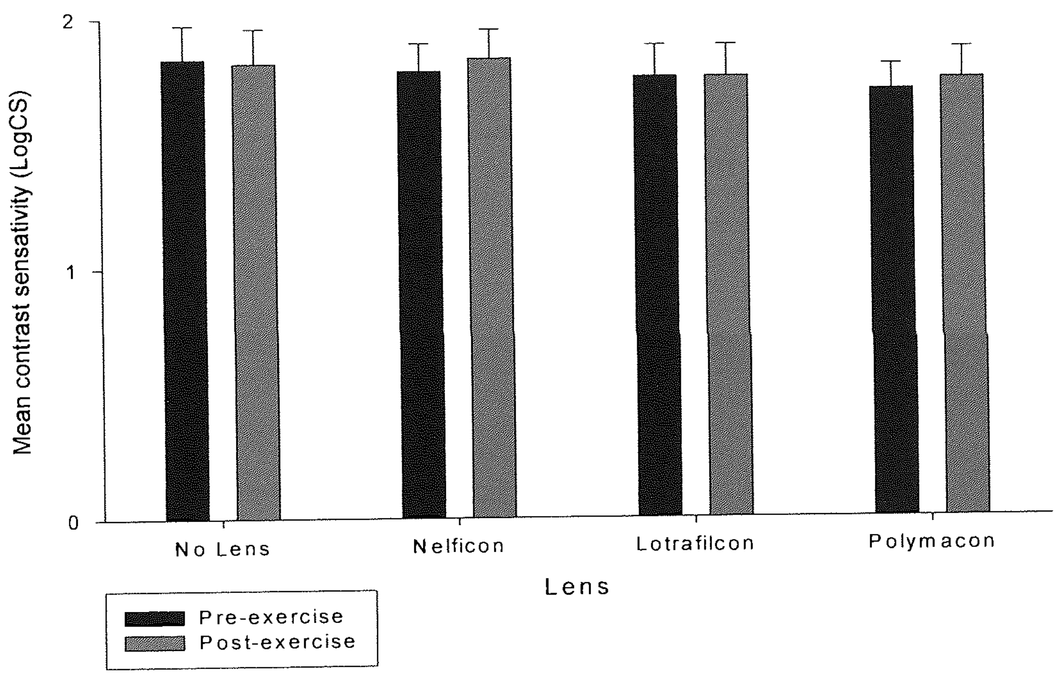

Figure 4.12
Mean contrast sensitivity (LogCS) pre and post 35 minutes exercise. Error bars = 1SD (n=12)

4.4.3 Change in OST with and without Contact Lenses – Control

Figure 4.13 illustrates the average OST from baseline of all 4 lens conditions (No lens, Nelfilcon, Lotrafilcon, and Polymacon) over a period of 35 minutes without exercise. There was a significant effect on OST with time (ANOVA; $F = 7.82$; $p < 0.001$). There was no significant effect on OST between lens conditions (ANOVA; $F = 1.09$; $p = 0.37$). There was a significant interaction suggesting time trends vary for the different lens conditions ($F = 5.55$; $p < 0.001$), and this difference varies quadratically with time.

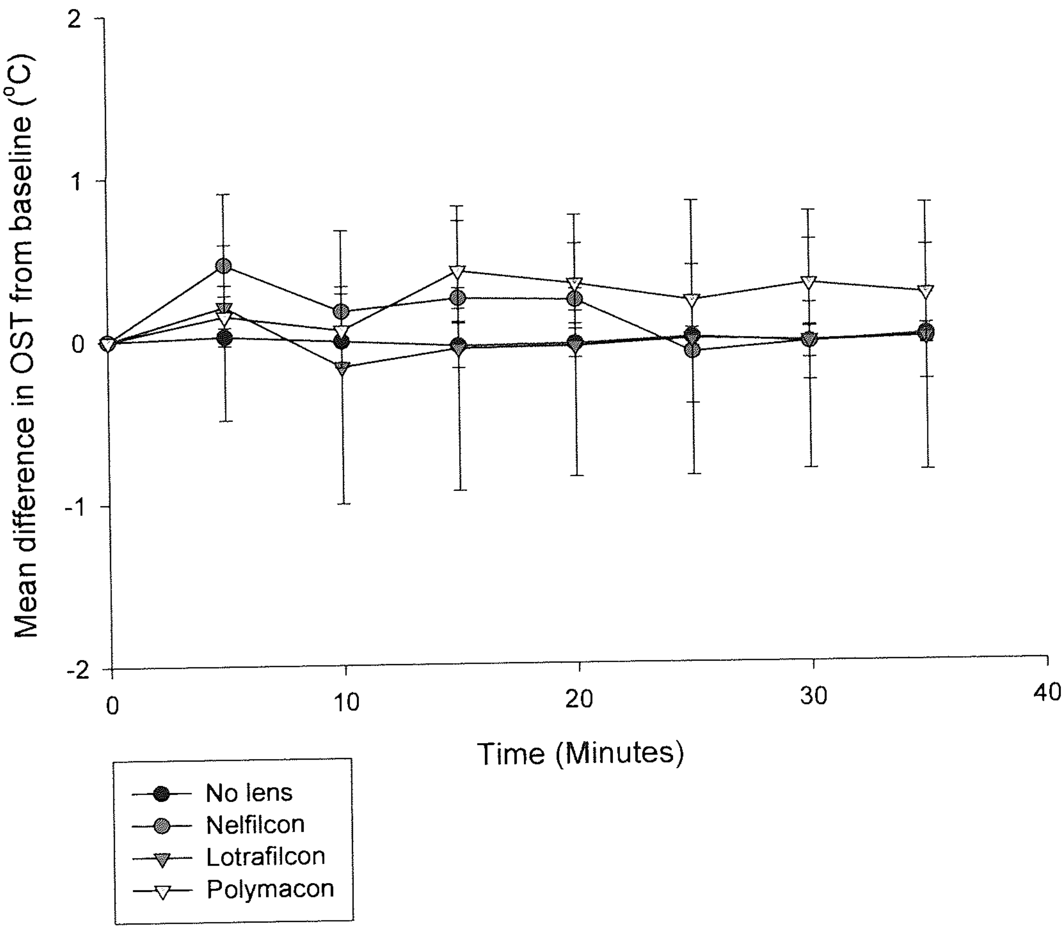

Figure 4.13
Mean OST change during a 35 minute period. Error bars = 1SD (n=12)

4.4.4 Change in OST with and without Contact Lenses – Exercise

Figure 4.14 illustrates the average OST from baseline of all 4 lens conditions (No lens, Nelfilcon, Lotrafilcon, and Polymacon) over a period of 35 minutes during exercise. There was no significant effect on OST with time (ANOVA; $F = 1.50$; $p = 0.18$). There was a significant effect on OST between lens conditions (ANOVA; $F = 6.53$; $p < 0.001$). There was a significant interaction suggesting time trends vary for the different lens conditions ($F = 3.79$; $p < 0.001$), and this difference varies cubically with time. As with-in subject ANOVAs do not indicate differences between individual conditions, univariate ANOVA was conducted at 10 minute (5 minutes post-warm-up), then at 5 minute intervals to identify differences between conditions (Table 4.4). This showed that there was a statistically significant difference between Nelfilcon and Lotrafilcon contact lenses from 5 minutes post-warm-up onwards, and between Lotrafilcon and Polymacon from 25 minutes (20 minutes post warm up).

	Post-hoc (Scheffe's)	
Time (minutes)	**F value**	**p value**
10	7.239	<0.001
15	3.607	<0.05
20	4.433	<0.008
25	4.934	<0.01
30	5.198	<0.01
35	4.600	<0.01

Table 4.4
Post-hoc analysis on OST and time

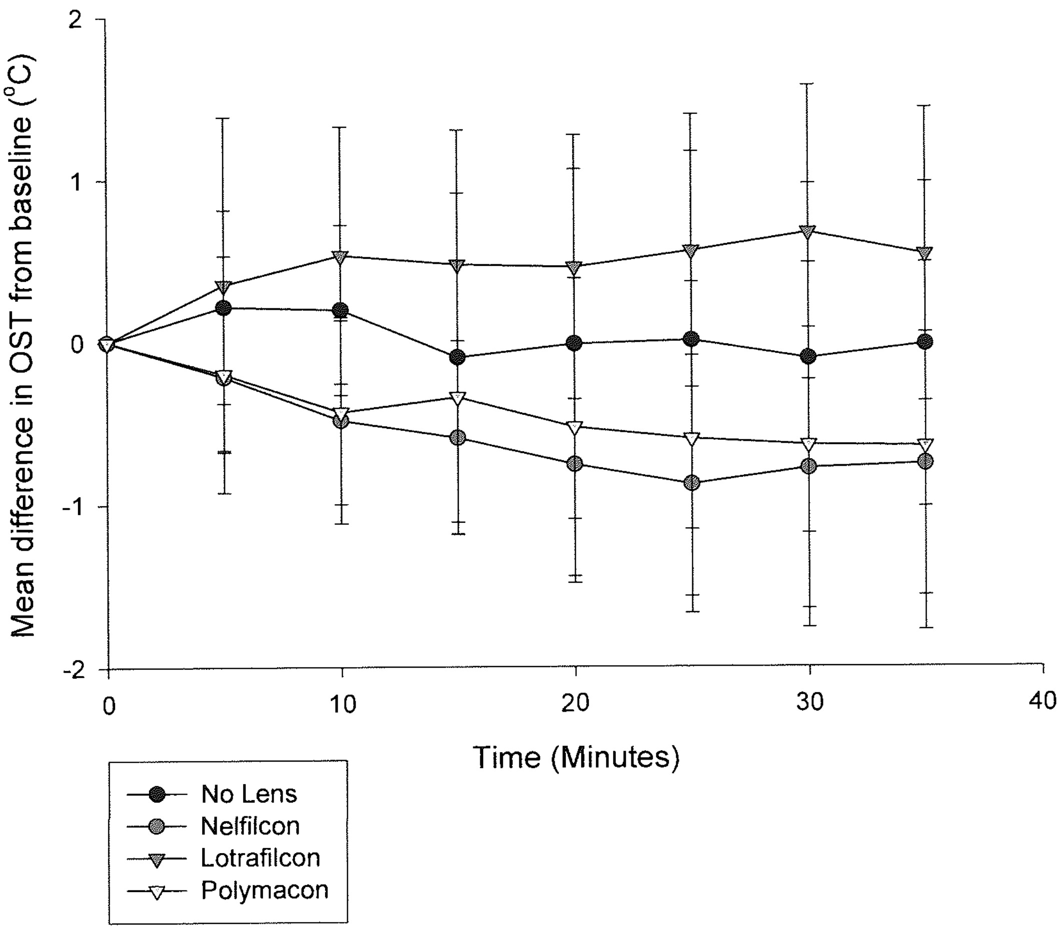

Figure 4.14
Mean OST change from baseline during 35 minutes exercise. Error bars = 1SD (n=12)

4.4.5 OST Comparisons between control and exercise period

Figure 4.15 illustrates the mean OST from baseline of the no lens condition during control (no exercise) and exercise over a period of 35 minutes. There was no significant effect on OST with time, condition and interaction between time and condition. (ANOVA; $F = 0.98$; $p = 0.45$, $F = 0.03$; $p = 0.88$, and $F = 0.60$; $p = 0.75$, respectively).

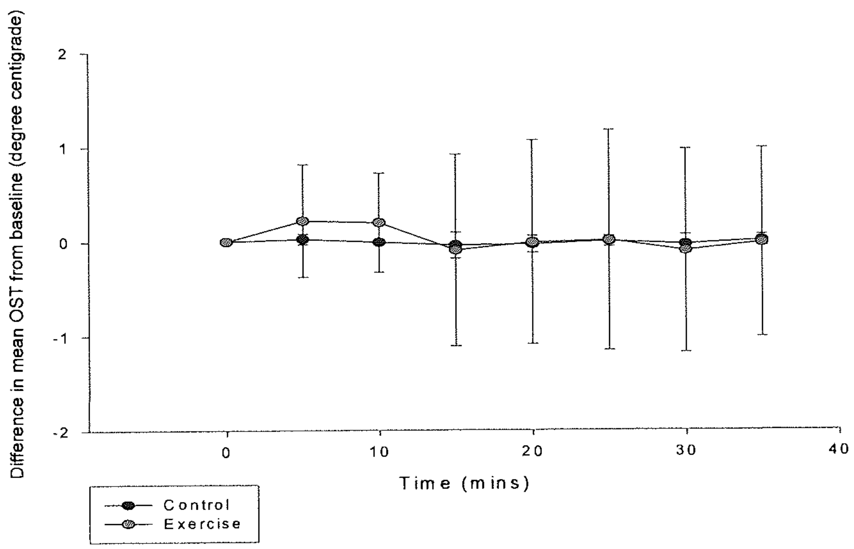

Figure 4.15
Comparison between mean OST during exercise and no exercise, error bars = 1SD (n=12)

Figure 4.16 illustrates the average OST from baseline of the Nelfilcon lens during control (no exercise) and exercise over a period of 35 minutes. There was a significant effect OST with time (ANOVA; $F = 12.69$; $p < 0.0001$). There was a significant effect on OST between conditions (ANOVA; $F = 22.81$; $p < 0.001$). There was a significant interaction suggesting time trends vary for the different lens conditions ($F = 9.83$; $p <0.0001$), and this difference varies linearly with time.

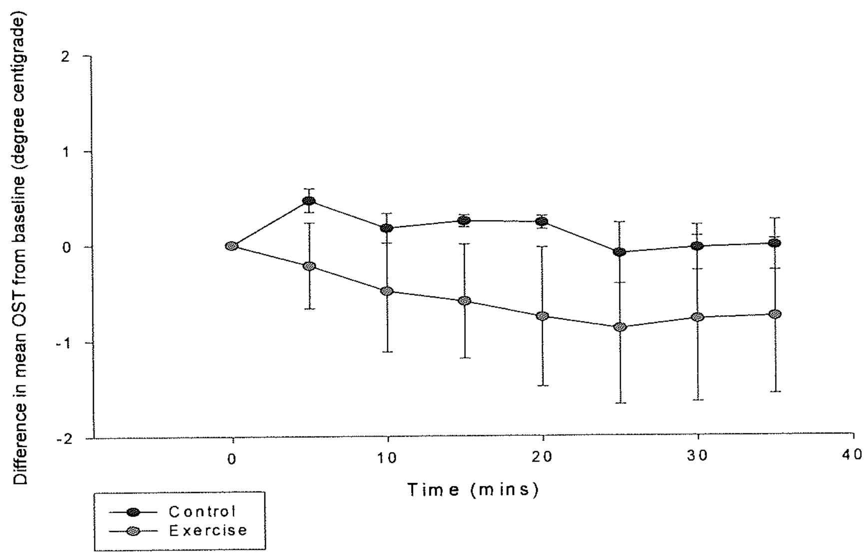

Figure 4.16
Comparison between mean OST during exercise and no exercise whilst wearing Nelfilcon material contact lenses. Error bars = 1SD (n=12)

Figure 4.17 illustrates the average OST from baseline of the Lotrafilcon contact lens during control (no exercise) and exercise over a period of 35 minutes. There was no significant effect on OST with time, condition and interaction between time and condition. (ANOVA; $F = 1.25$; $p = 0.28$, $F = 2.72$; $p = 0.13$, and $F = 1.92$; $p = 0.08$, respectively).

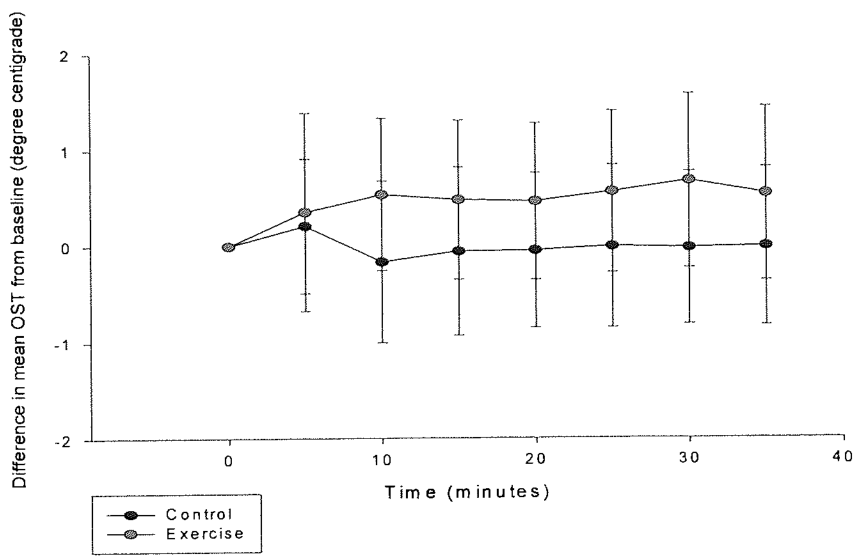

Figure 4.17
Comparison between mean OST during exercise and no exercise whilst wearing a Lotrafilcon material contact lenses. Error bars = 1SD (n=12)

Figure 4.18 illustrates the average OST from baseline of the Polymacon contact lens during control (no exercise) and exercise over a period of 35 minutes. There was no significant effect OST with time (ANOVA; F = 1.62; p = 0.14). There was a significant effect on OST between conditions (ANOVA; F = 8.80; p <0.05). There was a significant interaction suggesting time trends vary for the different lens conditions (F = 5.64; p <0.0001), and this difference varies linearly with time.

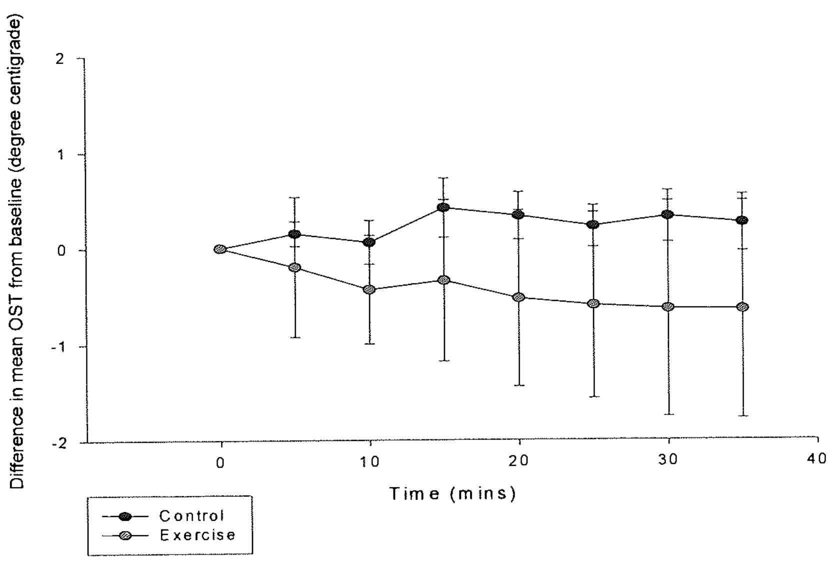

Figure 4.18
Comparison between mean OST during exercise and no exercise whilst wearing Polymacon material contact lenses. Error bars = 1SD (n12)

4.4.6 Change in Corneal Volume during Exercise

There was no statistically significant difference in the difference before and after 155 minutes in corneal volume between all conditions (No lens, Nelfilcon, Lotrafilcon, and Polymacon) in control condition. (Figure 4.19; ANOVA; F = 0.25; p = 0.065). When comparing the difference between before and after the control period of individual conditions, there was no significant difference seen for the Nelfilcon (T-Test; p = 0.09). However, there was a statistically significant difference in corneal volume with no lens, Lotrafilcon, and Polymacon (T-Test; p = <0.01). There was a statistically significant difference in the difference before and after 155 minutes (120 minutes adaptation followed by 35 minutes exercise) in corneal volume between all conditions (No lens, Nelfilcon, Lotrafilcon, and Polymacon) in exercise condition. (Figure 4.19; ANOVA; $F = 3.33$; $p < 0.05$). However, *post-hoc (Scheffe's)* could not identify this. When comparing the difference between before and after the exercise period of individual conditions, there was no significant difference seen for the Lotrafilcon (T-Test; $p = 0.49$) and the no lens condition (T-Test; $p = 0.18$). However, there was a statistically significant difference in corneal volume with Nelfilcon and Polymacon lens conditions (T-Test; $p = < 0.05$).

When comparing the normalised data (the difference post-exercise after control data taken into account) there was no significant difference between all the conditions (Figure 4.20; ANOVA; $F = 2.81$; $p = 0.86$).

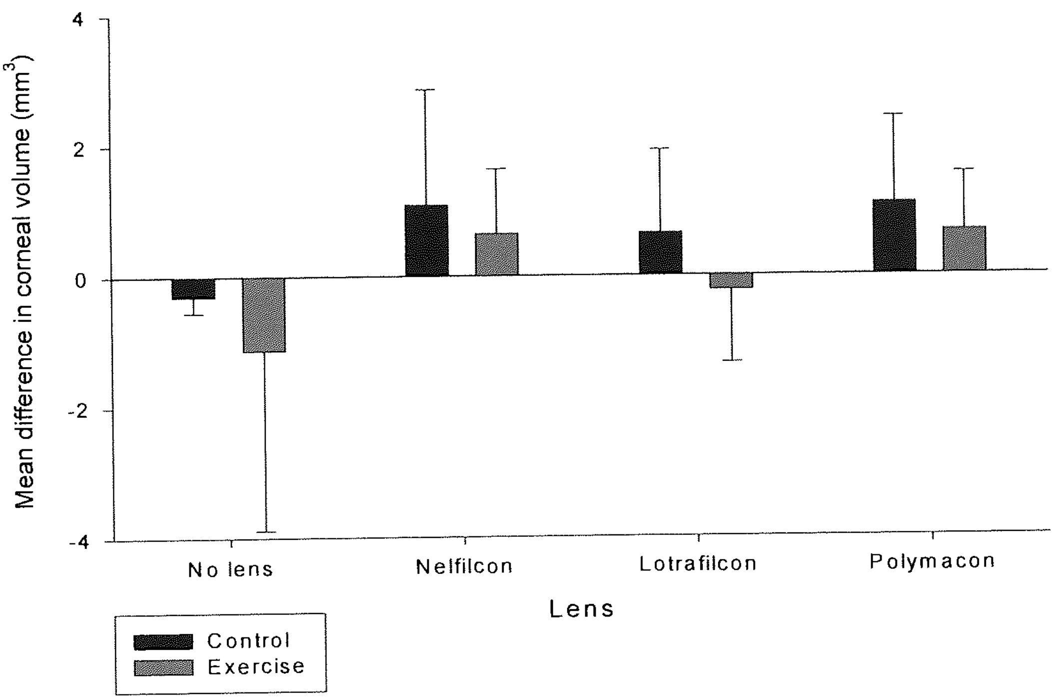

Figure 4.19
The mean change in corneal volume post-adaptation and test period, error bars = 1SD (n=12)

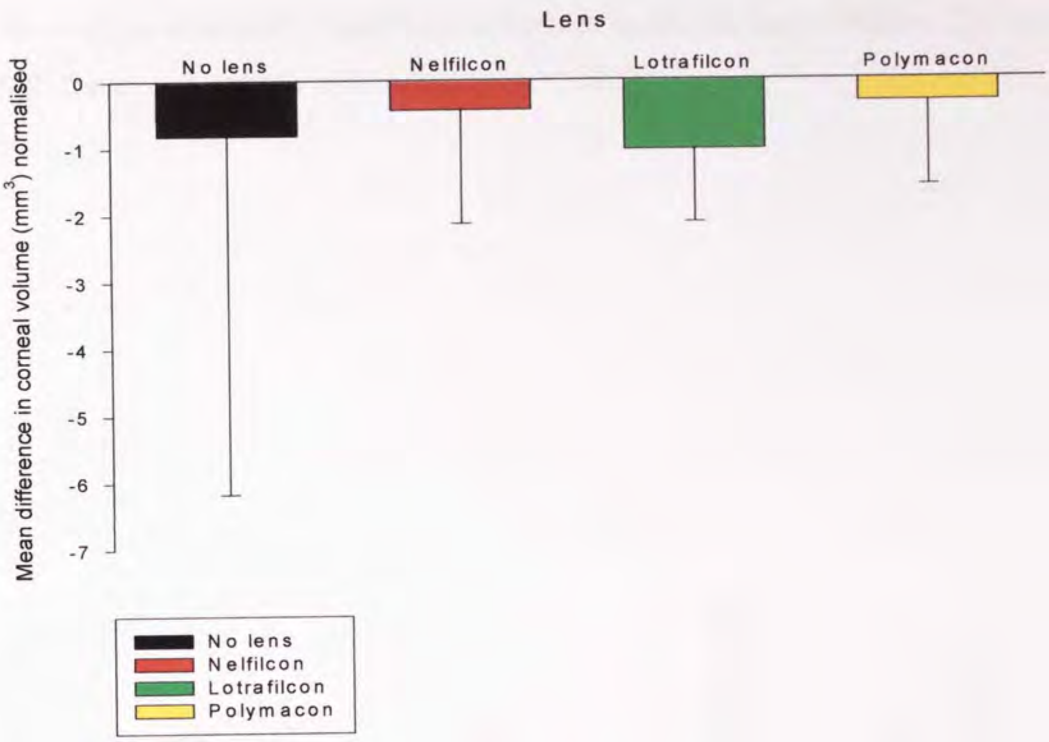

Figure 4.20
The mean difference in corneal volume post exercise (normalised data), error bars = 1SD (n=12)

4.4.7 Change in Bulbar Hyperaemia

4.4.7.1 Blood Vessel Coverage

There was no statistically significant difference in the difference before and after the control period of percentage area of blood vessel coverage between the conditions (No lens, Nelfilcon, Lotrafilcon, and Polymacon) (Figure 4.21; ANOVA; $F = 0.88$; $p = 0.45$). When comparing the difference between before and after the control period of individual conditions, there was no significant difference seen for the Nelfilcon (T-Test; $p = 0.55$), Lotrafilcon (T-Test; $p = 0.30$), and the Polymacon lens (T-Test; $p = 0.06$), however there was a statistically significant difference in the no lens condition (T-Test; $p = <0.001$). Again, there was no statistically significant difference in the difference before and after 35 minutes exercise of percentage area of blood vessel coverage between the conditions (Figure 4.21; ANOVA; $F = 1.95$; $p = 0.14$). When comparing the difference between before and after the exercise period of individual conditions, there was no significant difference seen for the Nelfilcon (T-Test; $p = 0.55$), and the Polymacon lens (T-Test; $p = 0.06$), however there was a statistically significant difference in the no lens condition (T-Test; $p < 0.05$), and the Lotrafilcon lens (T-Test; $p < 0.05$).

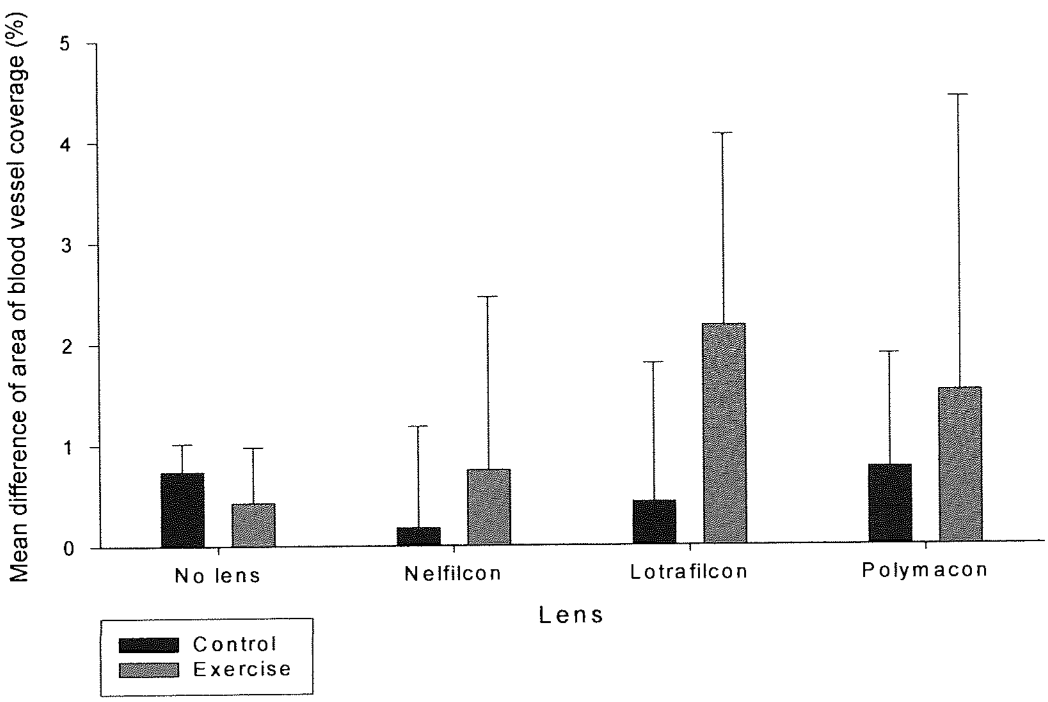

Figure 4.21
The mean difference in percentage area of blood vessel coverage before and after test condition, error bars = 1 S.D. n=12

4.4.7.2 Bulbar Redness

There was a statistically significant difference in the difference before and after the control period of bulbar redness between the conditions (No lens, Nelfilcon, Lotrafilcon, and Polymacon) (Figure 4.22; ANOVA; $F = 18.04$; $p < 0.001$). As with-in subject ANOVA does not indicate differences between individual conditions, univariate ANOVA were conducted (Scheffe's). This showed that there was a statistically significant difference between Polymacon with Nelfilcon and Lotrafilcon ($p = <0.01$) and between Lotrafilcon and no lens ($p = <0.01$). When comparing the difference between before and after the control period of individual conditions, there was no significant difference seen for the no lens condition (T-Test; $p = 0.62$), however there was a statistically significant difference in the Nelfilcon, Lotrafilcon, and Polymacon conditions (T-Test; $p = < 0.05$). There was no statistically significant difference before and after exercise of bulbar redness for all conditions (Figure 4.22; ANOVA; F = 2.33; p = 0.09). When comparing the difference between before and after the 35 minutes exercise period of individual conditions, there was no significant difference seen for all conditions (no lens (T-Test; p = 0.33), Nelfilcon (T-Test; p = 0.43), Lotrafilcon (T-Test; p = 0.12), and the Polymacon lens (T-Test; p = 0.14).

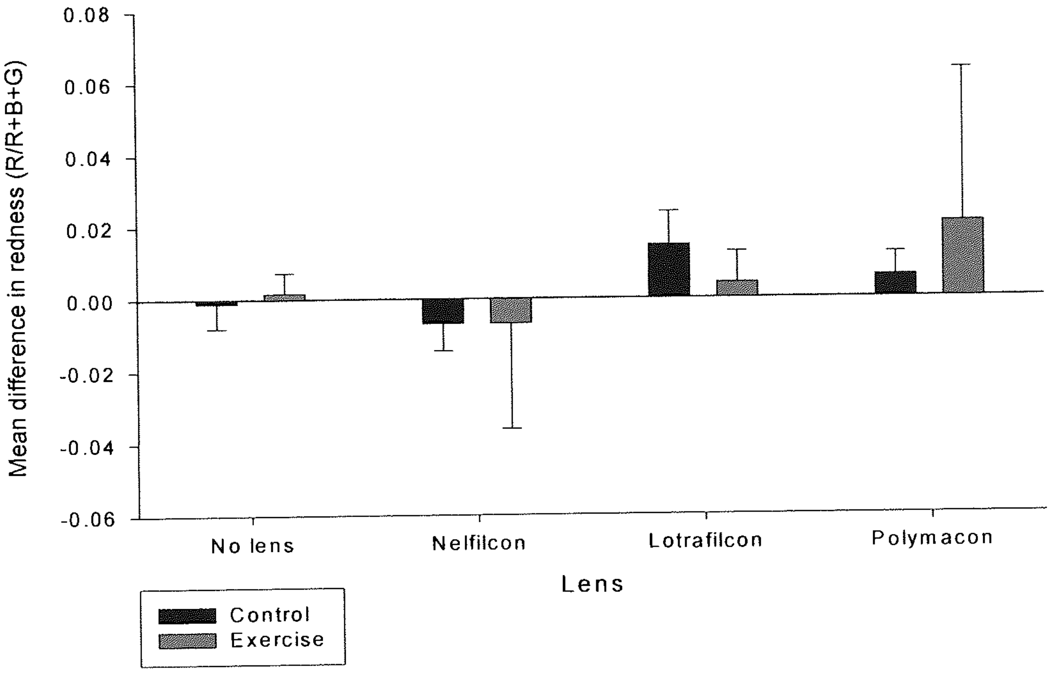

Figure 4.22
The mean difference in bulbar redness before and after test condition, error bars = S.D. n=12

4.5 DISCUSSION

Previous research has demonstrated that visual acuity improves post-exercise (Woods and Thompson, 1995), whilst Ishigaki demonstrated a decline (Ishigaki *et al.*, 1991). The results presented in this study demonstrated no significant change. There is no reason to think visual acuity would improve with exercise, other than perhaps the on eye stability performance that contact lenses exhibit over spectacles (see section 1.2.4 in Chapter 1). There was no significant difference seen in contrast sensitivity post-exercise for all conditions. These findings do not support previous studies by Koskela (1988) and Woods and Thompson (1995), in which they demonstrated an increase in contrast sensitivity post-exercise (although different methods of exercise and measuring contrast sensitivity were used). Again, there is no reason to think contrast sensitivity would improve with exercise, other than perhaps the on eye stability performance that contact lenses exhibit over spectacles or corneal swelling effects, although both of these would be expected to have negative effects.

It is known that exercise or strenuous activity increases body core temperature, thus resulting in an increase in radiant heat expelled from the body via the skin. To the author's knowledge there is no published data on the effect of ocular temperature and exercise. There was found to be an increase in OST on the cornea with no contact lens for the first 10 minutes (5 minutes post warm up) during exercise, but this was subsequently followed by a decrease to baseline. This suggests that the cornea exhibits a homeostatic function to exercise preventing heat gain to maintain cellular function. This study demonstrated an increase in OST for subjects wearing Lotrafilcon material contact lenses compared to a decrease in OST during Nelfilcon and Polymacon material lens wear compared to the no lens condition (although not statistically significant) during exercise over a 35 minutes exercise period (-0.7°C, -0.6°C, +0.5°C, and -0.01 °C, respectively).

It is evident that the contact lens material influence OST during exercise as there is a difference in OST during exercise compared to at rest with the Polymacon and Nelfilcon contact lens materials. This may be due to factors such as lens thickness (Martin and Fatt, 1986), water content and material (Purslow, 2005). The contact lenses did not differ greatly in thickness, but the higher water content of the Nelfilcon compared to the Polymacon lens did result in a lower OST, as has previously been found (Martin and Fatt, 1986). The results also support the findings of Purslow *et al.* (2005) in which they examined the change in ocular surface temperature with different contact lenses (no exercise), finding that SiH contact lenses produced a higher OST compared to the hydrogel contact lens examined. It is important to mention that their are limitations when using ocular thermography for measuring OST as the temperature which is captured by the camera is dependant on the tear film stability, thus recording the temperature of the tear film and not that of the true cornea. However, as previously mentioned, Lindahl (cited in Mapstone, 1968a) reported that the pre corneal tear film will emit and absorb the same temperature as the cornea. This is also true when measuring the OST with a contact lens *in-situ* as the camera is picking up the temperature of the anterior tear film on the contact lens and the contact lens itself, and not that of the cornea.

As previously mentioned (see chapter 1), Quevedo *et al.* (2000) demonstrated a statistically significant difference before and after training of the quality and quantity of tear film. This finding may elucidate the decrease in OST with Polymacon and further more with Nelfilcon compared to Lotrafilcon material due to the higher water contents (38%, 69%, and 24% respectively) and hence more dehydration on the eye during exercise. Quevedo and colleagues suggested avoiding high water contact lens as a result of their findings, although Martin and Fatt (1986) suggested that the small rise in OST beneath the contact lens was insignificant to cause corneal hydration.

To the author's knowledge, no research has been carried out on the effect of corneal oedema over a such short period of contact lenses wear (155 minutes).The study has demonstrated that the corneal volume in the normal situation (control) over this time period increased, with the Lotrafilcon lens increasing the least, however this was not significant compared to the no lens condition. This finding was not surprising as one may expect a small change due to the disruption of oxygen with contact lens wear (Brennan, 2005) thus leading to possible oedema. It was apparent that after exercise (including adaptation period) when wearing the Nelfilcon and the Polymacon lens the corneal volume, although increased, did so to a lesser extent compared to before exercise. It was unexpected to see a decrease in corneal volume compared to the control for all conditions after exercise as one would expect the cornea to increase during exercise due to the effect of anaerobic exercise leading to corneal oedema as previously suggested by Bromholt and Schnell (2000). However, this was not the case, so some other factor must come into play.

As the body generally dehydrates during exercise (Murray, 2007), could this also occur in the cornea and the tear film post-exercise. The cornea (no lens) volume further decreased with exercise compared to rest (although not significantly), and this may indicate that corneal/ tear dehydration occurs, masking any oedema effect to some degree. The same was true for all contact lens conditions; however it is difficult to differentiate between true corneal oedema and dehydration. To investigate this, it would be ideal to use contact lenses with the same Dk/t value with various water content, but as water is directly related to transmissibility of oxygen within a contact lens, these are not available. From the results one could state that it may be advisable to recommend SiH lenses as these seem to produce less corneal swelling compared to the other two HEMA lenses in this study. As SiH contact lenses provide good oxygen transmissibility compared to HEMA contact lenses, if exercise caused oedema due to anaerobic respiration, these lenses would provide excellent oxygen transmissibility. However, if corneal volume change was due principally to dehydration, a low water contact lens would prevent dehydration compared to a higher water contact lens. As it is difficult to differentiate between these two factors, SiH, with their higher oxygen transmissibility and lower water contents would benefit both situations.

Interestingly, Fatt (1971) reported an increase in OST with a reduction in stromal thickness, concluding that an increase of 1.1°C was equivalent to 0.1% reduction in stromal thickness. Although the temperature change seen in their study was too small to be significant, however it may explain the decrease in corneal volume with the SiH lens compared to the other two lens conditions during exercise.

As bulbar hyperaemia has been suggested as an important indicator of ocular health (Papas, 2000) and this has been associated with contact lens wear (Efron *et* *al.*, 1988), it was not unexpected to discover there was a slight increase in blood vessel coverage in the temporal segment of the bulbar conjunctiva in subjects wearing all 3 contact lenses in the controlled non-exercise situations, although this was not statistically significant. The Silicone hydrogel lens material did not out-perform traditional HEMA in this short examination. There was a significant increase in blood vessel coverage post-exercise (compared at rest) in the no lens and Lotrafilcon (SiH) lens conditions, however there was not a significant change seen when wearing the Nelfilcon and the Polymacon lenses (HEMA). Again this was not surprising as during exercise the core body temperature increases, thus expelling heat via blood vessels to maintain body core temperature and as the OST with the HEMA lenses decreased compared to the Lotrafilcon, this may have influenced the blood vessels in the bulbar region. The lack of increase in overall redness post-exercise for all conditions may have been due to the reduction of oxygen in the blood with body exercise counteractive the dilation of the blood vessels.

4.6 CONCLUSION

Visual acuity and contrast sensitivity were not found to be affected by exercise. The use of hydrogel contact lens material affects OST during exercise (including adaptation period). It seems that the change in OST with contact lenses is due to multiple of factors as opposed to any individual cause. Due to the potential increase in bacterial binding, *in vivo*, at lower temperatures (Wilcox *et al.*, 2001), it may be wise to recommend SiH contact lenses for sport as these show a small increase in OST compared to HEMA contact lenses, which show a small decrease.

During exercise the body requires more oxygen than at rest (Åstrand and Rodahl, 1998), and as the cornea is avascular it would be interesting to investigate corneal oxygen requirement during exercise. This will be discussed in the subsequent chapters.

CHAPTER FIVE

A NON CONTACT METHOD FOR MEASURING CORNEAL OXYGEN UPTAKE RATE

5.1 INTRODUCTION

The cornea requires oxygen to maintain function and integrity (Galvin *et al.*, 2000). The corneal epithelium utilises 40% of the total corneal oxygen consumption similarly the stroma uses a further 40%, in comparison to the corneal endothelium which only uses 20% of the total corneal oxygen (Buckley, 2006). The corneal epithelium receives most of its oxygen supply in the open-eye condition from the atmosphere (Galvin *et al.*, 2000) with 21% (equivalent to 155-159 mmHg partial pressure) atmospheric oxygen available at the epithelial outermost layer (Benjamin and Hill, 1986). Contact lenses can interrupt the path of this oxygen required by the cornea during wear (Brennan *et al.*, 1987) which can lead to loss of corneal function (Brennan, 2005). Therefore, contact lens manufacturers are actively searching for the ideal contact lens material to maintain required levels of oxygen to prevent any adverse effect. As oxygen has previously been a good indicator of contact lens performance (see chapter 1), the measurement of the uptake of oxygen by the cornea, with and without contact lenses *in situ* would allow a measure of physiological stress experienced by the cornea.

The literature has demonstrated that there are several methods of measuring corneal oxygen consumption either directly of indirectly from the cornea, with and without contact lenses. The most commonly used technique is the polarographic technique (see section 1.3.4.1). Each method has it advantages and disadvantages, and these are highlighted in Table 5.1.

Technique	Advantages	Disadvantages
Polarographic	1: *In vivo* method and provides measurements of corneal oxygen needs 2: Contact lenses are worn in the normal environment 3: RGP and soft contact lenses can be assessed	1: Invasive / contact method 1: Rate of oxygen used by eye may not only be due to contact lens e.g. temperature, osmolarity, and applanation forces. 2: Time lag before sensor applied 3: Small area of cornea is measured 4: Is there a direct relationship between all methods used to measure oxygen transmissibility of contact lenses
Goggle	1: Non invasive/ contact method	1: Can takes a long time 2–8 hrs 2: Is it a 'true' environment
Pachymetry	1: Non invasive / contact (unless using ultrasound pachymetry) 2: Contact lenses in correct lens environment.	1: Relationship to oxygen uptake is a changes in corneal thickness, but is there any oxygen deprivation before thickness changes are seen.
Phosphorescence	1: Non invasive / contact method (although dye is inserted into contact lens)	1: Only used with contact lenses 2: Dye is installed into eye 3: Estimation of corneal oxygen consumption

Table 5.1
Summary of advantages and disadvantages of existing techniques used to measure corneal oxygen uptake

Due to the disadvantages of the previous techniques, a non-contact method of measuring corneal oxygen demand *in-vivo* with and without contact lenses would be advantageous.

5.2 AIMS

The aim of this study was to develop a non-contact way of measuring oxygen uptake of the whole cornea, taking into account a contact lens (if worn) and blinking dynamics. A non-contact method of measuring the corneal oxygen uptake was chosen to avoid interference with the eye directly, preventing any disruption to the tear film, either by the use of local anaesthetics or by direct applanation forces, confounding measurements.

5.3 APPARATUS

After a search of current oxygen sensing technology, oxygen sensitive foil was chosen as suitable to meet the aims of non-invasive *in-vivo* measurement of ocular oxygen consumption. The Fibox 3 (Prescision Sensing GnbH, Regensberg, Germany) is a precision, temperature-compensated oxygen meter, designed for use with a fibre-optic oxygen minisensor (Figure 5.1).

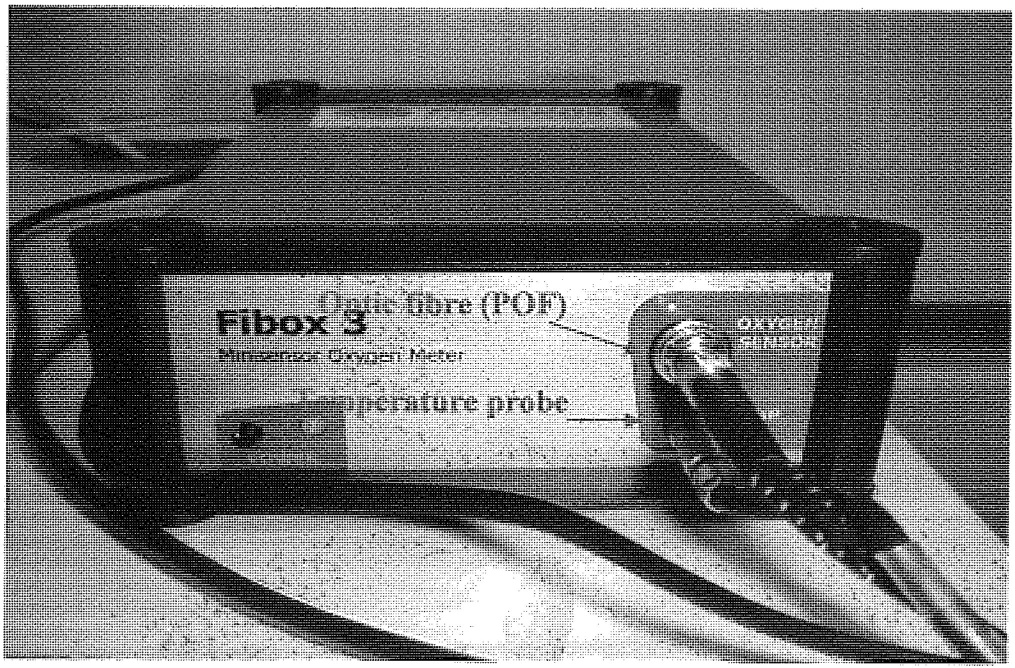

Figure 5.1
The Fibox 3 oxygen monitor with the temperature sensor and the optic fibre (POF) oxygen sensor (Precision Sensing GnbH, Regensberg, Germany)

The oxygen sensor consists of a Polymer Optical Fibre (POF) which has a polished distal tip coated with a planar oxygen-sensitive foil (Figure 5.2). The operating temperature of the Fibox 3 is between 0 – 50°C with up to 95% humidity.

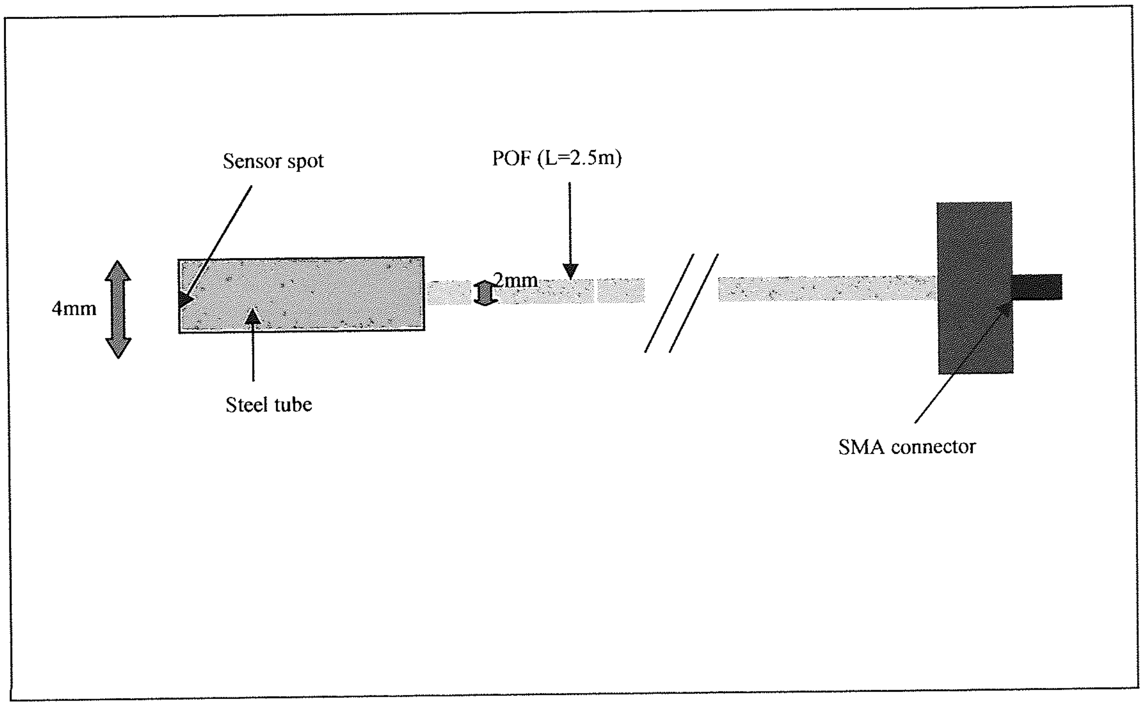

Figure 5.2
A schematic drawing of the Polymer Optical Fibre (POF) (redrawn from Precision Sensing GnbH, Regensberg, Germany, 2006)

The planar oxygen sensitive foil sensor is mounted onto a polyester support which measures 3 mm in diameter (Figure 5.3). The sensor must be shielded from ambient light as this can affect the sensor. To measure oxygen consumption, a volume of air around the eye has to be captured and the relative proportion of oxygen measured immediately after isolation and at time periods after isolation. The isolation of the eye from the normal surrounding atmosphere can only be maintained for a short period of time as the declining available oxygen would start to affect oxygen consumption over long periods of isolation. As the intention was aimed to measure the oxygen uptake with normal blinking and contact lenses *in-situ*, a sensor was mounted using clear-drying silicone glue to the inside of a water and air-tight swimming goggle (Figure 5.7). Measurements were found to be unaffected by this mounting and the goggle transmission. The oxygen sensitive foil spot reflectance was measured by a sensor mounted to the outside of the goggle, creating a non-invasive method.

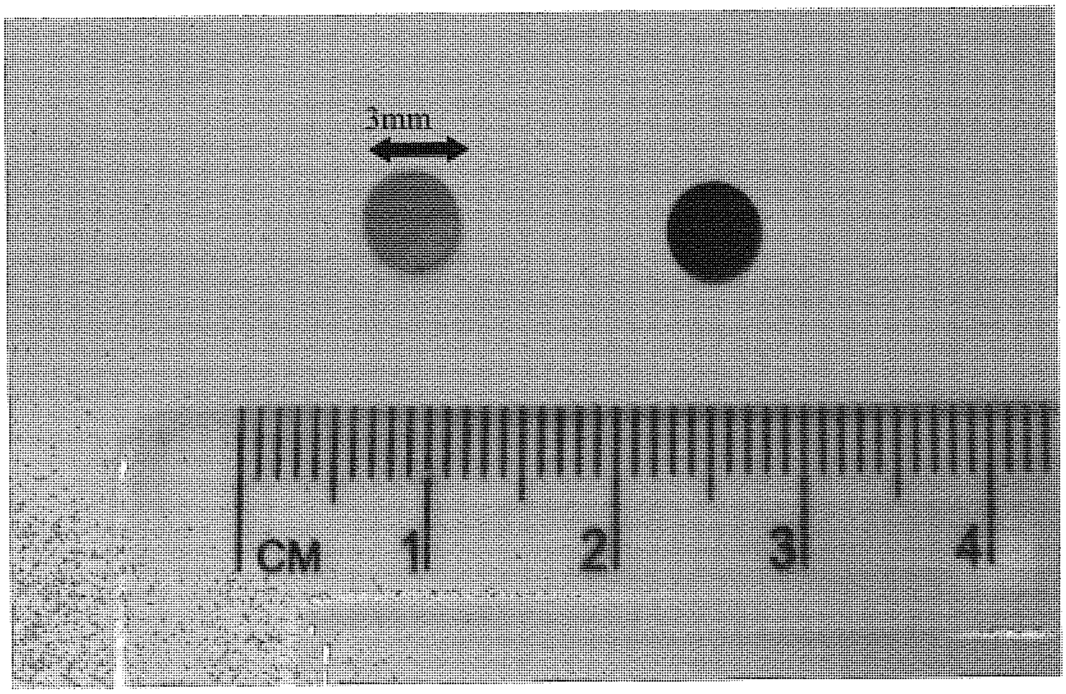

Figure 5.3
The oxygen sensitive foil sensor (red sensor) and the optical isolator (the black sensor)

The principle of measurement is based on dynamic luminescence quenching by molecular oxygen (Figure 5.4). The Fibox 3 monitor emits an excitation flash (2ms) wavelength 505nm (Figure 5.5) every 5 seconds onto the sensitive oxygen foil (luminophore). This results in excitation of the luminophore from its ground state to its active state thus the luminophore then emits fluorescence which is read by the optic fibre (POF). When there is a collision between a luminophore (sensitive oxygen foil) in its excited state and an oxygen molecule (quencher), energy is transferred to the oxygen molecule and it changes from its ground state. This radiationless deactivation result is known as dynamic quenching of luminescence. This in turn leads to the indicator molecule not emitting luminescence, and so the measurable luminescence signal decreases. No oxygen is consumed during the measurement and the set up is able to measure oxygen content in dry gases. The Stern-Volmer equation (Equation 5.1) describes the relationship between the oxygen concentration in the sample and the luminescence intensity.

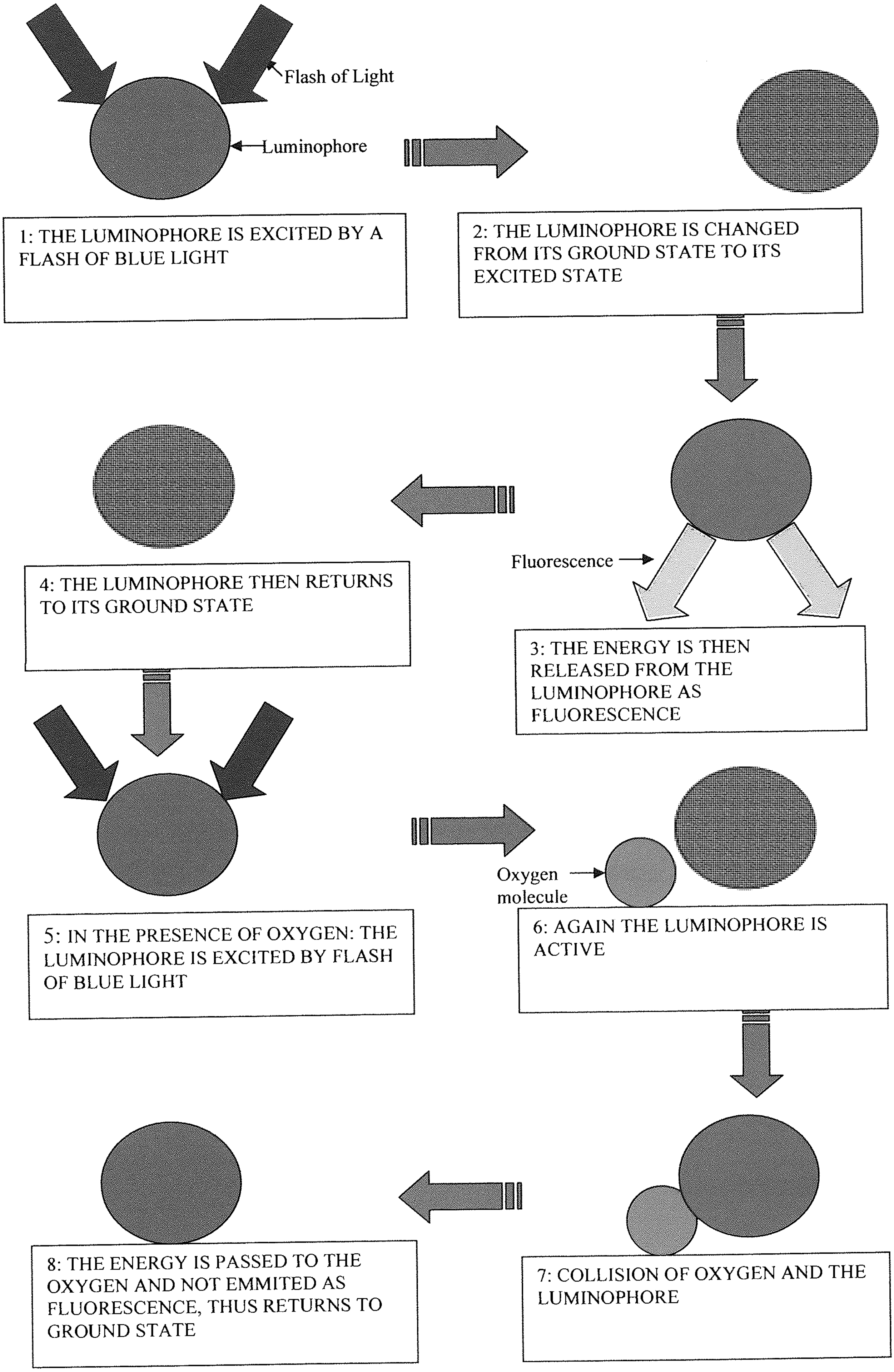

Figure 5.4
A schematic illustration of the dynamic quenching of luminescence process

Aston University

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Figure 5.5
Spectral radiance of blue light emitted from the Fibox 3 measured with the PhotoResearch PR-6050 SpectraScan (Photo Research, Chatsworth Place, Ca91311-4153, USA)

The data output was analysed and presented on the computer monitor by installing the oxyview PST3-US.32 software (Presens, Regensberg, Germany) (Figure 5.6) and the oxygen was recorded as 'oxygen percentage' in relation to percentage air saturation (Equation 5.2).

Figure 5.6
An example of the data output using the oxyview PST3-US.32 software. The top line is temperature and the bottom is oxygen percentage.

Stern-Volmer-equation

$$\frac{Io}{I} = \frac{to}{t} = 1 + Ksv.\ [O_2]$$

$$I = f([O_2])$$

$$t = f([O_2])$$

I:	Luminescence intensity in presence of oxygen
Io:	Luminescence intensity in absence of oxygen
t:	Luminescence decay time in presence of oxygen
to:	Luminescence decay time in absence of oxygen
Ksv:	Stern-Volmer constant (quantifies the quenching efficiency and therefore the sensitivity of the sensor)
$[O_2]$:	Oxygen content:

Equation 5.1
The Stern-Volmer equation, demonstrating the relationship between the oxygen concentration in the sample and the luminescence intensity used by the Fibox 3 set up

$$\%\ O_2 = \%\ \text{air saturation} \times 20.95/100$$

Equation 5.2
Conversion of oxygen formula explaining how the oxygen percentage is measured in relation to air saturation

5.3.1 Instrument Calibration

The Fibox 3 and the oxygen sensitive spot was calibrated by using two calibration solutions. The first was oxygen-free water and the second was air-saturated water. These were placed into a glass container ensuring the oxygen sensitive foil was fully covered and readings were then taken. The accuracy at 20°C is ± 0.15% at 1% air-saturation.

5.3.2 Laboratory Set-Up

The research was carried out in a room which was monitored for temperature and humidity. There was no external light and the room was illuminated by an average of 410 ± 12 lux (Light meter, Maplin N76CC, Rotherham, UK).

5.4 DESIGN OF TECHNIQUE

5.4.1 Design One

The first goggle used was a swimming goggle with the oxygen sensor on the inside surface of the goggle (Figures 5.7 and 5.8). The goggle had a silicone seal (Speedo, Sonar Model). The goggle was then placed over the subjects left eye and left in place for a length of time whilst monitoring oxygen percentage within the goggle (every 5 seconds via a flash of blue light) via the outside surface by the POF sensor and Fibox 3 oxygen monitor.

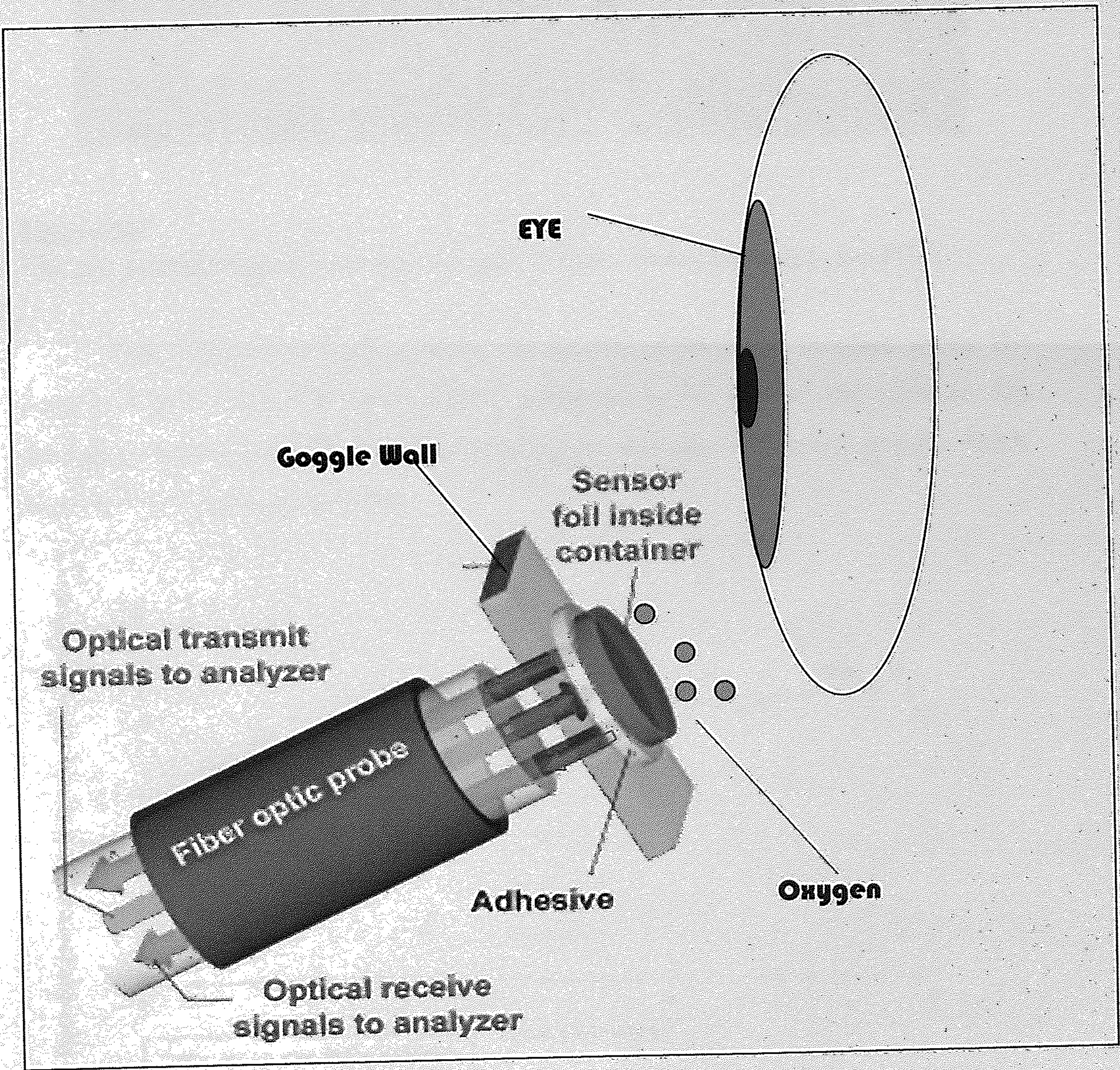

Figure 5.7
Illustration of the set up of the sensor within the swimming goggle (adapted from Precision Sensing GnbH, Regensberg, Germany, 2006)

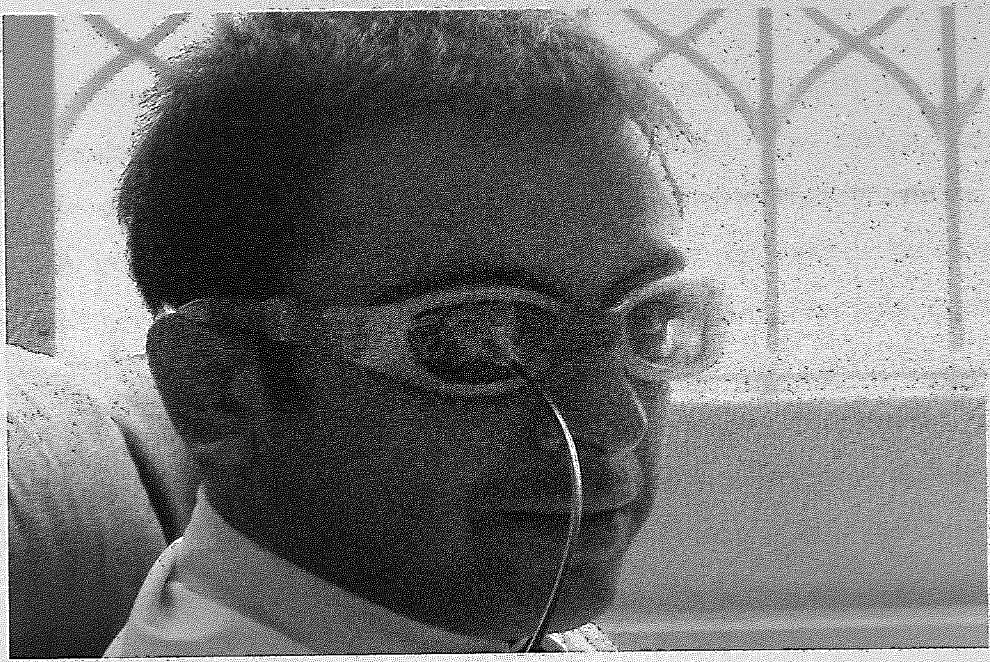

Figure 5.8
The goggle and oxygen sensor *in situ* on a subject. The black lead is the POF.

This design had limitations as the oxygen appeared to increase inside the goggle (Figure 5.9). The poor results appeared to be due to the silicone rim producing a poor air tight seal and temperature changes within the goggle which were not being compensated for.

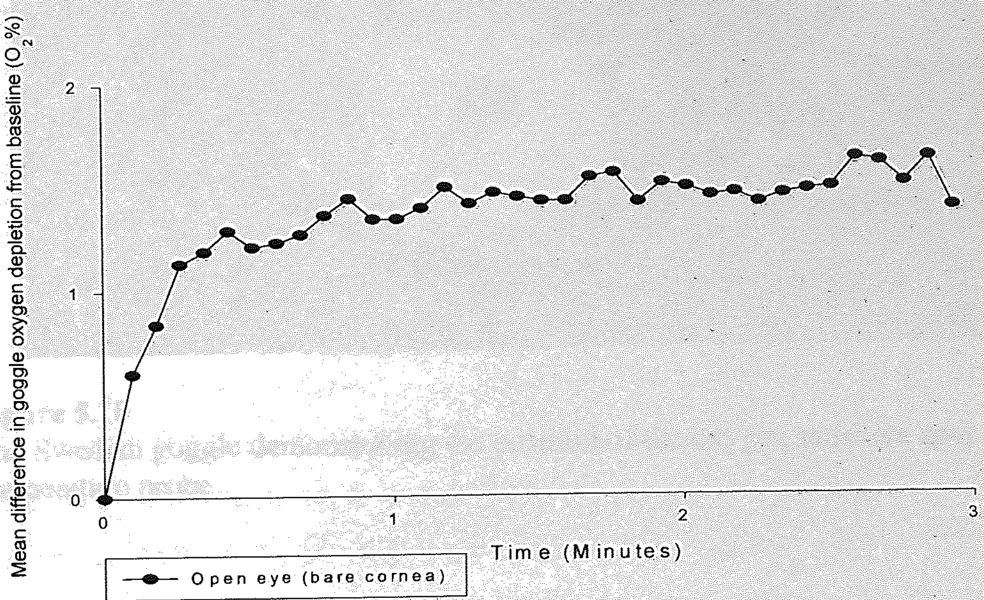

Figure 5.9
The output from the initial design one of the technique, demonstrating oxygen percentage increasing under the goggle

5.4.2 Design Two

The second design used a different style of swimming goggle; this was the *Swedish* model, Speedo (Nottingham, UK) (Figure 5.10). This revised design allowed the subject skin to form an air-tight seal regardless of facial anatomy. As discovered from design one, variations in temperature influenced the oxygen percentage inside the goggle. As temperature increases, so does the partial pressure of oxygen so this needed to be compensated for. A temperature recording probe was inserted into the goggle to measure temperature within the goggle (Figure 5.10). The oxygen percentage within the goggle was then adjusted by means of a computer program provided by Presens, Regensburg, Germany, using the Campbell equation (Equation 5.3). The subject's head was placed onto a head-rest for stability (See Section 5.6.2).

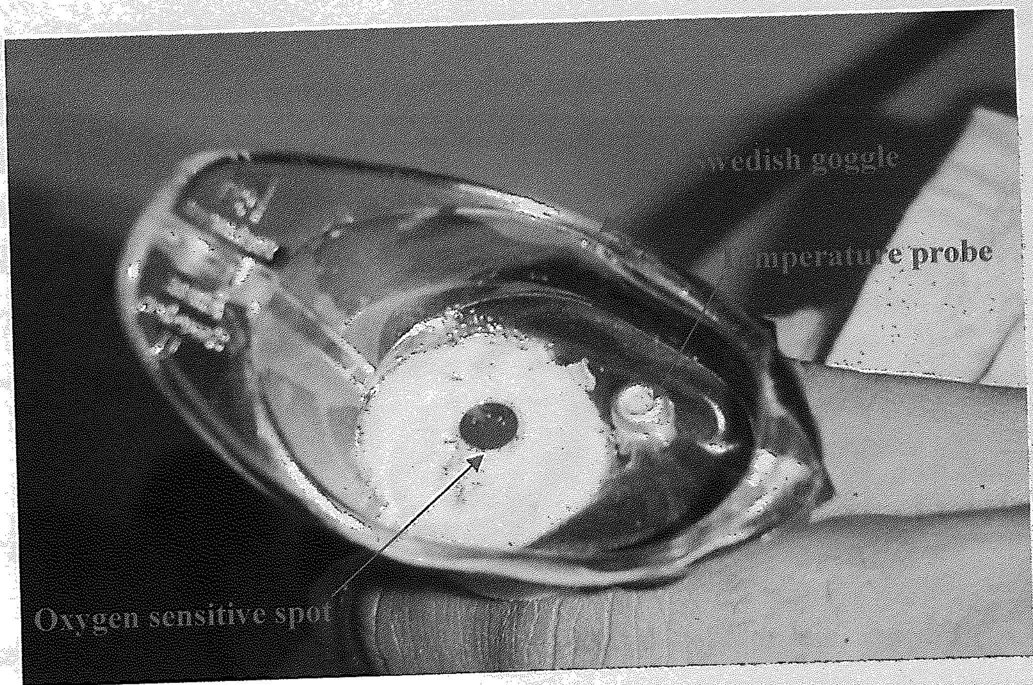

Figure 5.10
The Swedish goggle demonstrating the position of the oxygen sensitive spot and the temperature probe

Campbell equation

$$Pw(T) = \exp[A - (B/T) - C \times \ln T]$$

Pw (T):	Vapour pressure of water at temperature T in Kelvin
A,B,C:	Constants (52.57, 6690.9, and 4.681 respectively)

Equation 5.3
The equation used to compensate for temperature change within the goggle

5.5 ASSESSMENT OF TECHNIQUE

5.5.1 Corneal Volume Measurement

Corneal thickness plays an important role in corneal oxygen uptake (see chapter 1), suggesting that the thicker the cornea, the higher the oxygen demand (Larke *et al.*, 1981). Therefore, the volume of the cornea was measured immediately prior to the oxygen recordings (within 2 minutes of recording). The OCULUS Pentacam (OCULUS, Germany) was used to record these data and measurements were taken as explained in section 4.3.1.3. in chapter 4. This was repeated three times to improve accuracy and an average was taken.

5.5.2 Corneal Area Measurement

The literature has suggested that the area (central, inferior and superior) of the cornea influences corneal oxygen uptake (Benjamin and Hill, 1988a; Brunstetter *et al.*, 1999; Szczotka *et al.*, 1993). The area of an individual's exposed cornea was assessed by capturing a frontal image of the eye with a Takagi (Nagano, Japan) slit-lamp with attached Jai CV-S3200 (Yokohama, Japan) digital camera. The subject was instructed to look at a fixation point in front (at eye level) of them with their head on the slit-lamp head rest to mimic the conditions of wearing the goggle. The corneal area was then measured using a purpose-written software developed by

Professor James Wolffsohn (Aston University, Birmingham, UK) using Labview® software (National Instruments, Town, USA) (Figure 5.11). This was repeated three times to improve accuracy and an average was taken.

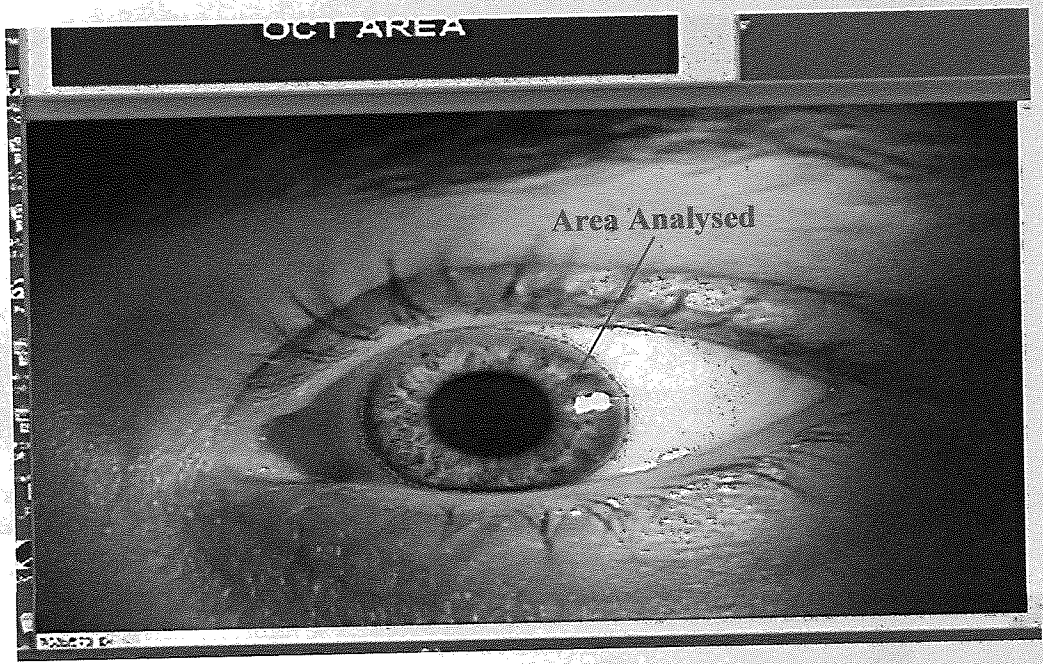

Figure 5.11
Screen view of image area analysing program (the area analysed is within the red outline)

5.5.3 Goggle Volume Measurements

The volume inside the goggle when sealed against the subject's eye was measured using a saline displacement technique (Figure 5.12 and 5.13). This was repeated three times to improve accuracy and an average was taken.

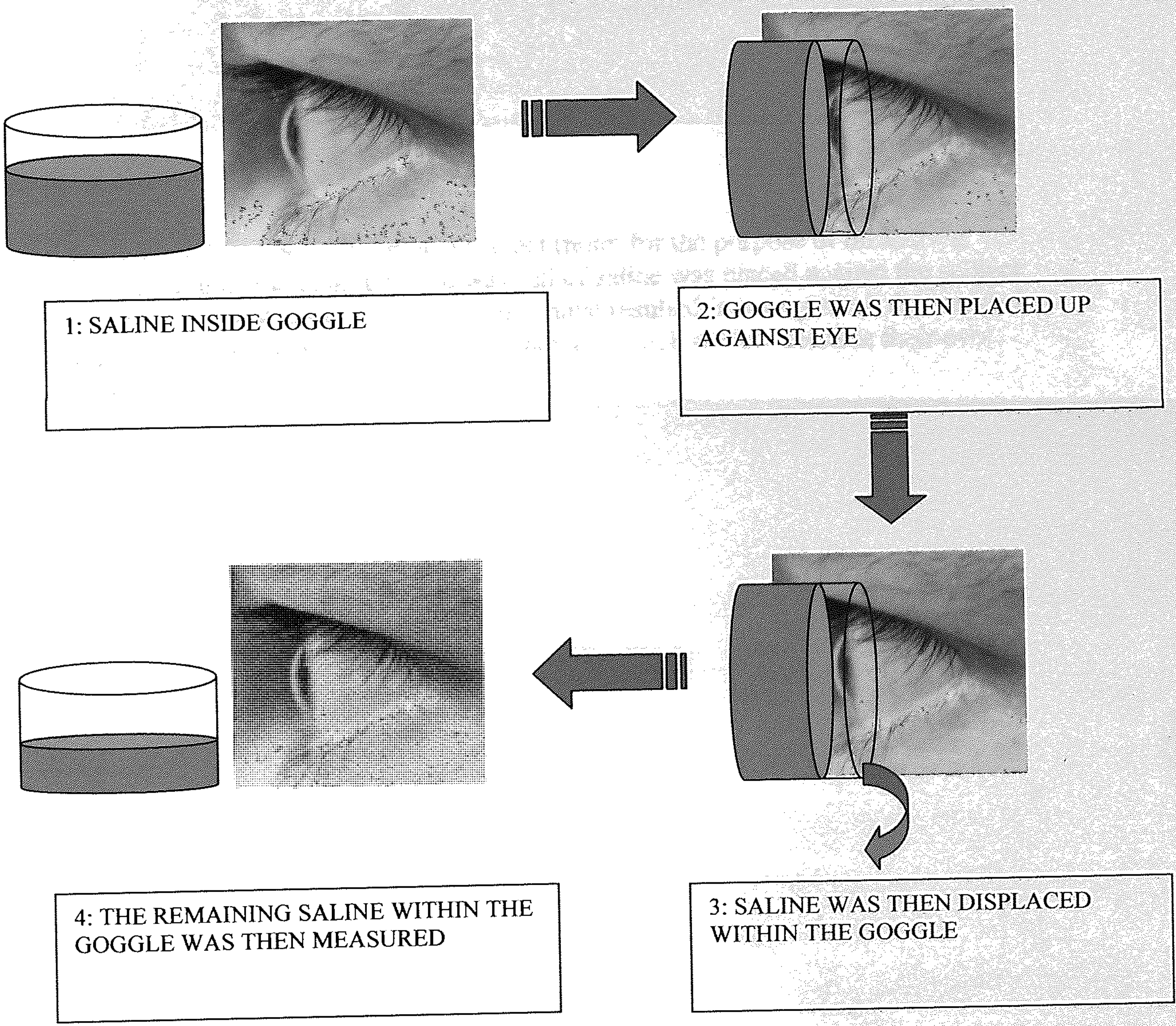

Figure 5.12
A schematic diagram of measuring the goggle volume

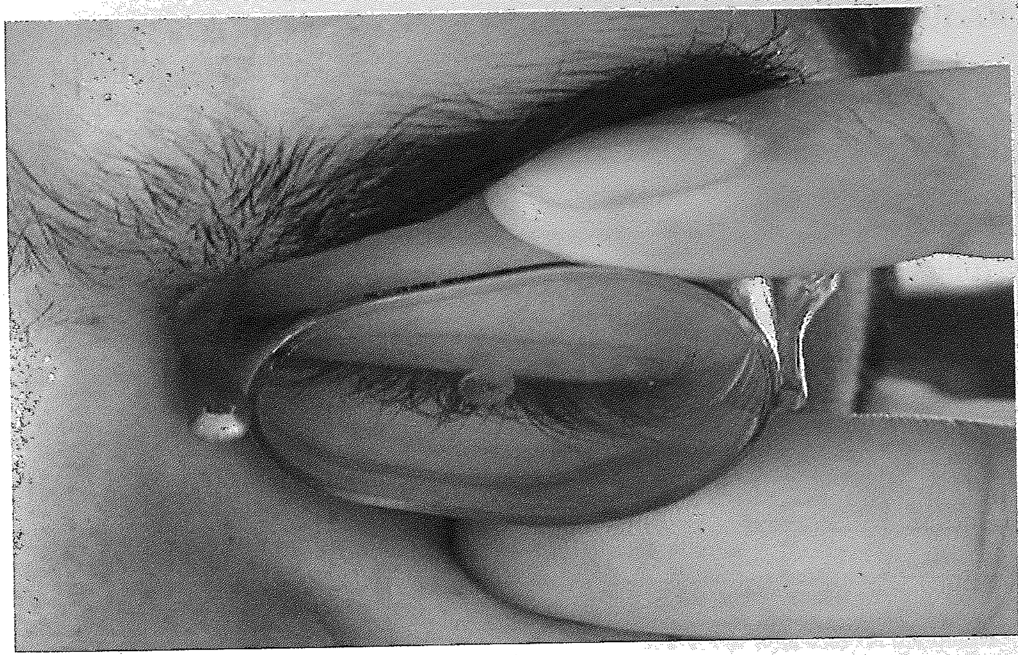

Figure 5.13
The goggle filled with saline on a subject (note: for the purpose of measuring goggle volume, the goggle which was full of saline was placed against the subject closed eye for patient comfort. This may have resulted in a very small difference in goggle area compared to the eye open, however each subject acted as their own control).

5.6 ABILITY TO DIFFERENTIATE BETWEEN CLINICAL OCULAR ENVIRONMENTS

5.6.1 Subjects

Ten subjects (mean age 30.5 ± 5.0 years with a 3:2 male to female ratio) were recruited from the under-graduate, post-graduate and staff population of Aston University. The requirements for the subject to enrol in the study were as followed (Table 5.2):

Inclusion Criteria	Exclusion Criteria
1. Good general health. 2. Best corrected visual acuity of 6/6 or better. 3. No known cataract or opacities on the ocular lenses or other ocular problems. 4. Have had a recent sight test within the past 24 months. Subjects were aware that this examination did not replace the need for regular eye examinations and contact lens check. 5. Aged between 18 and 45 years (pre-presbyopia). 6. Currently contact lens wearers with no history of contact lens complications.	1. Known active ocular pathology. 2. Cataract or opacities on the ocular lenses. 3. Any history of problems with contact lens induced complications in the past. 4. Any systemic condition e.g. diabetes, high blood pressure. 5. Amblyopia. 6. Previous refractive surgery.

Table 5.2
Inclusion and exclusion criterion used for the study

All subjects were interviewed with respect to their ability to adhere to the study protocol. The clinical procedures to be used in the study were also explained in detail prior to enrolment. Ethical approval was sought by Aston University Ethics Committee and a consent form was completed by each subject. The subjects were given the option of withdrawing from the experiment in accordance with the Helsinki Declaration of 2000.

5.6.2 Subject Set-Up

The subject was asked to sit at a slit-lamp head rest to minimise movement and instructed to look at a fixation cross with the contralateral eye (Figure 5.14).

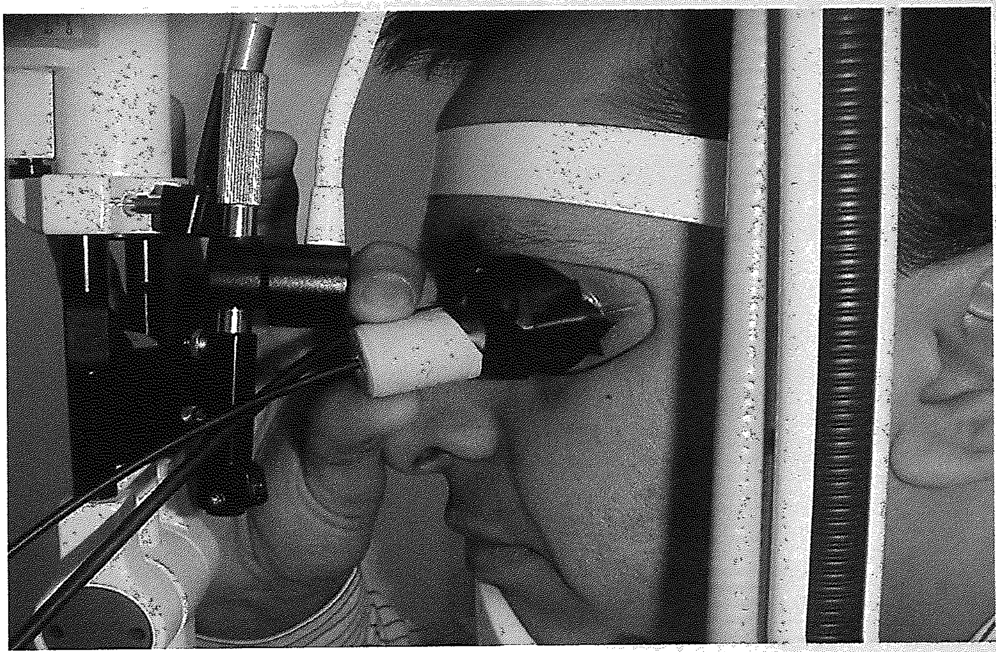

Figure 5.14
A subject at the slit lamp with the goggle device in place

5.6.3 Repeatability

Since this is a new technique for measuring corneal oxygen uptake, there was no established repeatability data, hence it was essential to demonstrate repeatability to establish the accuracy of this instrument design. Three consecutive readings (five minutes intervals) of 3 minutes each were conducted on ten subjects with open-eye conditions (Table 5.3) (mean age 30.5 ± 5.0 years, 6 males).

The data were analysed using Oxyview PST3-US.32 (Precision Sensing GnbH, Regensberg, Germany) and exported directly to a Microsoft Excel worksheet (Microsoft, Seattle, USA).

subject	Measurement 1	Measurement 2	Measurement 3	Mean	Standard Deviation
1	-0.882	-0.845	-0.72933	-0.81878	0.07964
2	-0.4	-0.446	-0.60033	-0.48211	0.104935
3	-0.537	-0.3585	-0.36865	-0.42138	0.100254
4	-0.568	-0.5768	-0.663	-0.6026	0.052493
5	-1.054	-1	-1.054	-1.036	0.031177
6	-0.734	-0.564	-0.466	-0.588	0.135602
7	-0.596	-0.549	-0.5725	-0.5725	0.0235
8	-0.572	-0.674	-0.623	-0.623	0.051
9	-0.867	-0.719	-0.837	-0.80767	0.078239
10	-0.702	-0.697	-0.6995	-0.6995	0.0025

Table 5.3
The goggle oxygen depletion from baseline after 3 minutes repeatable data

The results demonstrated good repeatability with a mean standard deviation of around 0.04 O_2% compared to the mean effect size of 0.65 O_2% for the oxygen uptake of the open-eye with no contact lens (this equates to 6%).

5.6.4 Experimental Protocol

All subjects attended in the morning (between 10am-12pm) for all visits in an attempt to minimise diurnal variations that may occur due to changing corneal thickness. A measure of oxygen consumption was taken under open-eye and closed-eye conditions for each subject and again with each of the contact lenses, in random order on separate occasions. Each subject acted as their own control with changes being related to baseline measures for each individual. The subjects adapted to the room environment for 20 minutes prior to measurements to allow stabilisation of corneal physiology since Purslow found that this was the case for thermography (Purslow *et al.*, 2005). Subjects were instructed to blink every 5 seconds when measurements were taken to mimic average blink rate (Stein, 2002). Contact lenses were inserted and removed by the examiner. The order in which the contact lenses were worn was randomised. Measurements were taken after contact lens insertion. The subjects were all previous soft contact lens wearers, but did not wear any contact lenses for at least 48 hours prior to the experimental session. The mean room temperature was 21 ± 3°C, and the mean humidity was 40 ± 3%.

5.6.5 Contact Lenses

Two types of soft contact lenses were chosen to assess the technique; the lenses chosen were used to demonstrate two extremes of oxygen transmissibility (Dk/t) materials (Table 5.4). Although some classification would place the contact lenses in the moderate and high Dk/t categories respectively (IACLE, 1998), for the purpose of this study the contact lenses have been categorised into Low Dk/t** and High Dk/t**. These lenses have also been classified into their appropriate ISO unit (ACLM, 2007) (see Table 5.4).

Contact Lens	**Polymacon**	**Balafilcon**
Material	Hema	SiH
Oxygen permeability (Dk)	8.5	99
ISO Dk Category	1	4
Oxygen Transmissability (Dk/t)	14	110
Research Category	Low Dk/t**	High Dk/t**
Water Content	38%	36%
Base Curve (mm)	8.7	8.6
Diameter (mm)	14	14
Modality	Conventional	Monthly
Centre thickness	0.06	0.09

Table 5.4
Summary of the contact lens materials and parameters at -3.00DS
Own categorisation. The Polymacon lens will be referred to as Low Dk/t and the Balafilcon lens will be referred to as High Dk/t**.

5.6.6 Oxygen Measurements

Measurements were taken every 5 seconds over a 3 minute period. The readings were taken with no contact lens *in situ* (no lens), with the Low Dk/t** contact lens and again with the High Dk/t** contact lens all in the open-eye condition. Another reading was taken with the eyelids closed (closed-eye) to establish the difference in goggle oxygen depletion between the eye open and the skin of the eyelids. A final measurement was taken on the subject's cheek to establish a control; this allowed evaluation of the effect of the eyelid on oxygen depletion within the goggle. As the aim of this research was to identify any differences between conditions, the output was recorded from baseline (21% O_2) for easy comparisons between conditions. The term 'goggle oxygen depletion' rate will be used to discuss the reduction of O_2 % within the goggle. Measurements were started 5 minutes post-contact lens insertion to allow standardisation with the polarographic technique.

5.7 RESULTS

The statistics were generated by SPSS version 15 and SigmaPlot 2000.

5.7.1 Corneal Volume

The average corneal volume over a 10 mm^2 area from the central cornea for the Low Dk/t**, High Dk/t and no lens condition was 59.98 ± 2.82 mm^3, 60.18 ± 3.08mm^3, and 59.90 ± 2.61mm^3, respectively (see Appendix). These were not statistical significant between groups (ANOVA; F = 0.03; p = 0.97).

There was no correlation between corneal volume and the goggle oxygen depletion rate from baseline at 3 minutes whilst wearing no contact lens (R = 0.10; p = 0.78; Figure 5.15), Low Dk/t** (R = -0.33; p = 0.36; Figure 5.16) and High Dk/t** (R = -0.33; p = 0.35; Figure 5.17) contact lenses.

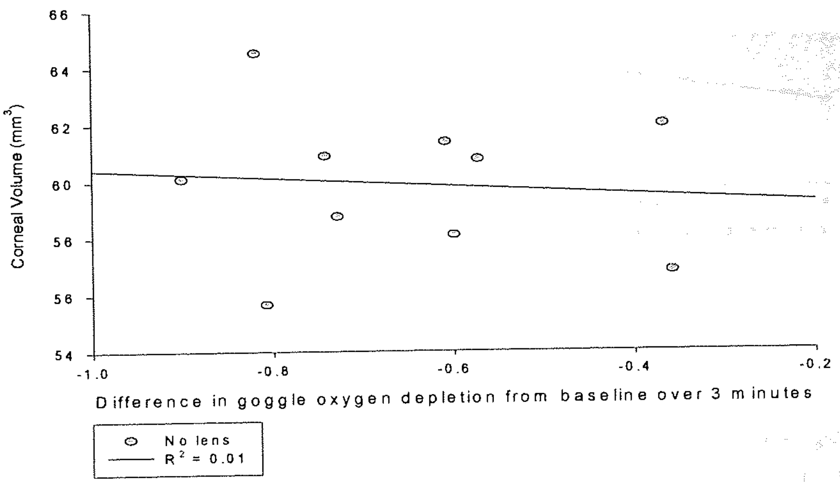

Figure 5.15
Correlation between corneal volume and the difference in goggle oxygen depletion from baseline over 3 minutes in the no lens condition (n=10)

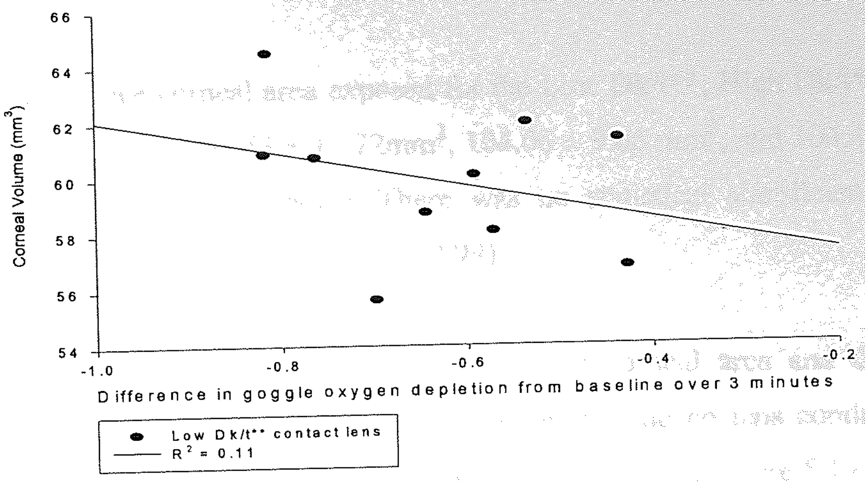

Figure 5.16
Correlation between corneal volume and the difference in goggle oxygen depletion from baseline over 3 minutes in the Low Dk/t** contact lens condition (n=10)

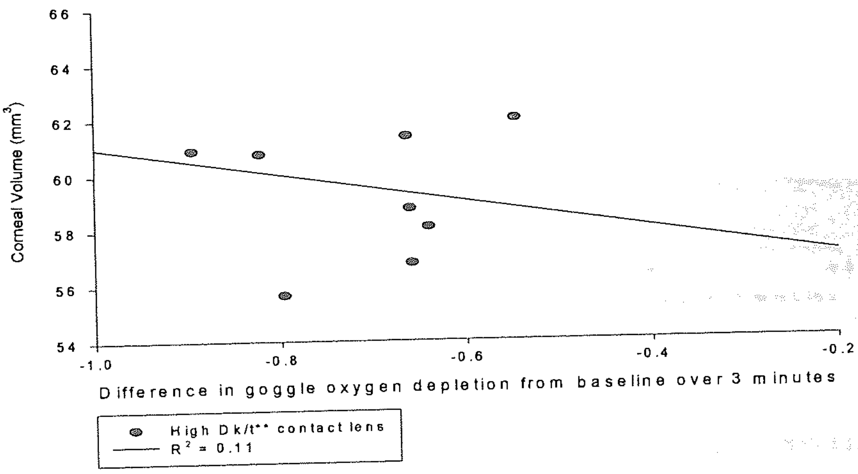

Figure 5.17
Correlation between corneal volume and the difference in goggle oxygen depletion from baseline over 3 minutes in the High Dk/t** contact lens condition (n=10)

5.7.2 Corneal Area

The average corneal area exposed for the Low Dk/t**, High Dk/t** and the no lens condition was 103.53 ± 13.72mm^2, 104.06 ± 9.05 mm^2, and 104.43 ± 10.21 mm^2 respectively (see Appendix). There was no statistical significant different between groups (ANOVA; F = 0.01; p = 0.99).

There was no correlation between exposed corneal area and the goggle oxygen depletion rate from baseline at 3 minutes for the no lens condition (R = 0.50; p = 0.14; Figure 5.18), Low Dk/t** (R = 0.42; p = 0.22; Figure 5.19) and High Dk/t** (R = 0.45 ; p = 0.188; Figure 5.20) contact lens conditions.

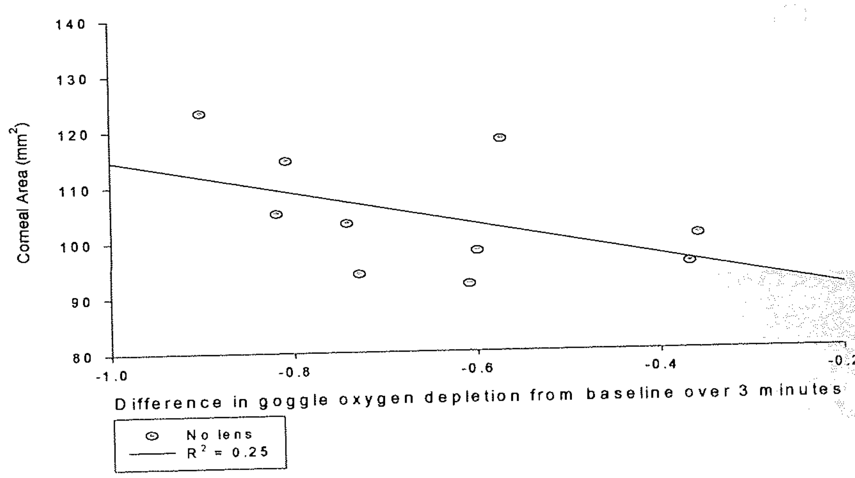

Figure 5.18
Correlation between corneal area and the difference in goggle oxygen depletion from baseline over 3 minutes in the no lens condition (n=10)

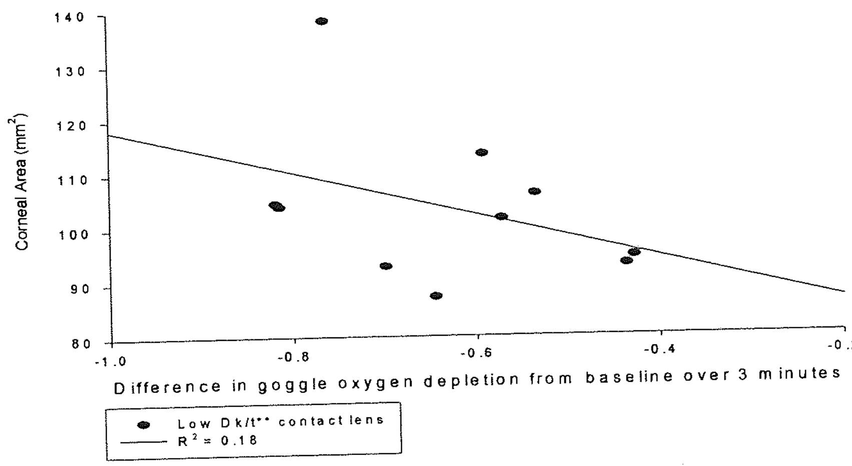

Figure 5.19
Correlation between corneal area and the difference in goggle oxygen depletion from baseline over 3 minutes in the Low Dk/t** contact lens condition (n=10)

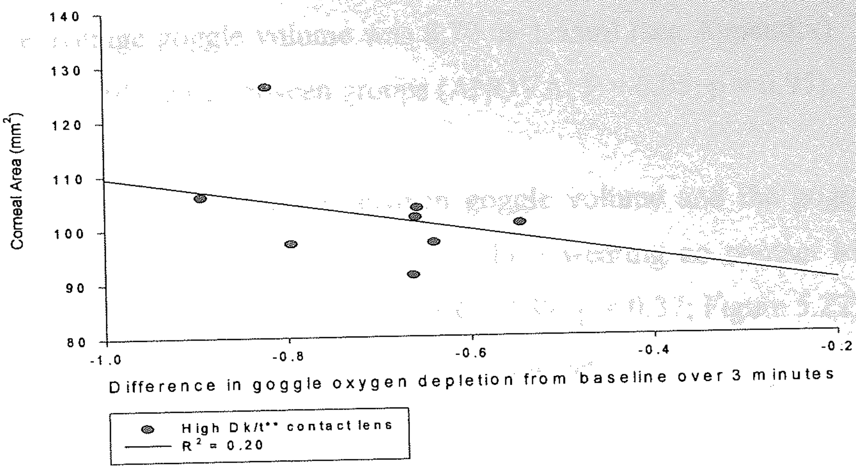

Figure 5.20
Correlation between corneal area and the difference in goggle oxygen depletion from baseline over 3 minutes in the High Dk/t** lens condition (n=10)

5.7.3 Goggle Volume

The average goggle volume was 8.70 ± 1.65ml (see Appendix). There was no statistical significance between groups (ANOVA; $F = 0.05$; $p = 0.95$).

There was no correlation between goggle volume and the goggle oxygen depletion rate from baseline at 3 minutes whilst wearing no contact lenses ($R = 0.45$; $p = 0.19$; Figure 5.21), Low Dk/t** ($R = 0.32$; $p = 0.37$; Figure 5.22) and High Dk/t** ($R = 0.01$; $p = 0.95$; Figure 5.23) contact lenses.

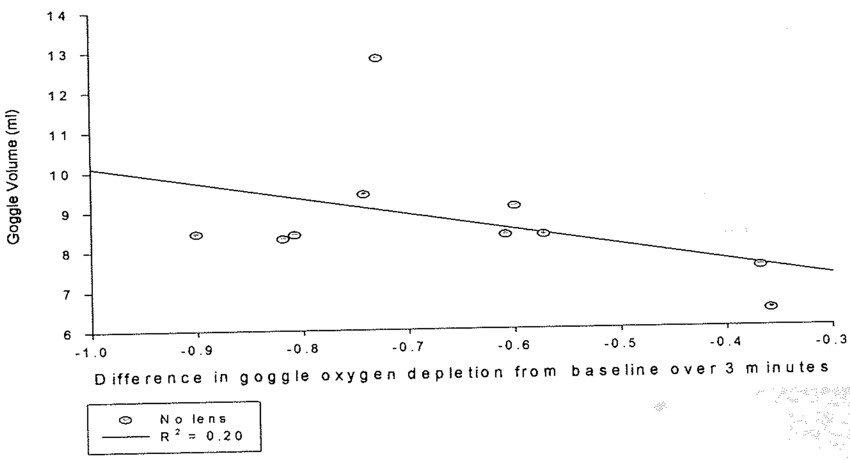

Figure 5.21
Correlation between goggle volume and the difference in goggle oxygen depletion from baseline over 3 minutes in the no lens condition (n=10)

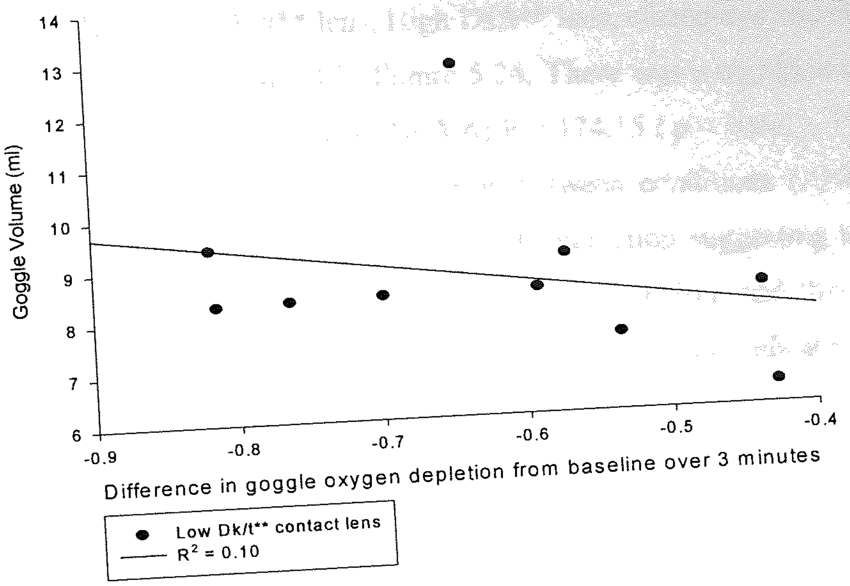

Figure 5.22
Correlation between goggle volume and the difference in goggle oxygen depletion from baseline over 3 minutes in the Low Dk/t** contact lens condition (n=10)

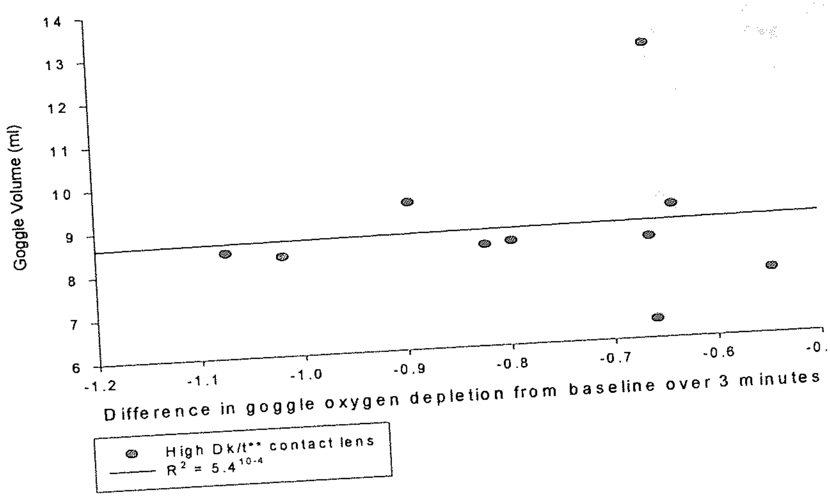

Figure 5.23
Correlation between goggle volume and the difference in goggle oxygen depletion from baseline over 3 minutes in the High Dk/t** contact lens condition (n=10)

5.7.4 Oxygen Decrease (Goggle Oxygen Depletion)

The average difference in goggle oxygen depletion from baseline for all 5 conditions (no lens, Low Dk/t** lens, High Dk/t** lens, closed-eye and skin) over a period of 3 minutes is illustrated in Figure 5.24. There was a significant effect on goggle oxygen depletion with time (ANOVA; $F = 174.15$; $p < 0.001$). There was a significant effect on goggle oxygen depletion between conditions (ANOVA; $F = 32.89$; $p < 0.001$). There was also a significant interaction suggesting time trends vary for the different lens conditions ($F = 17.50$; $p < 0.001$), and this difference varied linearly with time. As within subject ANOVA does not indicate differences between individual conditions, univariate ANOVA was conducted at 0.1minute, and then at 1 minute intervals to identify differences between conditions (Table 5.5). This showed that there was a statistically significant difference between closed-eye and skin conditions with the no lens and Low Dk/t** and High Dk/t** contact lens conditions by 1 minute of oxygen consumption. By 2 minutes, a significance was seen between the skin and the closed-eye condition.

	Post-hoc **(Scheffe's)**	
Time (minutes)	**F value**	**p value**
0.1	0.742	>0.05
1	19.354	<0.0001
2	27.852	<0.0001
3	34.269	<0.0001

Table 5.5
Post hoc analysis of all conditions on goggle oxygen depletion and time

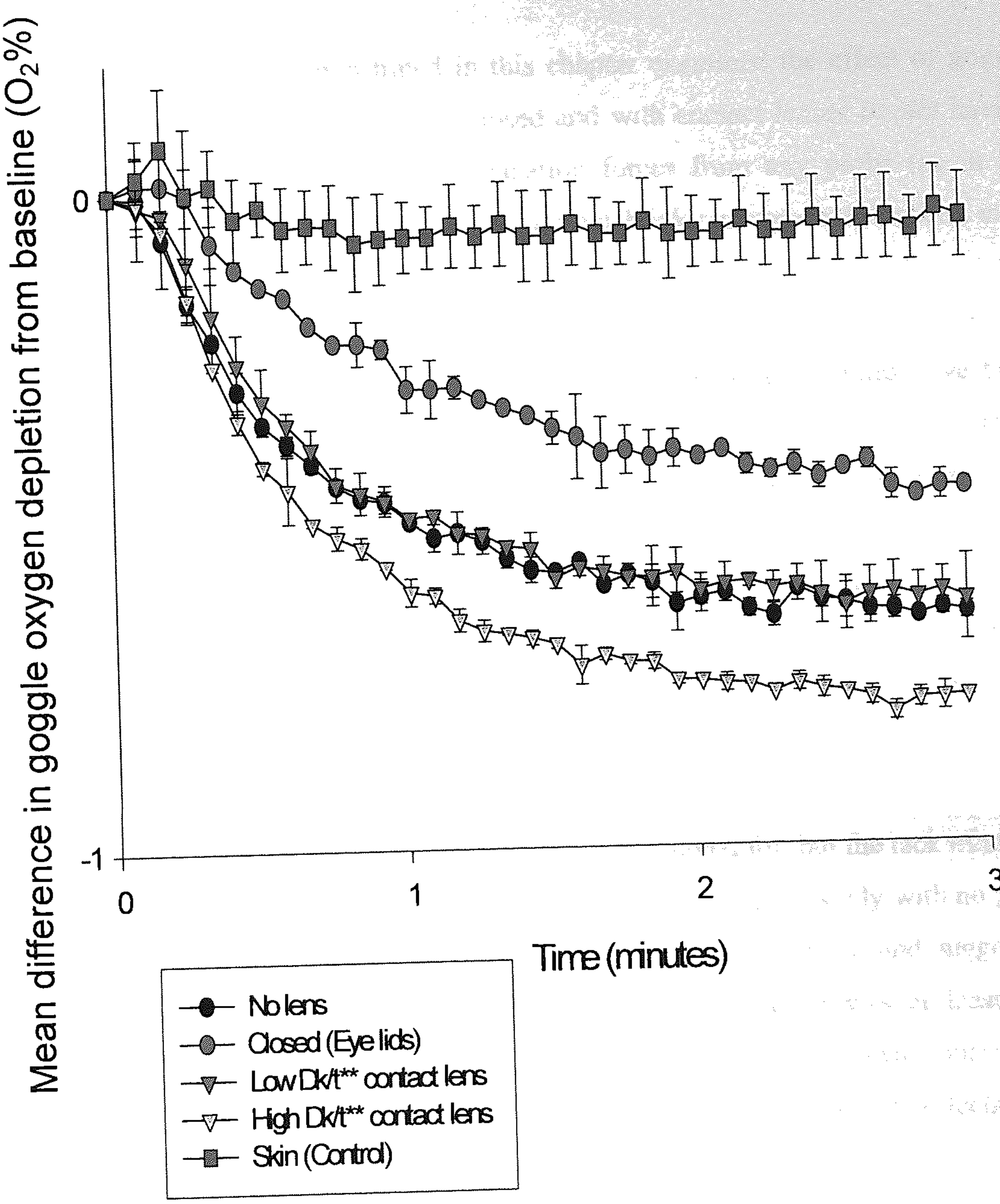

Figure 5.24
The difference in goggle oxygen depletion from baseline with no lens, closed-eye, Low Dk/t** contact lenses, High Dk/t** contact lenses and the skin within the goggle area (control). Error bars represent 1 SD (n=10)

5.8 DISCUSSION

The technique demonstrated in this chapter examined the effect of goggle oxygen depletion with the eye open, closed and with contact lenses *in situ* having the advantage of no influence of applanation forces from any probe (as in the polarographic technique), the eye in the normal blinking, non-anaesthetised state and also measured oxygen depletion in real time.

Previous techniques for measuring corneal oxygen uptake rates have been invasive and restrictive on blinking, thus affecting natural contact lens movement and tear circulation. Furthermore they are often time consuming and cumbersome. The technique demonstrated in this chapter highlights a non-invasive and quick assessment of apparent corneal oxygen uptake by measuring goggle oxygen depletion. The volume of air initially captured in the goggle did not show an affect on the rate of apparent consumption by the cornea. It would be predicted that the larger the volume of captured air within the goggle, the slower the apparent decrease in oxygen percentage from a cornea consuming the same oxygen rate. The saline displacement method allows for this to be accounted for, but the lack of effect seen may be due to the low number of subjects. As this is a pilot study with no prior data on measurements variability, power statistics were carried out and suggested that to achieve a 90% power the number of subjects needed was at least 12. However, in the subsequent experiments, subjects act as their own control by experiencing each of the conditions, and therefore goggle volume effects are neutralised.

Exposed corneal area did not appear to affect the oxygen depletion rate as the goggle covers the tissue surrounding the eye such as the eyelids and fornices, this result would suggest that total corneal oxygen usage is measured regardless of whether it is covered by the lids or not. Skin oxygen consumption was shown to be negligible compared to that measured when the goggle covers the eye. Fink *et al.* (1990b) demonstrated that a small palpebral aperture can hinder lens movement thus decreasing oxygenated tears to the surface under the contact lens. Unlike this technique, previous techniques did not account for this and other effects from the movement of contact lenses on the eye and resulting gas exchange with the cornea, limiting their accuracy in predicting the clinical reality.

Previous literature has shown that corneal thickness and volume play an important role when measuring corneal oxygen uptake (Larke *et al.*, 1981). As this new technique measures oxygen consumption over the entire cornea it may be more appropriate to look at corneal volume rather than corneal thickness (corneal thickness varies across the corneal profile but corneal volume would include this variation). The data shown with this new technique suggests that individual corneal volume did not influence the goggle oxygen depletion rate. This result is contrary to the suggestion by Larke *et al.* (1981) that the thicker the cornea the more oxygen is utilised.

When examining the use of the new technique in clinical conditions, it was shown that significantly more oxygen is consumed by the closed-eye than the surrounding skin. This finding supports Benjamin and Hill (1986), who found that the cornea still receives some atmospheric corneal oxygenation during closed-eye conditions due to lid flicker when the eye is closed. This could account for as much as 70% of the corneal required oxygen during closed-eye conditions, which would significantly change our understanding of the closed-eye environment if supported by data from a larger number of subjects.

There was a clear significant difference between goggle oxygen depletion between the closed-eye condition and the open-eye conditions with and without contact lenses. The technique demonstrates no significant difference in goggle oxygen depletion between the no lens condition and the Low Dk/t** and High Dk/t** contact lens condition over a period of three minutes. However, the High Dk/t** contact lens condition seemed to utilize more oxygen depletion within the goggle compared to the no lens and Low Dk** contact lens condition. From previous research suggesting that contact lenses can obstruct oxygen uptake by the cornea, it was unexpected that this technique demonstrated no change between a Low Dk/t** contact lens and the no lens condition and an even higher depletion of oxygen within the goggle with a High Dk/t** contact lens. These results may be explained by the contact lenses acting as an oxygen reservoir on initial insertion as previously suggested in 1981 by Hill, reporting a reduction in oxygen demand by the cornea when using a hydrogel under a PMMA lens compared to a PMMA lens alone, suggesting that an oxygen reservoir exists in hydrogel lenses. The further increase in goggle oxygen depletion with SiH (Balfilcon) materials may be explained by Florkey *et al.* (2003) in which they established that SiH lens materials may act as a short-term reservoir when oxygen tension across the lens is temporally reduced.

As the lenses in this study were inserted immediately after removal from their sterile packaging and the goggle oxygen depletion readings were taken instantaneously (after 5 minutes of contact lens insertion), these assumptions could be investigated further by examining the goggle oxygen depletion rate after the contact lenses have been *in situ* for a longer period of time, for instance after the subject has worn a lens for 4 hours, as this initial result may be recording an adjustment of the contact lens to the on eye condition.

The repeatability shown with this technique on the open-eye (no lens) was found to be good. Therefore, the technique seems to reliably measure oxygen depletion within the goggle which could be related to corneal oxygen consumption.

5.9 CONCLUSION

As the availability of highly oxygen permeable contact lens materials for use on the eye has been linked to a reduction in the risk of infections, inflammation and other contact lens-associated problems, the contact lens industry is determined to develop better contact lens materials. However, materials that allow better oxygen permeability can also have detrimental characteristics and therefore a balance needs to be found. As interference of oxygen supply to the cornea has been associated with contact lens performance on the eye, it is important that the measurement of corneal oxygen consumption can be measured accurately and with minimal interference with the contact lens *in situ*. The use of an air-tight swimming goggle with a non-contact oxygen sensor provides a quick and non-invasive method of measuring the effect of contact lenses on corneal oxygen in real time.

As this technique is a non-contact method, and oxygen demand to the body tissue is increased during sports, it would be interestingly to use this technique to measure the goggle oxygen depletion of the cornea during sports when the oxygen demand on skeletal muscle is higher and may also be higher at the cornea too. The oxygen consumption during exercise will be investigated in chapter 6.

CHAPTER SIX

CORNEAL OXYGEN UPTAKE DURING EXERCISE

6.1 INTRODUCTION

During exercise it has been well established that the oxygen uptake demand of the body tissues is increased (Åstrand and Rodahl, 1998). To the author's knowledge, the oxygen demand of the cornea during such an activity has not been fully investigated. The haemoglobin within the body carries oxygen to the tissues of the body via the arteries (Bursztyn, 1990). This increase in oxygen demand is provided from an increase in pulmonary ventilation (breathing), which has been shown to increase linearly with oxygen consumption (Figure 6.1), and in a more demanding situation will lead to an anaerobic supply of oxygen.

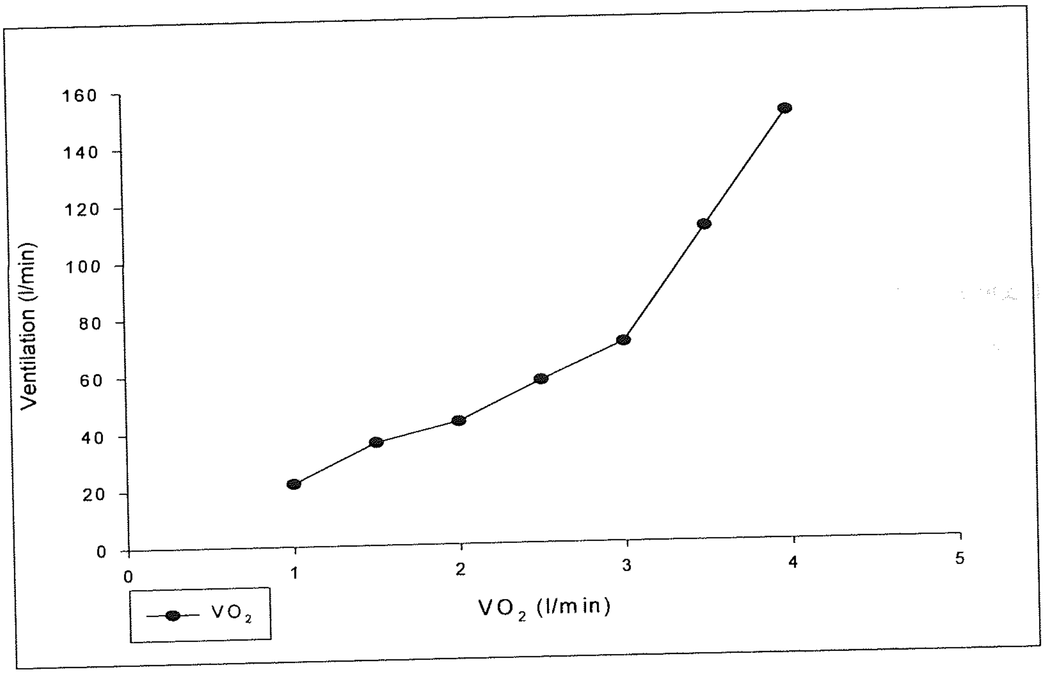

Figure 6.1
Pulmonary ventilation and oxygen consumption (VO_2) during light to moderate exercise the oxygen consumption and ventilation increase linearly up to about 55% of VO_2 maximum (redrawn from Maughan *et al.*, 1997)

Muscle oxygen consumption is dependent on Fick's Law (Equation 6.1). This is dependant on the oxygen content within the arterial blood and the extraction amount by the body tissue (Maughan *et al.*, 1997).

$$VO_2 = Q \times (CaO_2 - CvO_2)$$

VO_2 = Rate of oxygen uptake (ml min-1)

CaO_2 = Arterial Oxygen Content

CvO_2 = Venous Oxygen Content

Q = Cardiac Output

Equation 6.1
Fick's Law

Oxygen is required for effective energy production during exercise. There are two main metabolic processes within the human body that produce energy by the breakdown of glucose (glycolysis), as well as other organic substrates, to produce energy to generate adenosine triphosphate (ATP), which is utilised for muscle contraction when we exercise. Energy produced in the presence of oxygen is known as aerobic respiration, while energy produced in the absence of oxygen is termed anaerobic respiration (Figure 6.2). Glycolysis is the process by which the body breaks down glucose to produce pyruvate (Maughan *et al.*, 1997), once the body has broken glucose down the process can go in either two directions depending on whether oxygen is available (Vander *et al.*, 1998). If oxygen is available (aerobic respiration) the pyruvate enters the Kreb cycle (Figure 6.2) and breaks down into carbon dioxide, hydrogen and ATP. In the absence of oxygen (anaerobic respiration), the pyruvate produces the waste product lactate which in turn turns into lactate acid. Aerobic respiration is more efficient than anaerobic respiration (30 ATP produced per glucose molecule, 2 ATP yielded per glucose molecule, respectively).

It has been described by Spurway (1992) that during initial phase of exercise, the energy required for the muscles is produced anaerobically via glycolysis, whilst energy required during exercise that is prolonged more than 2 minutes is produced aerobically initially via glycogen, although it has been suggested that light exercise can be provided aerobically during the first minutes as there is oxygen bound to the myoglobin in the muscle and blood providing the muscle (Newsholme and Leech, 1983).

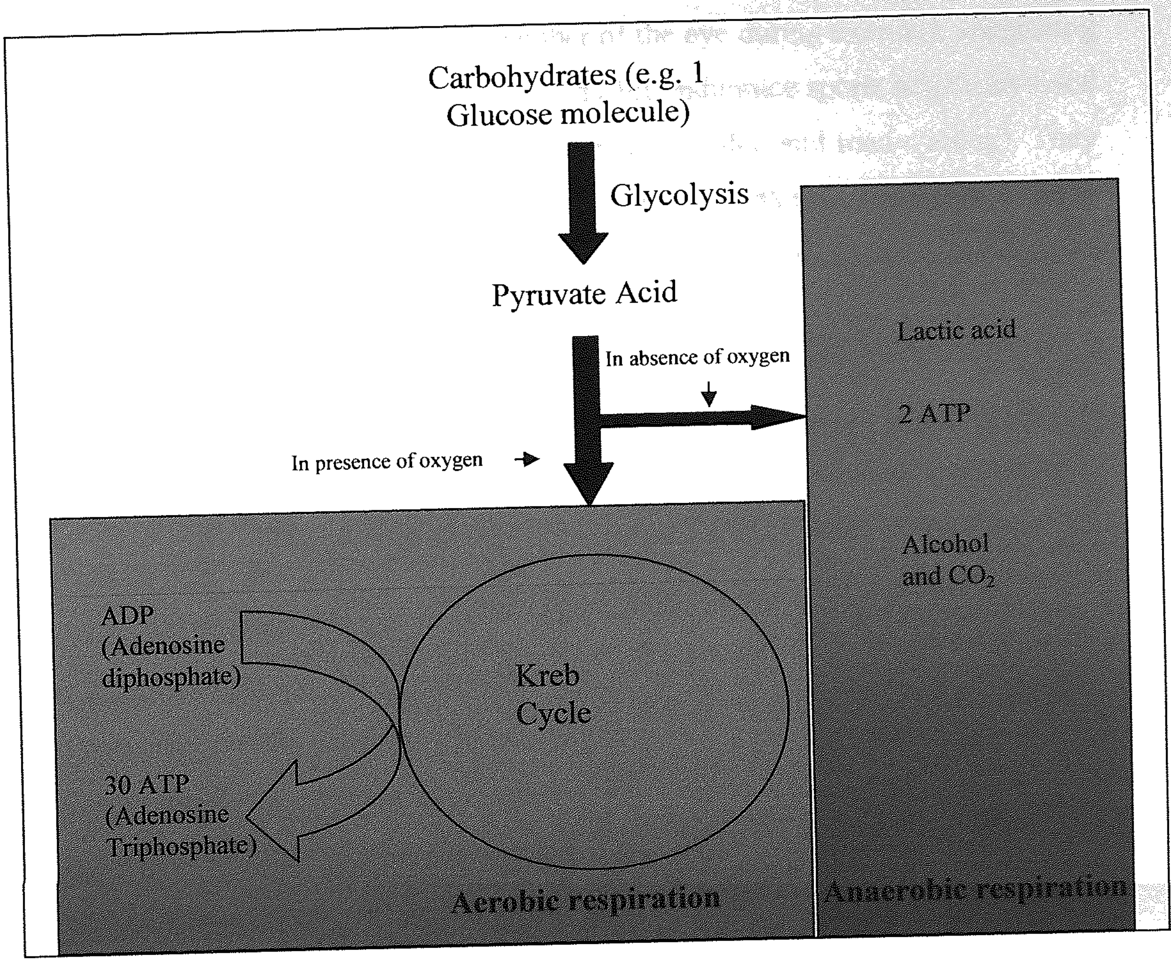

Figure 6.2
Diagrammatic representation of aerobic and anaerobic respiration

Contact lenses are widely used by those participating in sport for reasons discussed earlier (see Table 1.4 in Chapter 1). As oxygen demand throughout the body increases during exercise, the question arises whether the oxygen demand of the cornea also increases. As previously mentioned in chapter 1, oxygen does not diffuse through the total thickness of the cornea, it enters from both anterior (epithelium) and posterior (endothelium) surfaces of the cornea with a minimum oxygen tension in the stroma (Fatt *et al.*, 1974). The corneal oxygen consumption has been extensively discussed in chapter 1.

There seems to be a lack of literature on the oxygen requirement of the cornea during exercise, but it has been postulated that higher levels of oxygen are required during exercise and in many types of exercise, oxygen uptake increases linearly with the increase rate of exercise (Åstrand and Rodahl, 1986). Bomholt and

Schnell (2000) reported a high level of lactic acid and decreased levels of glucose in the blood vessels and in the anterior chamber of the eye during exercise, suggesting this could lead to corneal oedema, particularly for endurance sports which involved high rates of aerobic metabolic turnover (such as triathlon and road-cycling). They also frequently observed corneal oedema underneath contact lenses which quickly disappeared during rest; it was suggested to be in response to an increased oxygen demand of the cornea during exercise.

As the cornea is avascular, corneal epithelial oxygen is not supplied directly via blood vessels (except the limbal region) during the open-eye condition; so therefore, during exercise oxygen to the cornea must come from the atmosphere or via the aqueous as in the normal open-eye condition (Fatt *et al.*, 1974; Ruben and Guillon, 1994; Weissman *et al.*, 1981).

6.2 AIM

The aim of this study was to measure the oxygen required by the cornea during exercise with and without contact lenses using the non-contact dynamic quenching of luminescence method as developed in Chapter 5.

6.3 METHOD

The instrumentation as described in Chapter 5 was used to assess the apparent oxygen uptake rate (depletion of oxygen within the goggle). Measurements were taken over a 3 minute time period (every 5 seconds) with the goggle *in situ* over the subject's left eye. This was repeated every 5 minutes over an episode of 30 minutes exercise period, and continued until the pre-exercise goggle oxygen depletion rate was established. The readings were taken on the open-eye with no contact lens *in situ* (no lens), and with the Low Dk/t** contact lens and again with the High Dk/t** contact lens (see Table 5.4 in Chapter 5) *in situ* in random order on separate occasions. Subjects acted as their own control. As the aim of this study was to identify any change in goggle oxygen depletion rate during exercise with and without contact lenses using the non-contact dynamic quenching of luminescence method, the data is presented as the change of oxygen concentration from baseline (O_2%). The term goggle oxygen depletion rate will be used to discuss the reduction of O_2% within the goggle.

It can be seen from the results in chapter 5 that corneal volume, exposed corneal area, and goggle volume did not influence goggle oxygen depletion rate, and as the subjects acted as own control, these parameters were not measured.

Ten subjects were recruited from the under-graduate, post-graduate and staff population of Aston University. The average age was 30.5 ± 5.0 years with a 3:2 male to female ratio. Ethical approval was sought from the Aston University Ethics Committee. All subjects were interviewed with respect to their ability to adhere to the study protocol. The subjects were given the option of withdrawing from the experiment in accordance with the Helsinki Declaration of 2000.

The requirements for the subjects to enrol in the study were as followed (Table 6.1):

Inclusion Criteria	Exclusion Criteria
1. Good general health. 2. Best corrected visual acuity of 6/6 or better. 3. No known cataract or opacities on the ocular lenses or other ocular problems. 4. Currently contact lens wearers with no history of contact lens complications. 5. Pass the PAR-Q questionnaire (see Appendix). 6. Actively participate in exercise (defined as 30 minutes exercise 5 times a week). 7. Have had a recent eye exam and contact lens examination/ aftercare within 12 months. Subjects are aware that this does not replace the need for regular eye examinations and contact lens check. 8. Aged between 18 and 45 years (pre-presbyopic).	1. Known active ocular pathology. 2. Cataract or opacities on the ocular lenses. 3. Any history of problems with contact lens induced complications in the past. 4. Any systemic condition e.g. diabetes, high blood pressure. 5. Amblyopia. 6. Previous refractive surgery. 7. Subjects who do not actively participate in sports (defined as 30 minutes exercise 5 times a week). 8. Subjects who answer yes to any of the questions to the PAR-Q questionnaire.

Table 6.1
Inclusion and exclusion criteria

6.3.1 Experimental Protocol

The study was conducted in a room that was monitored for temperature and humidity. The mean room temperature was 21 ± 3°C, and the humidity was 40% ± 10%. There was no external light and the room was illuminated by fluorescence lighting (see section 5.3.2 in Chapter 5).

An ergometer exercise cycle was chosen for reason explained in section 4.3.1.7 in chapter 4. The subjects were sat on the exercise bike and the non-contact oxygen devise was held in place by the examiner during the exercise period (Figure 6.3). The subject was instructed to blink at a normal rate (every 5 seconds) and to look at a fixation cross as described in section 5.5.2. The subject wore a headband to prevent eye rubbing due to sweat running into the eyes. Subjects performed thirty minutes exercise, including a five minute warm up at maximum heart rate between 60 – 70% (as discussed in section 4.3.1.8 in Chapter 4) with each of the conditions (no lens, Low Dk/t** and High Dk/t** contact lens) in randomised order, on separate occasions.

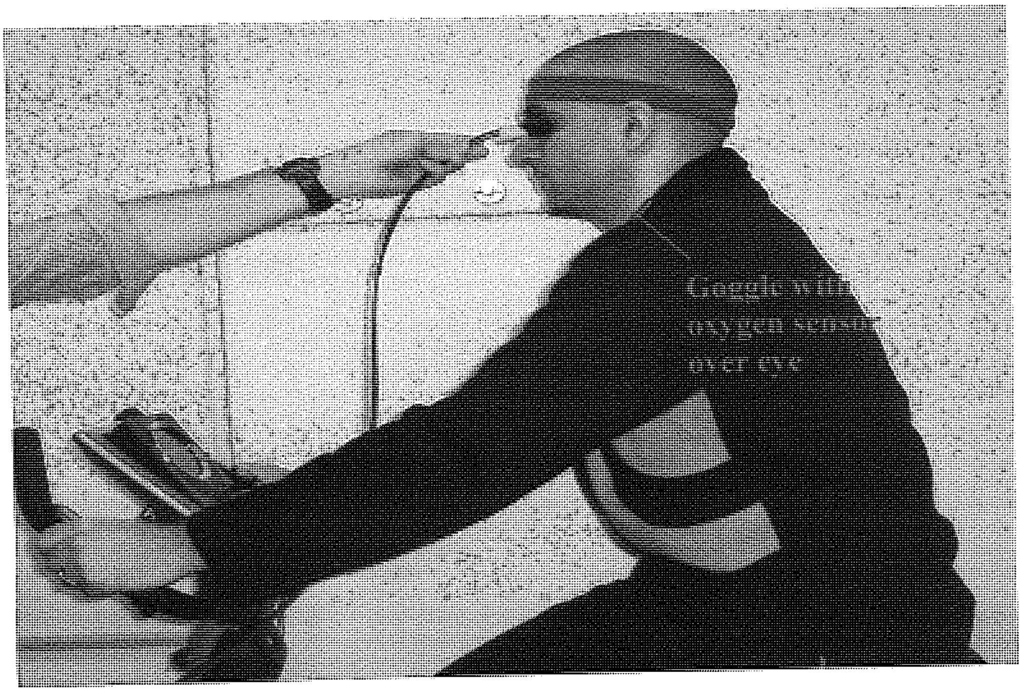

Figure 6.3
The experimental set-up

All subjects attended in the morning to minimise diurnal variations that may occur in corneal thickness. The subjects were adapted to the room environment for 20 minutes prior to measurements. The subjects were all previous soft contact lens wearers, but did not wear contact lenses 48 hours prior to the experimental session. Contact lenses were inserted in the right and left eyes, and removed by the examiner.

6.3.2 Contact Lenses

Two types of soft contact lenses were chosen. The lenses chosen were used to demonstrate the effect of soft contact lenses of Low Dk/t** and High Dk/t** materials during exercise (see Table 5.4 in Chapter 5). -3.00DS contact lenses were fitted regardless of subjects' refractive error, as this is the lens parameters quoted in the literature (ACLM, 2007).

The data was analysed via Oxyview PST3-US.32 (Precision Sensing GnbH, Regensberg, Germany) and exported directly to a Microsoft Excel worksheet (Microsoft, Seattle, USA).

6.4 RESULTS

6.4.1 Oxygen depletion

Figure 6.4 illustrates the mean in goggle oxygen depletion from baseline of all 3 conditions (no lens, Low Dk/t** and High Dk/t**) over an exercise period of 30 minutes followed by a rest period of 30 minutes. During the exercise period there was a statistically significant increase in goggle oxygen depletion rate with time (ANOVA; $F = 10.51$; $p < 0.001$). There was a significantly different effect on goggle oxygen depletion between conditions (no lens, Low Dk/t** and High Dk/t** contact lenses; ANOVA; $F = 4.52$; $p < 0.05$). There was a significant interaction suggesting time trends varies for the different lens conditions (ANOVA; $F = 2.12$; $p < 0.05$), and this difference varied quadratically with time.

As within-subject ANOVA does not indicate differences between individual lens conditions, univariate ANOVA was conducted at 5 minute, then at 10, 20 and 30 minutes to identify differences between lens conditions (Table 6.2). This showed that there was a statistically significant difference between the Low Dk/t** and the High Dk/t** contact lens conditions at 10 minute, but this effect was no longer evident at 15 minutes.

During the post-exercise period there was a statistically significant reduction in goggle oxygen depletion with time ($F = 15.30$; $p < 0.001$), but there was no significant difference effect on goggle oxygen depletion rate between lens conditions (no lens, Low Dk/t** and High Dk/t** contact lenses; ANOVA; $F = 0.20$; $p = 0.82$) and time and lens interaction (ANOVA; $F = 1.08$); $p = 0.39$).

	***Post-hoc* (Scheffe's)**	
Time (minutes)	**F value**	**p value**
5	1.193	>0.05
10	7.773	<0.05
20	1.443	>0.05
30	0.178	>0.05

Table 6.2
Post-hoc analysis on goggle oxygen uptake and time

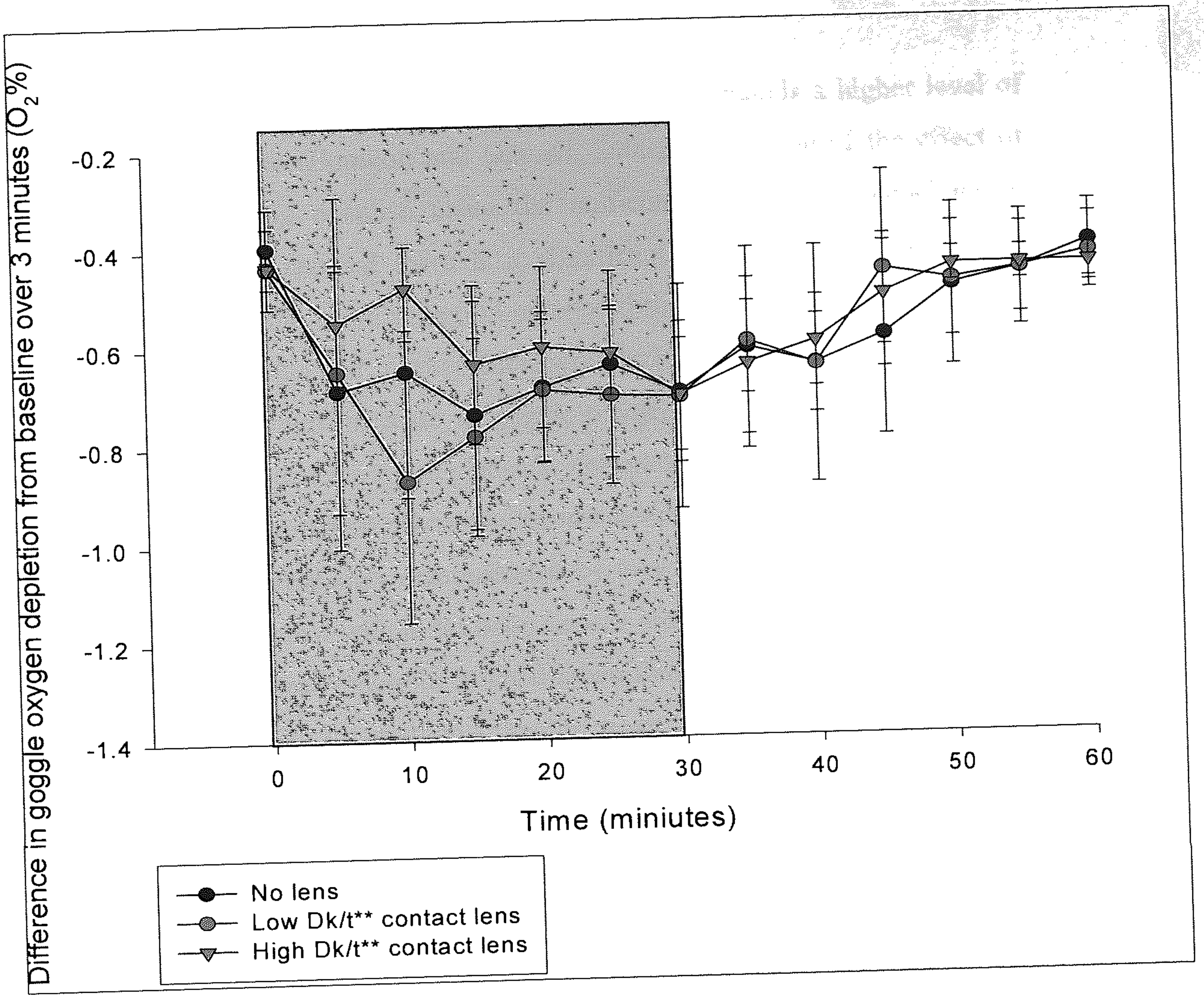

Figure 6.4
Oxygen depletion rate within the goggle with no lens, Low Dk/t** and High Dk/t** contact lenses during and after exercise. The green shaded area represents the measurements during exercise, whilst the white area represents the measurements in the post-exercise period. Error bars = 1 SD. n = 10

6.5 DISCUSSION

Previous research has suggested that the cornea demands a higher level of oxygen during exercise (Bomholt and Schnell, 2000). Evaluation of the effect of oxygen demand during exercise using the non-contact dynamic quenching of luminescence method showed there is a significant increase in goggle oxygen depletion rate during the exercise period compared to pre-exercise, thus indicating the corneal oxygen demand further increases during exercise. However, there appears to be a maximum increase in goggle oxygen depletion rate at around 10 minutes, then the rate decreases and plateaus. This plateau could be as a result of the maximal oxygen requirement when the cornea adapts to the increase in corneal oxygen demand, as previously demonstrated by Newsholme and Leech (1983), in which, the oxygen uptake within the body tissues increases during the first minute of exercise. Then a steady state is reached when the oxygen uptake is met by the demands of the tissue. Alternatively, at this point the cornea's requirement for additional oxygen maybe produced anaerobically, thus producing lactate acid which may result in corneal oedema. Corneal oedema after exercise has been previously suggested by Bromholt and Schnell (2000). After cessation of exercise the goggle oxygen depletion rate reduced with time and established a pre-goggle oxygen depletion rate for the no lens condition at around 20 minutes, suggesting a similar effect which occurs throughout the body tissue after 60 minutes post-exercise (Åstrand and Rodahl, 1998).

As previously reported, contact lenses can inhibit the amount of oxygen available to the anterior surface of the cornea (Fatt and Ruben, 1996; Hill and Fatt, 1963; Holden *et al.*, 1990; Ichijima *et al.*, 1998). As with the no lens condition of the study, the goggle oxygen depletion rate increased during exercise with the Low Dk/t** and High Dk/t** contact lenses *in situ*, but there was no significance between these conditions. Interestingly when a High Dk/t** SiH contact lenses was *in situ*, the oxygen demand as measured by goggle oxygen depletion was significantly less than that of the Low Dk/t** contact lenses in place at 10 minutes during the exercise period, however this effect was no longer evident after 15 minutes. This may further support suggestions that SiH (High Dk/t**) contact lenses may operate as an oxygen reservoir (Florkey *et al.*, 2003), thus initially providing the cornea with the required oxygen demand during exercise. The pre-exercise goggle oxygen depletion levels with the Low Dk/t** and the High Dk/t** contact lenses returned to base level after 10-15 minutes. The quick return to baseline supports research by Bomholt and Schnell (2000) in which they found that corneal oedema underneath contact lenses disappeared quickly post-exercise.

6.6 CONCLUSION

Apparent corneal oxygen demand (goggle oxygen depletion) when measured using the non-contact dynamic quenching of luminescence method is increased during exercise and quickly returns to base line post-exercise, both with and without contact lenses *in situ*. Lenses designed specifically for sports should take into consideration the oxygen demands of the cornea during physical exercise as this may increase in a similar fashion to the oxygen demands of skeletal muscle. The Nike MaxSight™ (Bausch and Lomb, Rochester, New York, USA) contact lens is a lens deigned specifically for sport. It is made from Polymacon, the oxygen performance of which was investigated in this chapter. The next chapter investigates the visual performance of this lens.

CHAPTER SEVEN

THE OPTICAL PERFORMANCE OF NIKE MAXSIGHT™ SPORT SPECIFIC CONTACT LENSES

7.1 INTRODUCTION

7.2 AIM

7.3 METHOD

7.4 RESULTS

7.5 DISCUSSION

7.6 CONCLUSION

7.1 INTRODUCTION

Sport is regarded as one of the three main reasons optometrists feel patients request contact lenses (Cardall *et al.*, 2007) as they have many advantages over spectacles when playing sport (see Table 1.4 in Chapter 1). New performance-enhancing contact lenses have been designed and developed for athletes to help to improve contrast between the object, e.g. the ball, and the background by the use of tinted contact lenses using short wavelength filters.

Yellow-tinted lenses (short wavelength filter) can alter the overall transmittance and chromatic vision (ability to see colours) (De Fez *et al.*, 2002) and have been reported to improve visibility in dull weather and dim light (Kelly, 1990). Such lenses have also been suggested for use as low vision aids (Faye, 1984) and also used by sports vision enthusiasts to enhance athletic performance. Short wavelength filter lenses have also been demonstrated to improve vision compared with grey filters (Kelly, 1990; Lee *et al.*, 2002; Rabin and Wiley, 1996; Yap, 1984).

Many studies have been carried out investigating the relationship between contrast sensitivity and coloured filters (De Fez *et al.*, 2002; Leguire and Suh, 1993; Perez-Carrasco *et al.*, 2005; Wolffsohn *et al.*, 2002). Contrast sensitivity has been shown to be improved with yellow filters (seemore filter 480nm cut-off) at high spatial frequencies (Zigman, 1992). However, Hovis *et al.* (1989) showed monocular contrast sensitivity functions (CSF's) with a blue blocker lens (orange tint absorbing wavelengths shorter than 525nm), and a luminance matched 0.76 ND filter, were statistically identical.

Yap, (1984) investigated the effect of a yellow filter (a long-pass filter (wavelength not stated in the paper) intended for 'night driving', luminous transmission of 80%) on monocular contrast sensitivity. He concluded that contrast sensitivity was increased with a long-pass yellow filter under photopic conditions, but not under most spatial frequencies under mesopic conditions.

The effect of yellow tinted lenses on brightness was investigated by Kelly, (1990). Kelly demonstrated that yellow tinted lenses (Kodak #9 yellow filter) enhanced brightness by as much 40% although over a limited luminance range, concluding that yellow tinted lenses enhance brightness.

It is well documented that short wavelength filters can also affect colour discrimination (Aarnisalo and Penkonen, 1990; Hovis *et al.*, 1989; Aarnisalo, 1987; De Fez *et al.*, 2002). Aarnisalo, (1987) investigated the effects of yellow filter glasses on colour discrimination of normal observers. Ten subjects were examined with the Farnsworth-Munsell 100-Hue test using a Macbeth daylight lamp whilst wearing a variety of filter lenses (Schott filters GG 400, GG420, GG 435, GG 455, GG 475, GG495 and OG 515). The study demonstrated that the latter three filter lenses produced a tritan (blue-yellow colour defect) error for normal observers. Hovis *et al.* (1989) also demonstrated a severe tritan colour vision defect in five colour normal subjects wearing blue blocker lenses (orange tint absorbing wavelengths shorter than 525nm). De Fez *et al*, (2002) supported Aarnisalo's (1987) findings as they also demonstrated a tritan-like defect with short wavelength filters.

Hovis *et al.*, (1989) reported that the improvement of visual performance is dependent upon the spectral characteristics of the target and the background. Previous studies have demonstrated that the enhancement of contrast for medium and long wavelengths targets viewed on a short wavelength background has been enhanced by the use of yellow filters (Hovis *et al.*, 1989; Kelly, 1990).

Stereopsis (ability to judge depth) has also previously been claimed to be improved with the use of short wavelength filter lenses. Hovis *et al.* (1989) investigated stereoacuity with blue blocker lens using a Howard-Dolman apparatus on 10 subjects. He found that stereoacuity was not affected by the blue blocker lenses at moderate photopic levels concluding that the study was consistent with a previous study by Mueller and Lloyd, (1948) (cited in Hovis *et al.,* 1989). They also commented that subjects reported that objects at supratheshold contrast level appeared to stand out from the background when wearing the lenses, concluding that, due to the Rayleigh scattering of short wavelengths due to haze when viewing through the blue lens reduced light scatter, thus objects appearing clearer and closer.

Ocular chromatic aberration has been reported to affect the quality of a retinal image (Bradley, 1992), of which three elements of chromatic aberration affects have been primarily implicated (chromatic difference of focus, chromatic difference of magnification, and chromatic difference of position) (Thibos *et al.*,1991). Chromatic difference of focus describes the variation in the focusing power of the eye with wavelength. Thibos *et al.* (1991), stated that the effect of chromatic aberration on image contrast was approximately correspondent to about 0.20 Dioptre of defocus. They also described that there could be an effect on retinal image size depending on the wavelength of light, stating that this magnification could be as large as 0.8% and this was known as chromatic difference of magnification. Thibos *et al.* described the chromatic difference of position as a spatial phase shift, thus affecting the judgment of hue, saturation, or brightness resulting in luminance contrast of an image being reduced. By reducing the effect of chromatic aberration, it is believed that this may enhance vision, especially during sports. The main purpose of developing sport-specific contact lenses is to enhance contrast and increase visual comfort when playing particular sports. There have been attempts to create a sport-specific contact lens in the past, with Levey designing a micro-scleral contact lens for sport (Levey, 1964) and Ciba vision producing a lens for tennis (ProSoft).

The Nike Maxsight™ contact lenses are made by Bausch and Lomb (Rochester, New York) specifically for sports use. They use patented 'Light Architecture Optics™' to filter specific wavelengths, especially the short wavelength of light to enhance key visual elements such as a ball or background, whilst reducing sun glare (Donnelly, 2005) (Figure 7.1 and 7.2). They claim the result is the ability to see a ball or other selected objects with greater clarity. Nike Maxsight™ are available commercially in two tints, one being Grey-Green (which reduces blue and orange-yellow light), for sporting activities played in bright backgrounds, such as golf and running. The other tint is an Amber tint (Amber allows for more efficient transition between sun and shade), designed for use with fast moving ball sports in variable light such as football (soccer), tennis and hockey. These lenses also filter out >95% of UVA and UVB, although UV absorbing contact lenses are not substitutes for protective UV absorbing eyewear such as UV absorbing goggles or sunglasses. The Nike Maxsight™ contact lenses reduce chromatic aberration of the eye to 1.1 Dioptre (Donnelly, 2005). These lenses are designed for use in outdoor photopic daylight lighting conditions and not under artificial lighting conditions.

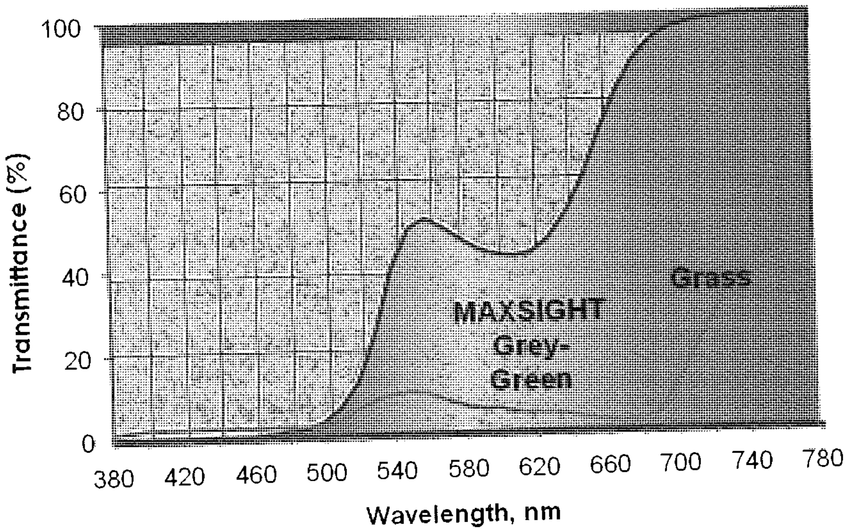

Figure 7.1
The transmittance graph of the Grey-Green Nike Maxsight™ contact lens (Reproduced with kind permission from Bausch and Lomb, Kingston, UK)

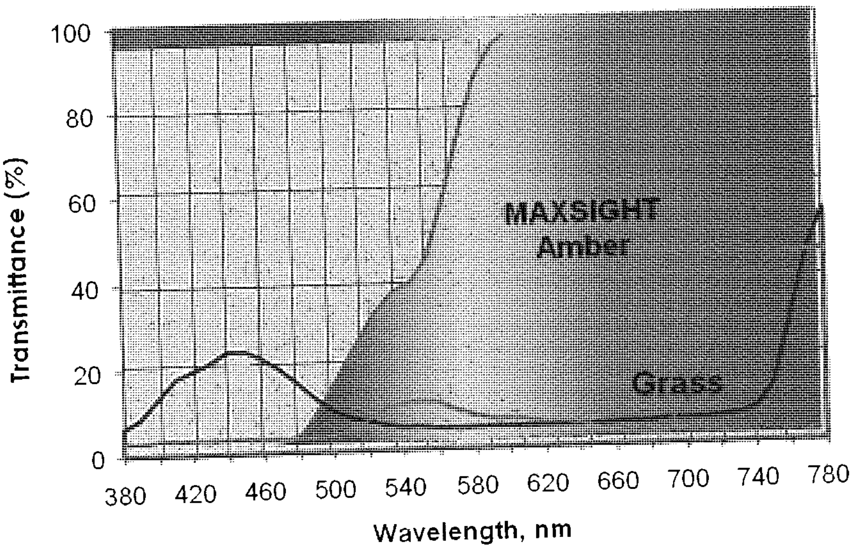

Figure 7.2
The transmittance graph of the Amber Nike Maxsight™ contact lens (Reproduced with kind permission from Bausch and Lomb, Kingston, UK)

Nike Maxsight™ contact lenses have previously been shown to have a significant effect on contrast sensitivity when worn by relatively low astigmatic or spherically refracted patient in outdoor lighting (Porisch, 2007), although Porisch concluded that there was no evidence that the sport-tinted lenses provide any clinically significant difference when considering contrast enhancement.

As these contact lenses are ideally used for outdoor photopic lighting conditions, it would be useful to determine the optical properties of such lenses within the optometric consulting room to give an understanding to the practitioner of how these lenses perform under consulting lighting conditions. Also, as short wavelength filters can influence our colour perception (Aarnisalo and Penkonen, 1990; Hovis *et al.*, 1989; Aarnisalo, 1987; De Fez *et al.*, 2002), it is interesting to see if the Nike Maxsight™ contact lenses manipulate our colour perception when worn.

7.2 AIM

The aim of this study was to investigate the optical performance of the Nike Maxsight™ contact lenses with emphasis on visual acuity, contrast sensitivity under indoor photopic lighting within the optometric practice, and to investigate the effect of wearing the lenses on colour discrimination.

7.3 METHOD

7.3.1 Contact Lenses

The Nike Maxsight™ contact lenses were investigated alongside clear Optima 38 (Bausch and Lomb, Rochester, New York) contact lens as a control (Figure 7.3). The contact lens parameters are summarised in Table 7.1.

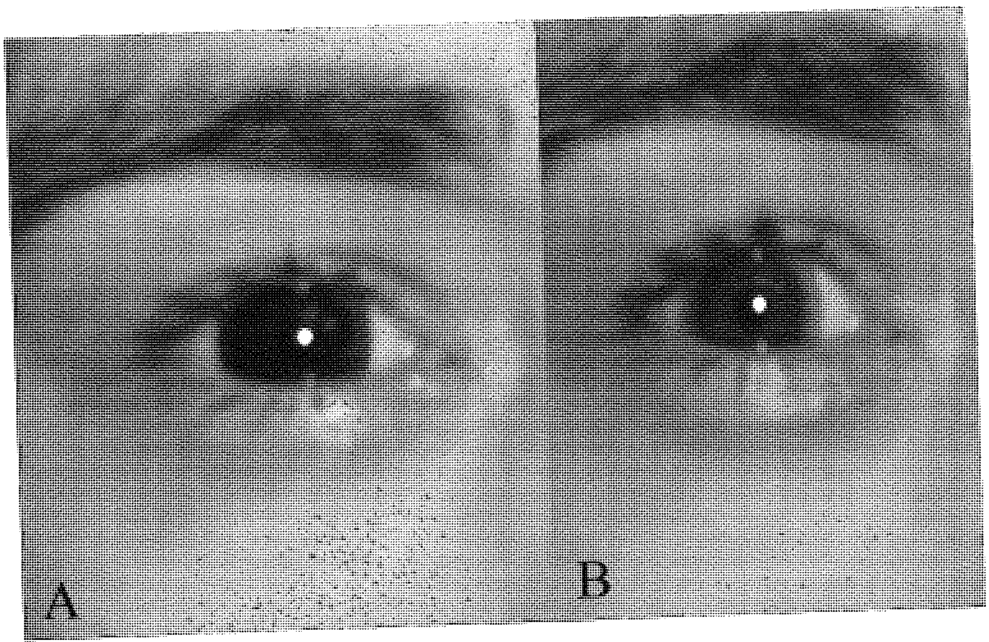

Figure 7.3
The Nike Maxsight™ contact lenses *in situ*. A: Grey-green; B: Amber

Material	Polymacon (Optima38)	Polymacon (Nike Maxsight™ Grey-Green)	Polymacon (Nike Maxsight™ Amber)
Oxygen permeability (Dk)	8.5	6.4	6.4
Water Content (%)	38	38.6	38.6
BOZR (mm)	8.7	8.7	8.7
Total Diameter (mm)	14	14.3	14.3
Light Transmittance	N/A	36%	50%
Modality (Disposable)	Conventional	Monthly	Monthly
Centre Thickness at -3.00D (mm)	0.06	0.06	0.06

Table 7.1
Contact lens materials and parameters as quoted at -3.00DS

7.3.2 Visual Acuity (VA) and Contrast Sensitivity (CS)

The Bailey-Lovie LogMAR visual acuity chart and Pelli-Robson charts were used to assess VA and CS (see section 4.3.1.5 in Chapter 4).

7.3.3 Colour Vision Test

The FM 100-Hue colour vision test is widely used for research purposes (Vingrys and King-Smith, 1988). The test detects chromatic discrimination anomalies and is often seen as the gold standard. It is viewed under a MacBeth daylight lamp (Newburgh, NY) which produces 200 lux on a black background. The test consists of 85 coloured caps which vary in hue. The subjects are asked to place the caps in colour order. The caps are numbered and produce an error score by which a colour vision defect can be determined. The cap numbers were analysed by a computer programme (Figure 7.4) and Vingrys' Analysis (Vingrys and King-Smith, 1988) produced a Total Error Score, C-Index, S-Index, and Vingrys Angle. The C-Index or confusion index is used to assess the severity of the colour defect. The S-Index is known as the scatter index which assesses the individuals' randomness, scatter, polarity or selectivity in the subject's placement of caps, and

Vingrys Angle is the primary axis of colour confusion (Vingrys and King-Smith, 1988).

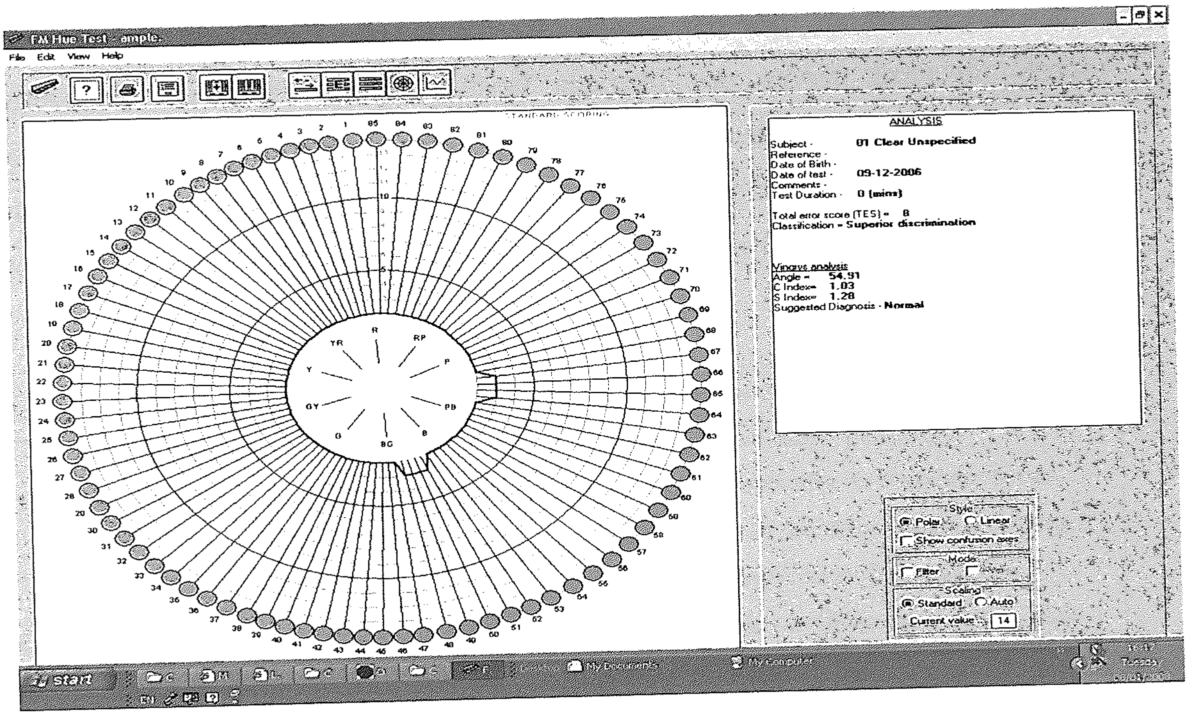

Figure 7.4
The recording sheet as produced by the computer program (Macbeth, FM Scoring software)

7.3.4 Subjects

Twenty four healthy subjects were assessed. Power statistics suggested that 90% power could be achieved with 22 subjects. The mean age was 28.2 ± 5.72 years with a 2:3 male to female ratio. All subjects were staff and students at Aston University, Birmingham, UK. Ethical approval was sought from the Aston University Ethics Committee. The subjects were given the option of withdrawing from the experiment in accordance with the Helsinki Declaration of 2000. The requirements for the subjects to enrol in the study were as follows (Table 7.2).

Inclusion Criteria	**Exclusion Criteria**
1. Good general health.	1. Known active ocular pathology.
2. Best corrected visual acuity of 6/6 or better.	2. Cataract or opacities on the ocular lenses.
3. No known cataract or opacities on the ocular lenses or other ocular problems.	3. Any history of problems with contact lens induced complications in the past.
4. Have had a recent sight test within the past 24 months. Subjects were aware that this examination did not replace the need for regular eye examinations and contact lens check.	4. Any systemic condition e.g. diabetes, high blood pressure.
5. Aged between 18 and 45 years (pre presbyopia).	5. Amblyopia.
6. Currently contact lens wearers with no history of contact lens complications.	6. Previous refractive surgery.
7. No known colour vision defect as screened by FM 100 hue colour vision test	7. Any colour vision defect.

Table 7.2
Inclusion and exclusion criterion used for the study

All subjects were interviewed with respect to their ability to adhere to the study protocol. The clinical procedures to be used in the study were also explained in detail prior to enrolment.

7.3.5 Experimental protocol

All subjects attended in the morning to minimise diurnal variations (between 10am-12pm). The subjects were previous soft contact lens wearers, but did not wear contact lenses for at least 48 hours prior to the experimental session. The subject's current contact lens Rx was used to select the contact lenses for this study (Note: Nike Maxsight™ contact lenses only come in one base curve and total diameter, so therefore for fair comparison with the clear optima lens, similar parameters were chosen to the Nike Maxsight™ contact lens). The subjects were adapted to the contact lenses for 20 minutes prior to measurements. The contact lenses were inserted and removed by the examiner. The sequence that the lenses were worn was randomised. Monocular visual acuity through the test contact lens was taken at a distance of 3 metres (right eye). Monocular contrast sensitivity acuity was taken through the test contact lens at a distance 1 meter (right eye). The FM-100 Hue colour vision test was assessed through the test contact lenses (subjects were shown how to use the test, but no retest or practice was applied as observers can improve with practice (Vingrys and King-Smith, 1988)).

7.4 RESULTS

The statistics were generated by SPSS version 15, Excel, and SigmaPlot 2000.

7.4.1 Visual Acuity

There was no statistically significant effect on visual acuity between all three lenses (Figure 7.5; ANOVA; $F = 0.02$; $p = 0.98$).

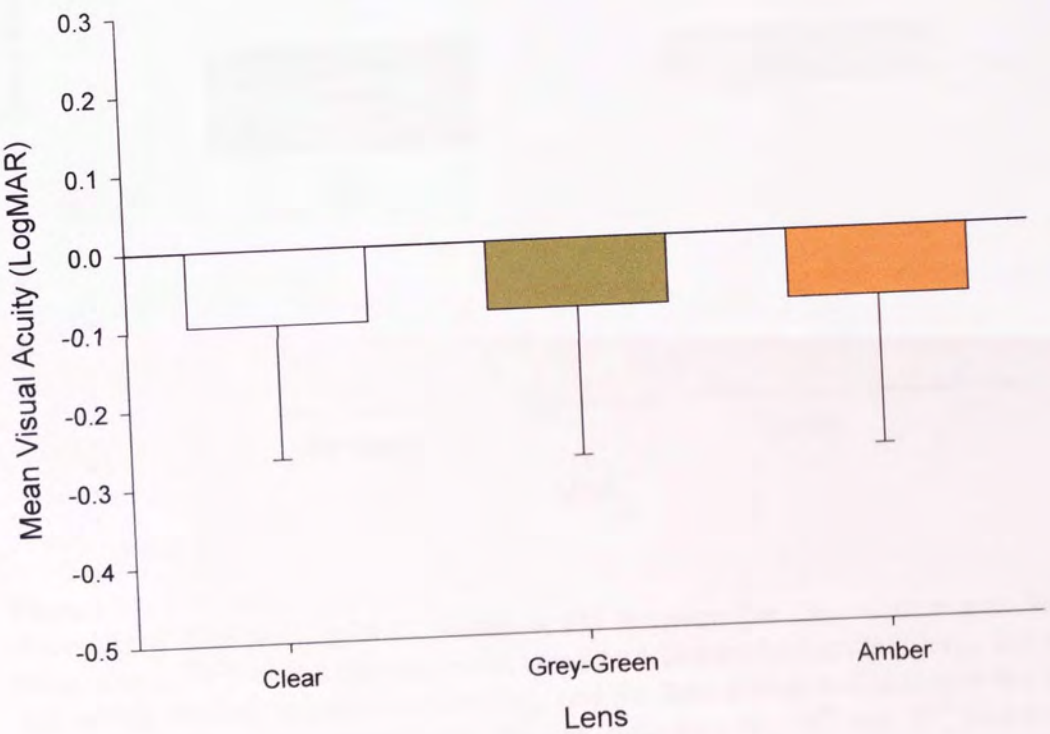

Figure 7.5
Mean visual acuity in LogMAR of the Clear, Grey-Green and Amber lenses. Error bars = 1 SD (n=24)

When the data was normalised by taking the clear lens into consideration (Optima 38), there was no statistically significant difference in LogMAR acuity between the Grey-Green and Amber Nike Maxsight™ contact lenses (Figure 7.6; T-Test; $p = 0.34$).

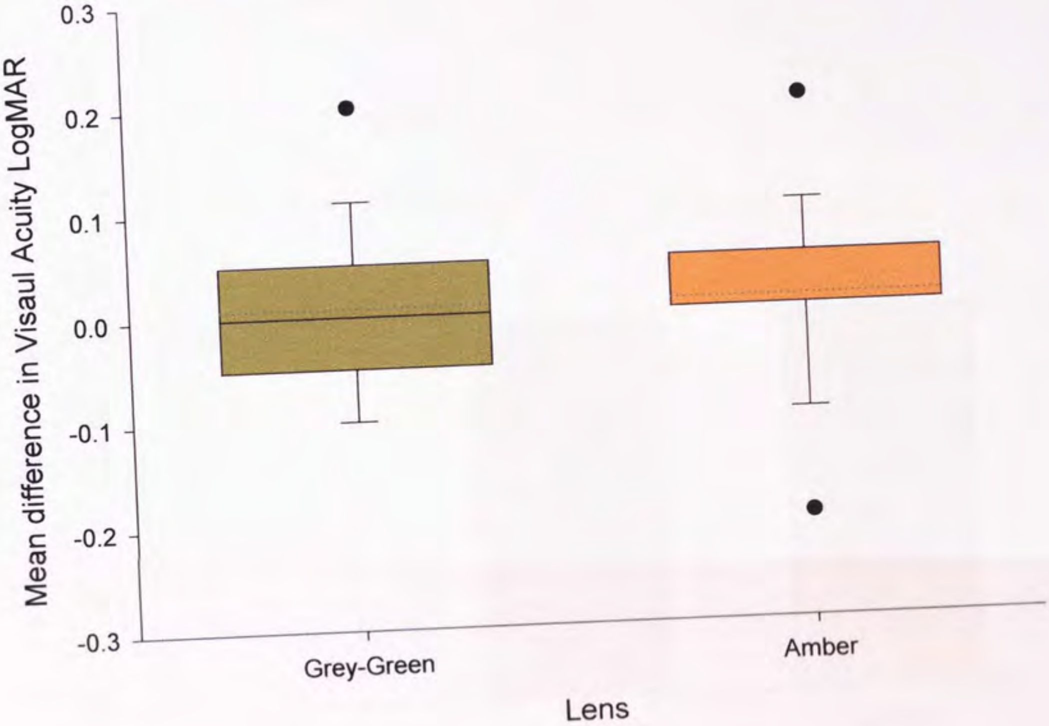

Figure 7.6
Normalised data for LogMAR visual acuity between the Grey-Green and Amber Nike Maxsight™ contact lenses when compared to the clear contact lens. The solid line within the box indicates the median, and the dotted blue line indicates the mean value. Error bars above and below the box indicates the 90th and 10th percentiles. Data points show outliers outside the 95% confidence interval (n=24)

7.4.2 Contrast Sensitivity

There was no statistically significant effect on contrast sensitivity between all three lenses (Figure 7.7 ; ANOVA; F = 1.08; p = 0.34).

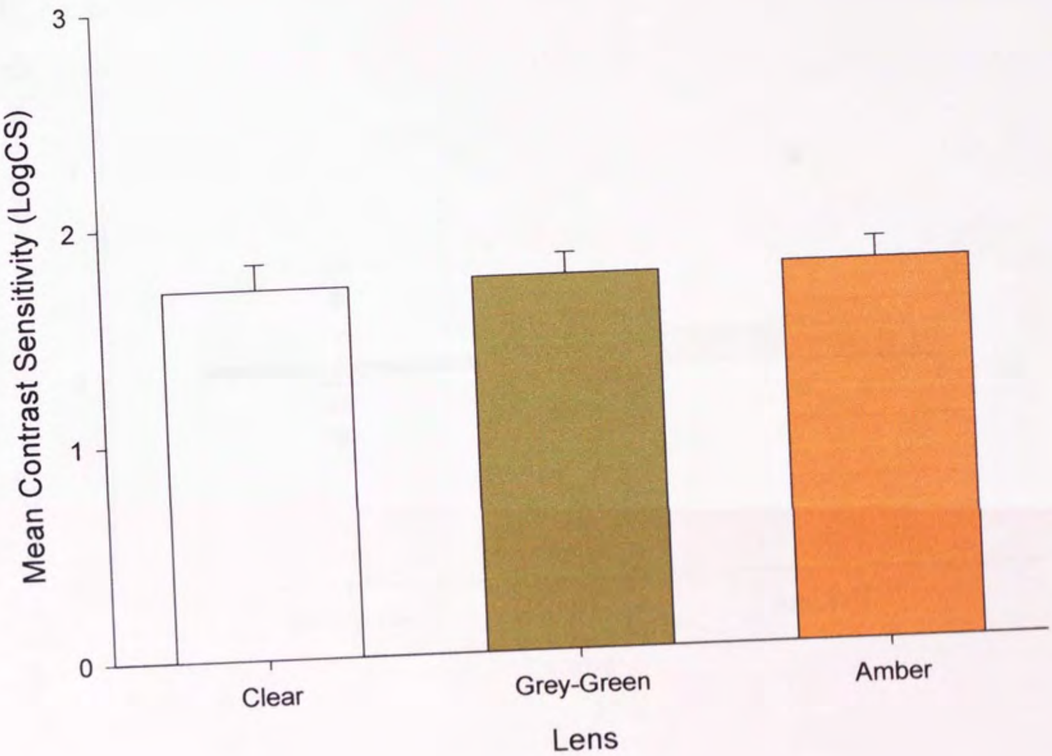

Figure 7.7
Mean contrast sensitivity in LogCS of the Clear, Grey-Green, and Amber contact lenses. Error bars = 1 SD (n=24)

When normalising the data by taking the clear lens into consideration (Optima 38), there was no statistically significant difference in LogCS acuity between the Grey-Green and Amber Nike Maxsight™ contact lenses (Figure 7.8; T-Test; p = 0.13).

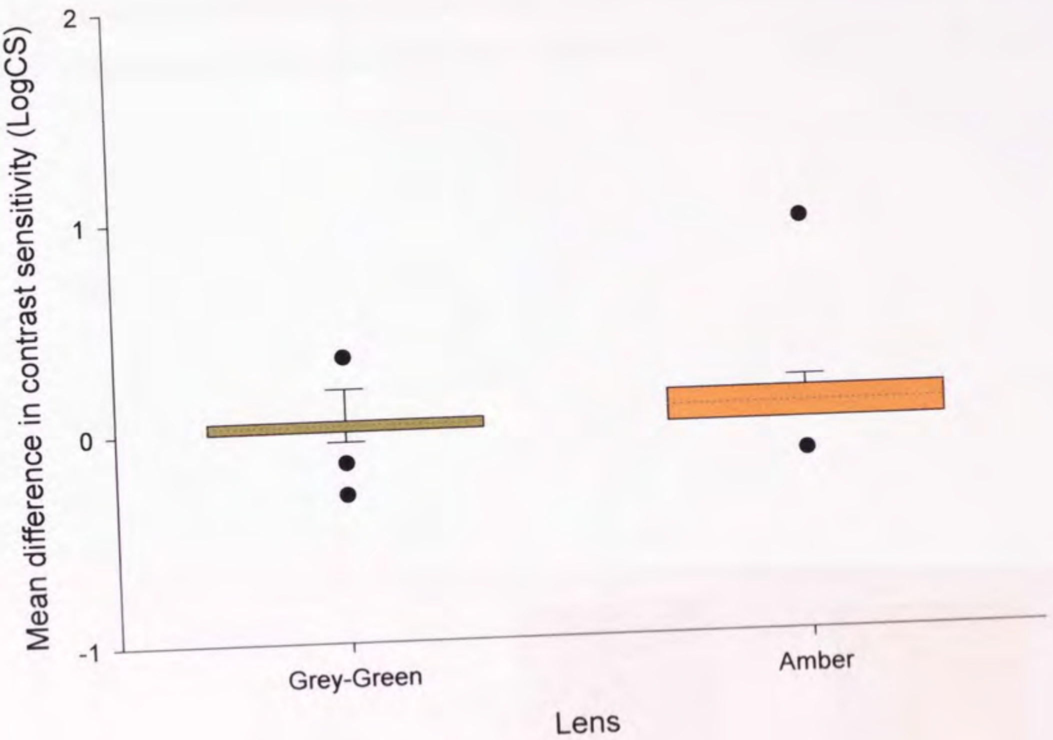

Figure 7.8
Normalised data for LogCS contrast sensitivity between the Grey-Green and Amber Nike Maxsight™ contact lenses when compared to the clear contact lens. The solid line within the box indicates the median, and the dotted blue line indicates the mean value. Error bars above and below the box indicates the 90th and 10th percentiles. Data points show outliers outside the 95% confidence interval (n=24)

7.4.3 Farnsworth-Munsell 100-Hue

There was a statistically significant difference in error scores between the three lenses (Figure 7.9; ANOVA; $F = 57.4$; $p < 0.001$). As within-subject ANOVA does not indicate differences between individual lens conditions, univariate ANOVA was conducted to identify differences between lens conditions (Scheffe). This showed that there was a statistically significant difference between the clear lens with the Grey-Green and Amber ($p = <0.0001$).

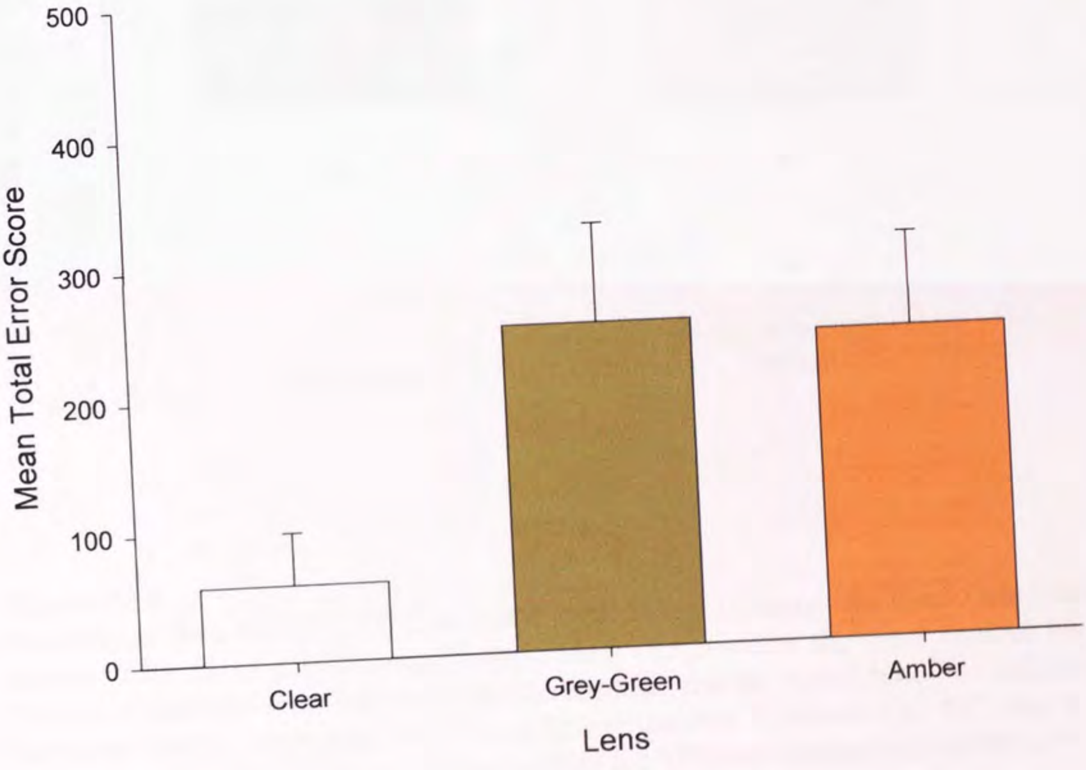

Figure 7.9
Mean FM 100-Hue Total Error scores of the Clear, Grey-Green, and Amber contact lenses. Error bars indicate ± SD (n=24)

When normalising the data by taking the clear lens into consideration (Optima 38), there was no statistically significant difference in error scores between the Grey-Green and Amber Nike Maxsight™ contact lenses (Figure 7.10; T-Test; $p = 0.20$).

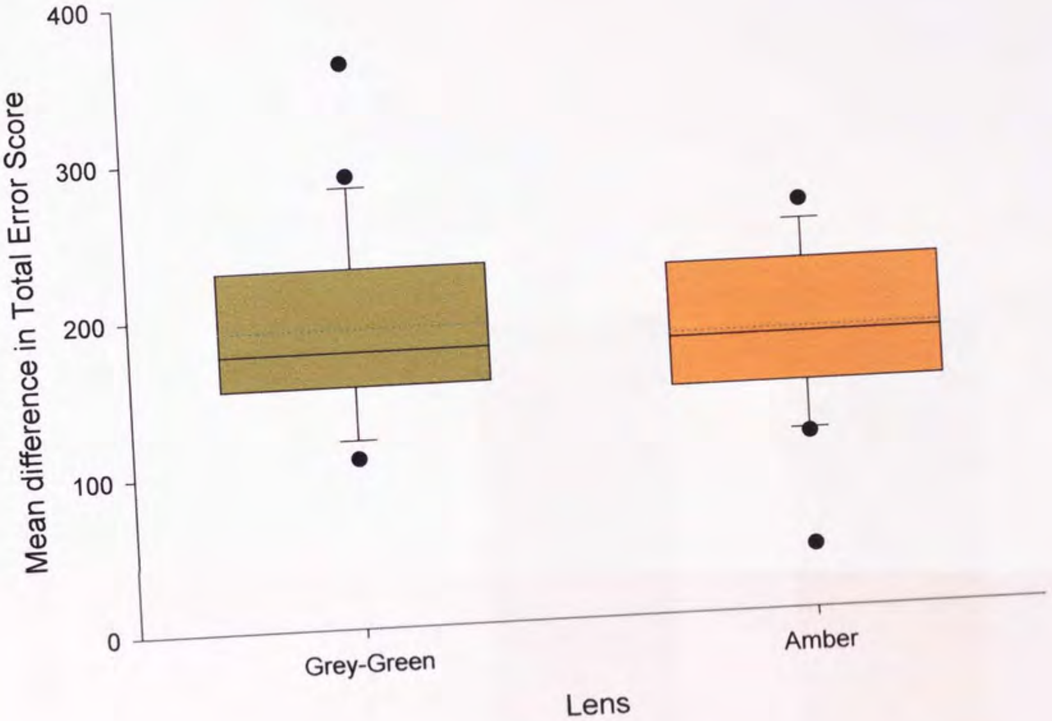

Figure 7.10
Normalised data for FM 100-Hue Total Error Score between the Grey-Green and Amber Nike Maxsight™ contact lenses when compared to the clear contact lens. The solid line within the box indicates the median, and the dotted blue line indicates the mean value. Error bars above and below the box indicates the 90th and 10th percentiles. Data points show outliers outside the 95% confidence interval (N=24)

There was a statistically significant difference in the mean C-Index result between the three lenses (Figure 7.11; ANOVA; F = 86.9; p <0.001). As within-subject ANOVA does not indicate differences between individual lens conditions, univariate ANOVA was conducted to identify differences between lens conditions (Scheffe). This showed that there was a statistically significant difference between the clear lens with the Grey-Green and Amber (p = <0.0001).

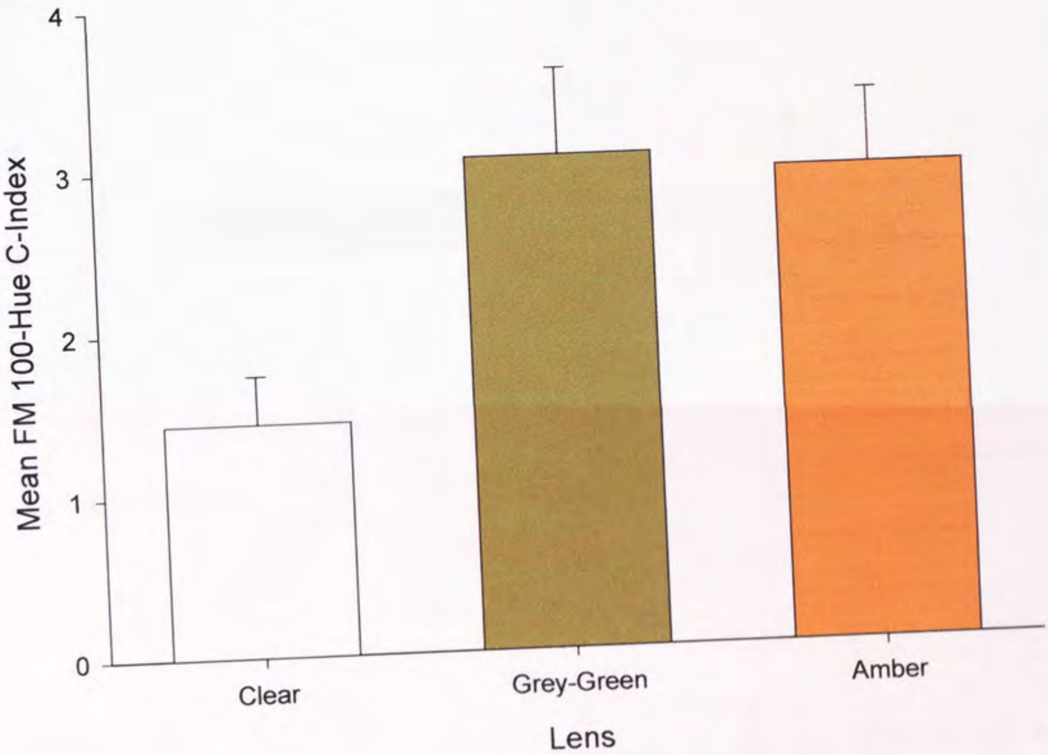

Figure 7.11
Mean FM 100-Hue C-Index of the Clear, Grey-Green, and Amber contact lenses.
Error bars = 1 SD (n=24)

When the data was normalised by taking the clear lens into consideration (Optima 38), there was no statistically significant difference in mean C-Index between the Grey-Green and Amber Nike Maxsight™ contact lenses (Figure 7.12; T-Test; p = 0.36).

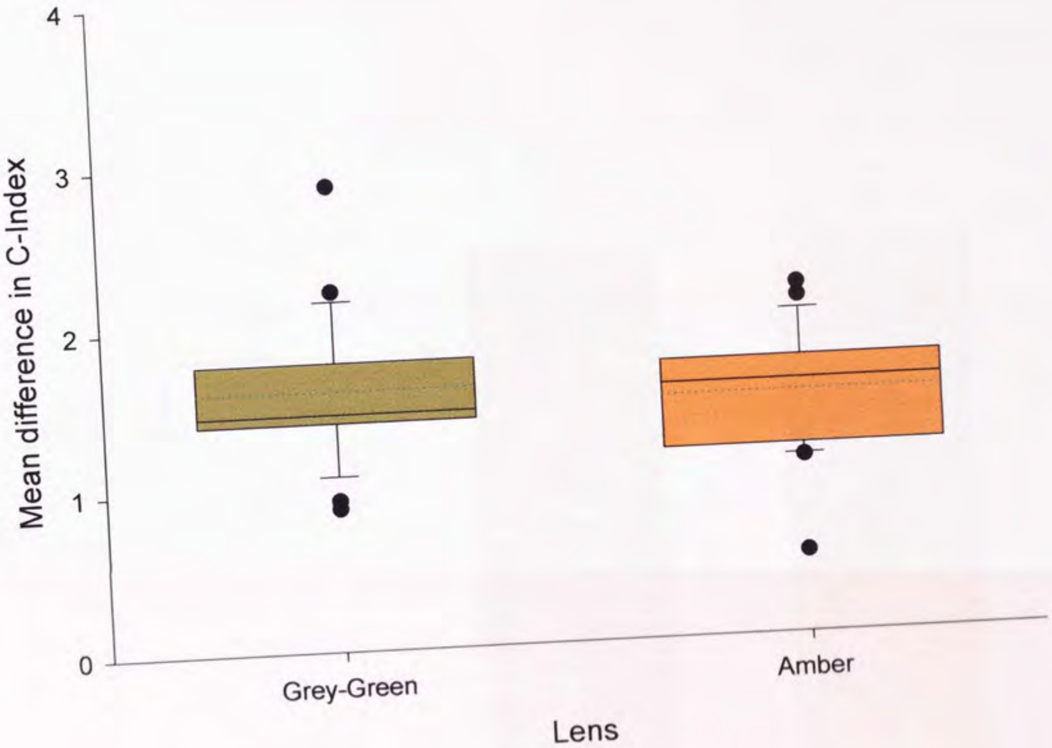

Figure 7.12
Normalised data for FM 100-Hue C-Index between the Grey-Green and Amber Nike Maxsight™ contact lenses when compared to the clear contact lens. The solid line within the box indicates the median, and the dotted blue line indicates the mean value. Error bars above and below the box indicates the 90th and 10th percentiles. Data points show outliers outside the 95% confidence interval (n=24)

There was a statistically significant difference in the mean S-Index result between the three lenses (Figure 7.13; ANOVA; $F = 18.8$; $p < 0.001$). As within-subject ANOVA does not indicate differences between individual lens conditions, univariate ANOVA was conducted to identify differences between lens conditions (Scheffe). This showed that there was a statistically significant difference between the clear lens with the Grey-Green and Amber ($p = <0.0001$).

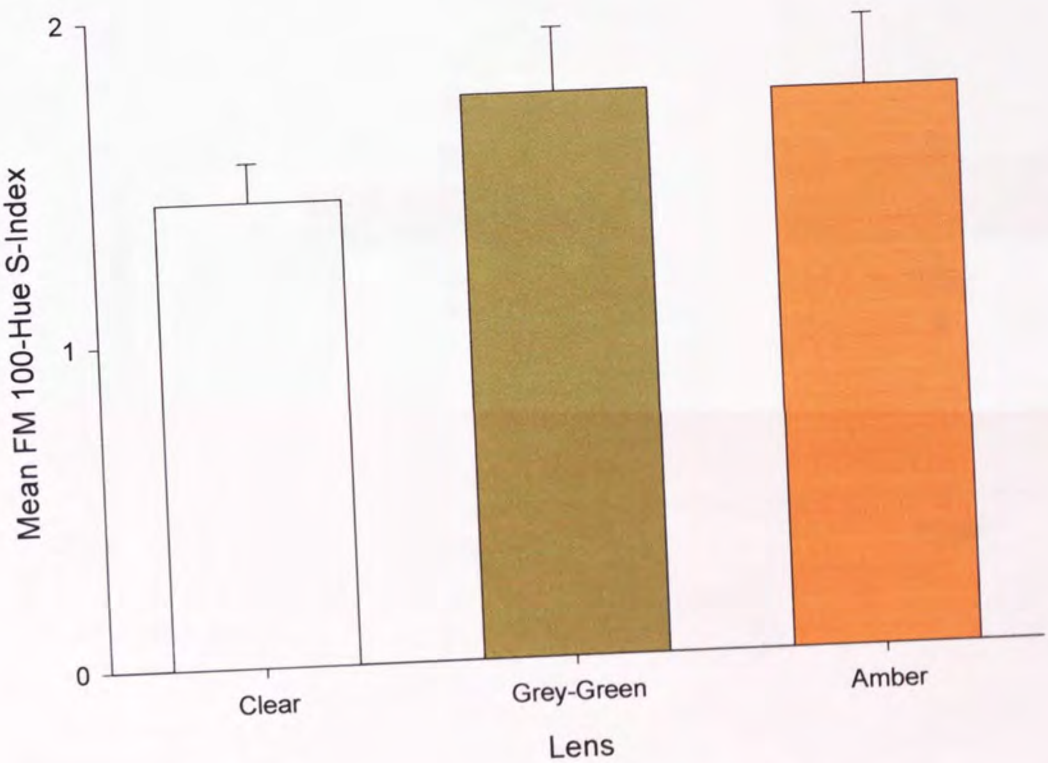

Figure 7.13
Mean FM 100-Hue S-Index of the Clear, Grey-Green, and Amber contact lenses.
Error bars = 1 SD (n=24)

When the data was normalised by taking the clear lens into consideration (Optima 38), there was no statistically significant difference in mean S-Index between the Grey-Green and Amber Nike Maxsight™ contact lenses (Figure 7.14; T-Test; $p = 0.82$).

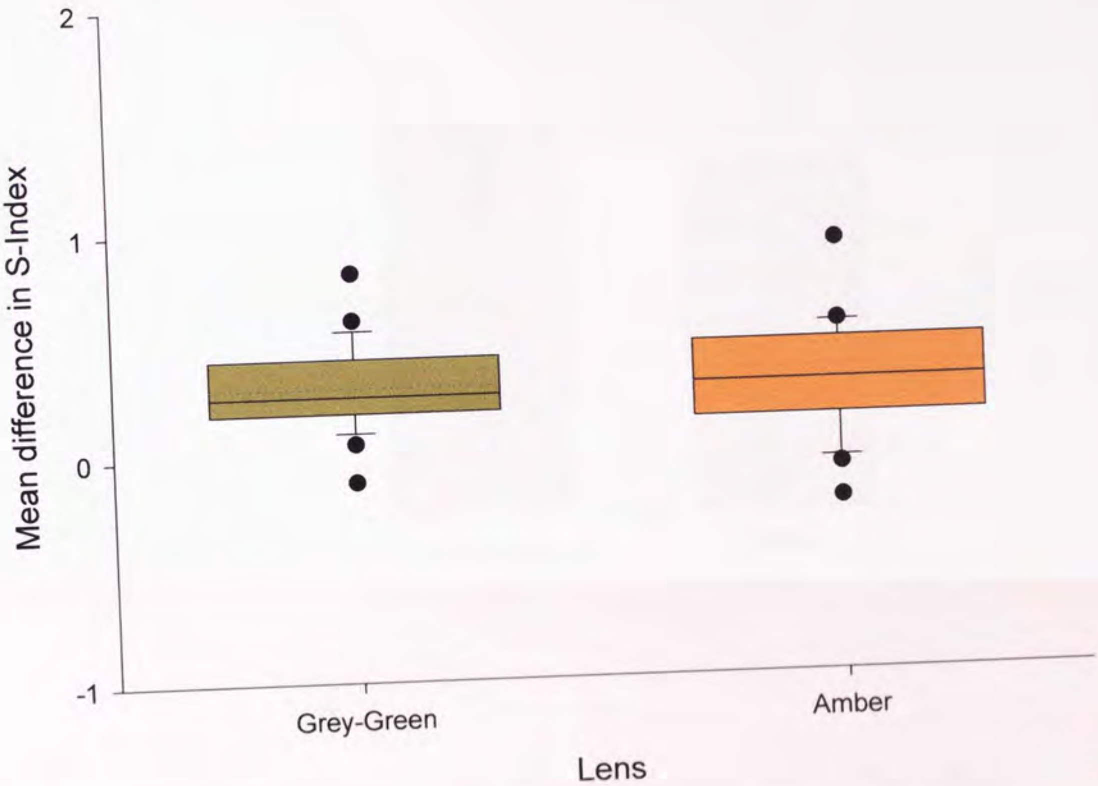

Figure 7.14
Normalised data for FM 100-Hue S-Index between the Grey-Green and Amber Nike Maxsight™ contact lenses when compared to the clear contact lens. The solid line within the box indicates the median, and the dotted blue line indicates the mean value. Error bars above and below the box indicates the 90th and 10th percentiles. Data points show outliers outside the 95% confidence interval (n=24)

There was no statistically significant effect on Vingrys' angle between all three lenses (Figure 7.15; ANOVA; F= 0.79 p = 0.46).

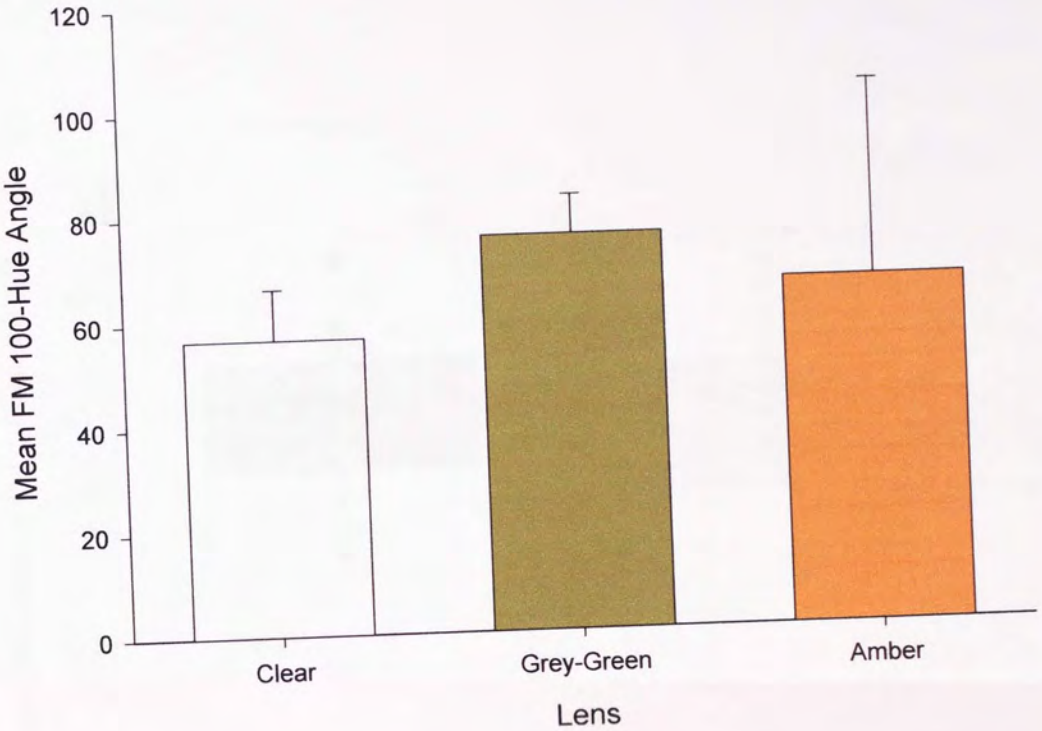

Figure 7.15
Mean FM 100-Hue Vingrys' Angle of the Clear, Grey-Green, and Amber contact lenses. Error bars = SD (n=24)

When the data was normalised by taking the clear lens into consideration (Optima 38), there was no statistically significant difference in mean Vingrys' Angle between the Grey-Green and Amber Nike Maxsight™ contact lenses (Figure 7.16; T-Test; $p = 0.95$).

Figure 7.16
Normalised data for FM 100-Hue Vingrys' Angle between the Grey-Green and Amber Nike Maxsight™ contact lenses when compared to the clear contact lens. The solid line within the box indicates the median, and the dotted blue line indicates the mean value. Error bars above and below the box indicates the 90th and 10th percentiles. Data points show outliers outside the 95% confidence interval (n=24).

7.5 DISCUSION

It should be noted that the Nike Maxsight™ Grey-Green and Amber contact lenses contain tints that are for use for outdoor photopic conditions when playing sports. They are not intended for indoor lighting conditions.

It would appear from the study that LogMAR Visual Acuity was unaffected by the Nike Maxsight™ Grey-Green and Amber contact lens when compared to the clear control contact lens, when examining under artificial lighting (85 cd m^2).

Contrast sensitivity testing had been used in many studies to evaluate the performance of contact lenses (Bernstein and Brodrick, 1981; Cox and Holden, 1990; Kirkpatrick and Roggenkamp, 1985; Tomlinson and Mann, 1985; Wachler *et al.*, 1999) and is extremely important in sports as only a small number of sports involve high contrast targets and backgrounds (Berman, 1993). Contrast sensitivity testing has also been proved to be important in athletes wearing contact lenses since it has been shown that high contrast acuity charts may not detect sub-optimal lens performance, whereas contrast sensitivity measures are more sensitive (Grey, 1986; Nowozyckyj *et al.,* 1988; Oxenberg *et al*., 1989). Contrast sensitivity of subjects wearing the Nike Maxsight™ lens measured with a Pelli-Robson Chart under recommended testing condition within the optometric testing room was not significantly affected when compared to a clear control contact lens.

The study confirms that the Nike Maxsight™ does not affect visual acuity under artificial lighting conditions and has little effect on contrast sensitivity. The unimproved contrast sensitivity may be because indoor lighting tends to emit more blue light than photopic outdoor lighting (Purcell, 2007), thus the Nike Maxsight™ lenses would block more of the light indoors. Due to this finding it is important to remember that when evaluating the effect of contrast sensitivity of such contact lenses in the optometric examination room, the contrast sensitivity benefits of coloured contact lenses cannot be measured under clinical conditions. However, when subjects (n=5) wore the Nike Maxsight™ contact lenses outdoors in daylight conditions they anecdotally reported an improvement on glare and comfort compared to a clear lens, however this was not measured subjectively or objectively. Therefore, it would be useful to measure visual acuity and contrast sensitivity under glare conditions in future studies.

The lack of improvement in contrast sensitivity in this study may have been a result of the choice of contrast sensitivity testing apparatus. Zigman (1992) demonstrated an improvement of contrast sensitivity at high spatial frequencies with the SeeMore yellow filter with the VisTech contrast sensitivity chart. However, the Pelli-Robson chart only measures contrast sensitivity at one spatial frequency, but this chart was chosen as this has been used extensively in clinical research and clinical practice and is available in most optometric practices.

The Farnsworth-Munsell 100-Hue test demonstrated that colour discrimination was affected by the use of the Nike Maxsight™ Grey-Green and Amber tinted lenses. Although there was no difference seen in Error Scores between the Nike Maxsight™ lenses, there was a significant difference when compared to the control clear lens, indicating poor colour discrimination. This was also true for the C-Index (Severity of colour confusion) and S-Index (Scatter index). Interestingly the mean Vingrys Angle (primary axis of colour confusion) was not significantly affected in the Nike Maxsight™ contact lenses although there was a high standard deviation (Grey-Green +66.80 ± 36.86, Amber +66.99 ± 36.55) compared to the control (clear +57.17 ± 9.81). Only three subjects were diagnosed as having a tritan colour defect with both Amber and Grey-Green Nike Maxsight™ compared to clear contact lenses; suggesting there is only a weak association with previous research indicating that colour normal subjects wearing blue blocker lenses (orange tint absorbing wavelengths shorter than 525nm) demonstrate a tritan colour defect (Aarnisalo, 1987; De Fez *et al*., 2002; Hovis *et al*., 1989). Nevertheless, an article by Boyer *et al*. (2005) draws to the readers attention that the colour of sports equipment can be chosen as to avoid colour confusion in colour defect individual, however a case report by Harris and Cole (2005) illustrated that abnormal colour vision can be a modest disadvantage when playing cricket as some find it difficult seeing the red ball on the green grass background.

7.6 CONCLUSION

Any visual benefits of the Nike Maxsight™ contact lenses were not seen when measuring the visual performance within an optometric consulting room. However, colour discrimination effects are measurable in these conditions. Further work evaluating the lens in outdoor conditions may be warranted, although the environment is far less controllable.

CHAPTER 8

SUMMARY AND CONCLUSIONS

8.1 SUMMARY

Sport is regarded as one of the largest industries world wide. The use of contact lenses has been suggested as the most appropriate form of refractive correction when participating in sport or exercise, due to the inconvenience spectacles may create when participating in such an activity and due to contact lenses flexibility and non-permanence.

In this thesis, it has been demonstrated that eye care practitioners believe that sport is a principal reason why patients choose contact lenses. Although many modalities of contact lenses are currently available, daily disposable are the most common first choice lens to be fitted for sports; this may be due to the convenience that these lenses have over other modalities. It was established that optometric practitioners are still unsure whether it is safe to fit contact lenses for swimming, probably due to the potential risk of microbial keratitis that is associated with swimming pools.

Since sport is a primary reason for contact lens wear, it was not surprising to find that significantly more patients choose to wear their contact lenses over spectacles when participating in such activities. This reason clearly highlights the benefits that contact lenses exert over spectacles. This thesis demonstrated that under half of opticians are not asking their patients if they participate in sporting activity during routine questioning. In addition, this thesis has demonstrated that half of patients that wear contact lenses for swimming do so without goggles. It seems that patients are unsure of the importance of correct procedures with regards safe contact lens wear during sports, highlighting the importance for the need for practitioner training in this area. Hence, a poster for contact lens practice was developed to emphasise the importance of safety considerations when wearing contact lenses for sport, to both the practitioner and the patient.

Hitherto, the effect of exercise on the cornea when wearing contact lenses has not been investigated fully. Visual acuity and contrast sensitivity were not found to be significantly affected by 30 minutes of cycling. Ocular Surface Temperature (OST) increase during controlled exercise when wearing a Silicone Hydrogel (SiH; Lotrafilcon) contact lens compared to a reduction in OST seen with the HEMA contact lenses (Polymacon and Nelfilcon). It is essential, therefore, to study further the effect of corneal physiology and contact lens wear regarding other forms of exercise. This will allow a more in-depth understanding of best practice when prescribing contact lenses for a variety of sports.

It was established that the corneal volume when wearing SiH contact lens decreases post exercise, perhaps due to dehydration of the cornea or reduction of the tear film thickness. This reduction in corneal volume was not evident with HEMA contact lenses, although the corneal volume had decreased compared to rest, suggesting that corneal swelling may have masked a dehydration effect.

The effect of contact lenses on restricting oxygen supply to the cornea is not fully understood and the literature details many previous techniques with varying limitations. In this thesis, corneal oxygen demand was measured using a novel non-contact method of dynamic quenching of luminescence, and a protocol for using such a devise was established. The new non-contact technique highlighted beneficial outcomes over the previous methods of measuring such a parameter, and demonstrated the difference in goggle oxygen depletion with the SiH lens compared to the no lens condition and a HEMA lens. The data showed an increase in goggle oxygen depletion (although not significant) which may support the theory that these contact lenses exhibit a temporary oxygen reservoir (Florkey *et al.*, 2003). The bespoke devise showed good within-visit repeatability and demonstrated a statistical difference between the closed-eye and open-eye condition. It allowed the measurement of contact lenses *in vivo* without interference, such as the applanation of a probe as demonstrated in the polarographic technique. Further studies will examine the difference between more types of contact lenses and the normal variation in corneal oxygen demand with a larger sample size and with patient demographics such as age and gender. Furthermore, measurements with this technique will be taken after the contact lens has been *in situ* for a longer period of time to investigate if the corneal oxygen demand further changes.

During exercise, the body utilises more oxygen than at rest, the hypothesis whether the cornea does the same was investigated by measuring the oxygen depletion with the newly developed technique (dynamic quenching of luminescence). The oxygen depletion rate was increased during a period of controlled exercise, with and without contact lenses. As with the open-eye (no lens), corneal oxygen consumption increased during exercise with a SiH contact lens and a HEMA contact lenses *in situ*. Goggle oxygen depletion rate was lower when wearing SiH (Balafilcon) contact lenses compared to HEMA contact lenses at 10 minutes during the exercise period. This may support suggestions that SiH contact lenses may operate as an oxygen reservoir thus initially providing the cornea with the required oxygen demand during exercise (Florkey *et al.*, 2003).

Finally, the thesis examined new commercially available contact lenses marketed for enhancing sport performance. The Nike Maxsight™ Amber and Grey-Green contact lenses contain tints that are designed for outdoor photopic conditions when playing sports; they are not intended for indoor-lighting conditions. This was apparent as both visual acuity and contrast sensitivity were unaffected for both lenses when examined in the ophthalmic testing room (85 cd m^2), highlighting the difficulty of demonstrating an advantage to these lenses in the optometric examination room due to the low transmittance of the tints. However, it was possible to demonstrate that colour discrimination was affected by the use of the Nike Maxsight™ Amber and Grey-Green tinted lenses in the clinical environment and that this could enhance image contract in certain circumstances.

8.2 CONCLUSION AND CLINICAL IMPLICATIONS

In conclusion, this thesis has highlighted the usage of contact lenses in sport, and illustrated the need for more education on the use of contact lenses in sport for both the optometric practitioner and patient. Due to these concerns an educational poster was established to illustrate safe use of contact lenses during sport prescribing and the implications of swimming whilst wearing contact lenses.

As it has been highlighted that there is a need to implement further education on the use of contact lenses in sport, it is imperative to assess further the patients experience regarding advice given by their optometric practitioner once a series of CET article on such training has been printed. This seems an effective way of educating the optical practitioner as CET is now compulsory within the UK for the optometrist, and the contact lens optician to continue contact lens practice.

The thesis has identified limitations of current techniques for measuring corneal oxygen consumptions and shown the ability to measure oxygen uptake from the cornea with and without contact lenses by use of a novel non-contact method using the dynamic quenching of luminescence principle. However, it is important to still ascertain the range of corneal oxygen consumption to establish those individuals that require the highest corneal oxygen uptake rather than just the average. This new technique may revolutionise how we currently measure corneal oxygen uptake with and without contact lenses, allowing real time measurements with minimal interference.

Although the differences in oxygen consumption between contact lenses was not statistically significant, a difference in rate was clearly evident, suggesting that it would be essential to test this new technique on a larger cohort. It would be interesting to develop the oxygen technique still further, for example using the dynamic quenching of luminescence method inside of a vaulted scleral contact lens to measure the depletion on the bare cornea. This technique has demonstrated a whole new approach to measuring corneal oxygen with and without contact lenses *in vivo*.

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APPENDIX

PAR-Q QUESTIONNAIRE

SUPPORTING PUBLICATIONS

APPENDIX TABLE 1: Corneal Volume

APPENDIX TABLE 2: Corneal Area

APPENDIX TABLE 3: Goggle Volume

Supporting Publications:

Cardall M, Naroo SA, Wolffsohn JS (2007). Developing a novel non-contact method of measuring direct oxygen consumption by the cornea. CLAE **30** (5): 308.

Cardall M, Naroo SA, Wolffsohn JS (2006). Prescribing trends for Contact Lenses in Sport. CLAE **29** (4): 208

Cardall M (2006). Contact Lenses in Sport: A general overview. Optician **231**: 22-26

Cardall M, Anguige N, Naroo SA, Wolffsohn JS (2007). Contact lens fitting trends in sport: Part 1: The patient's experience. Optometry Today **47** (19): 40-43

Cardall M, Naroo SA, Wolffsohn JS (2008). Corneal oxygen consumption measured by a novel non-contact method, **DALLOS AWARD 2008,** Presented at the BCLA 2008 in Birmingham, UK

PAR-Q Physical Activity Readiness Questionnaire

Please answer the following questions
(Indicate correct answer with a cross)

	Yes	No	
1:	☐	☐	Has your doctor ever said you have heart trouble?
2:	☐	☐	Do you frequently have pains in your heart or chest?
3:	☐	☐	Do you often feel faint or have spells of severe dizziness?
4:	☐	☐	Has a doctor ever said your blood pressure was too high?
5:	☐	☐	Has your doctor ever said you have bone or joint problems such as arthritis that gas been aggravated by exercise, or might be worse?
6:	☐	☐	Is there a good physical reason not mentioned here why you should not follow an activity program even if you wanted too?
7:	☐	☐	Are you over 65 and not accustomed to vigorous exercise?

If you answered YES to one or more questions...
If you have not recently done so, consult with your personal doctor by telephone or in person before increasing your physical activity and/or taking a fitness test.

If you answered NO to all questions...
If you answered PAR-Q accurately, you have reasonable assurance of your present suitability for exercise.

Signed (Volunteer)..

DATE..

Adapted from: http://www.phac-aspc.gc.ca

Developing a novel non-contact method of measuring direct oxygen consumption by the cornea

CLAE (2007) **30** (5): 308

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Purpose: The physiological integrity of the cornea is dependant on the amount of oxygen available to its surfaces. Contact lens wear disrupts the diffusion of oxygen to the cornea. Prior techniques to measure the oxygen consumption of the cornea were invasive, assessed only part of the cornea and often involved anaesthesia. The aim of this study was to design and test a novel non-contact method of measuring oxygen consumption of the cornea.

Method: An oxygen sensitive material was mounted within an air-sealed goggle positioned over one eye of 10 subjects (mean age 29.1 ± 4.7 years, 2:1 male/female). The materials luminescence was assessed in real-time using a fibre optic and a temperature probe inside the goggle was monitored for compensation of the oxygen output reading. One minute assessments of the rate of oxygen depletion within the goggle were made in open-eye and closed-eye conditions, along with open-eye conditions with the subject fitted with Polymacon and balafilcon soft contact lens. The order of the conditions was randomized and each was repeated three times.

Results: There was a significant uptake of oxygen over the 1 minute assessment period ($F=73.2$, $p<0.001$). There was a significant difference between the four conditions ($F=18.6$, $p<0.001$), with the closed-eye unable to use as much oxygen as the open-eye. There was no significant difference between the open-eye oxygen uptake and the uptake with a contact lens fitted, but the eye was unable to use as much oxygen when wearing the Polymacon compared to the balafilcon material contact lens ($p=0.02$).

Conclusion: The technique was able to measure oxygen depletion of the whole cornea without the need for corneal contact or topical anaesthetic. The technique was also able to differentiate between open and closed eye conditions and contact lens materials.

Talk presented at the British Contact Lens Association Annual Conference, Manchester, UK, May 2007

Prescribing trends for Contact Lenses in Sport

CLAE (2006) **29** (4): 208

Martin Cardall, Shehzad A. Naroo, James S. Wolffsohn.
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Purpose: The purpose of this study was to investigate the prescribing trend of contact lenses for a variety of sporting activities.
Method: A one page questionnaire was distributed among optometrists at non contact lenses Continuing Education Training (CET) meetings in 2005.
Results: Over 50% of first choice lenses for sporting activities are daily disposables. More than 75% of practitioners indicated sports, inconvenient to spectacles and cosmetic reasons as the three main reasons for patient wanting contact lenses. 91% of optometrists fit contact lenses. The average number of years optometrists are in practice who fit contact lenses was 13.27±11.08 compared to 21.94±8.15 years that do not fit contact lenses. 33.3 % (n=90) of optometrists who fit contact lenses do not recommend them for swimming, as opposed to only 25% of optometrists (n=20) who have an avid interest in sports vision.
Conclusion: Sports is a primary reason that optometrists believe patients require contact lenses. Daily disposable contact lenses seem to be the most popular first choice lens for all sports highlighted in this study. The reason for this may be due to the modality choice has the advantage of elimination of lens surface deposits and lens ageing and disposability. The other benefit especially for sports are that they require no care system thus the athlete can insert and remove lenses almost anywhere, and spare sets can be carried with them at little cost. The study was limited by the small sample size, thus more investigation is need to validate these preliminary results, nevertheless this study highlights interesting findings for contact lens prescribing and the athlete.

Poster presented at the British Contact Lens Association Annual Conference, Birmingham, UK, June 2006

Contact lenses in sport
A general overview

Martin Cardall gives an overview of the use of contact lenses in sport and provides details of their role in a variety of specific sporting environments (CET Module C2970)

THE SPORTS INDUSTRY is considered as the second largest industry worldwide[1] and, although figures vary according to Leisure Database (the online database company) an estimated 9.9 per cent of the total population were members of a gym in 2003, a rise of 1 per cent compared to 2001.[2] However, in general, participation in a sport, game or physical activity decreases with age.[3] In the UK there are over 12,000 opticians (ophthalmic and dispensing) who can potentially serve the sports vision market.[1]

The literature indicates that optimal visual correction can enhance sporting performance.[4] There are many ways to correct vision – spectacles, contact lenses and refractive surgery.[5] Although spectacles have stability of vision, for some people they may present an inconvenience for sporting and leisure pursuits[6] (Table 1). Contact lenses seem to be a useful alternative for vision correction for sporting activities.[7]

The first documented use of contact lenses for sporting activities was with moulded polymethyl methacrylate (PMMA) 'hard' scleral lenses following the introduction of plastics in the 1930s.[8] The introduction of the soft contact lens in the early 1970s was a great move forward for athletes.

With the vast array of contact lenses on the market today, they seem to be the ideal visual correction for most people involved in sports.[9] This has led to many practitioners prescribing contact lenses specifically for sports. With an increasing number of people participating in exercise, contact lenses are not just useful for elite athletes, but also for the recreational participant. Thus sports participation by the ametropic athlete has successfully been revolutionised by the use of contact lenses.[10,11]

Recent research by Naroo *et al*[5] established that over a quarter of patients who chose contact lenses reported sports as a primary motivating factor. Bowden and Harknett[12] showed that 45 per cent of female and 65 per cent of male patients participated in sports, of which over 94 per cent wore their contact lenses for sports.

Nike MaxSight sports tinted contact lenses aim to filter selected wavelengths

EXERCISE AND THE EYE

The metabolic demands of muscle tissue are increased during exercise and this is accompanied by a number of respiratory and cardiovascular adjustments. There are two main primary responses that have been reported in the literature to occur in the eye as a result of exercise.[13] These are a decrease in intraocular pressure (IOP) and alteration to ocular blood flow.[14-18]

The reduction in IOP during exercise has been demonstrated in a number of studies.[14-18] Regular aerobic exercise has been associated with a reduction in IOP. It has been suggested that this may represent an effective non-pharmacological intervention for patients suspected of having glaucoma.[18]

The presence of an effective compensatory auto-regulatory system for retinal circulation, in connection with an increase in ocular perfusion pressure induced by exercise, was confirmed in a study by Németh *et al* in 2002.[19] There seems to be a lack of studies looking at the oxygen uptake of the eye during exercise, but a paper by Bomholt and Schnell[20] stated that higher levels of oxygen are required during exercise, an increase in lactic acid and decreased levels of glucose in the blood vessels and in the anterior chamber of the eye in turn leads to corneal oedema.

CLs AND TYPES OF SPORT

Many factors influence the type of contact lens that may be chosen for a given sport. RGP contact lenses, for example, are contraindicated in contact sports. With the immense selection of contact lenses on the market today, cautious consideration is needed when fitting the athlete.

Swimming and water sports

There are approximately 10 million people who participate in swimming in the UK and it is regarded as one of the most popular recreational activities.[1]

Generally, contact lens manufacturers do not recommend contact lens wear for water sports.[5] Chlorine and other pool contaminants may remain in the contact lens and cause complications, including keratitis[7] and there is also the risk of losing a lens in the swimming pool.

Acanthamoeba infections have also been associated with swimming.[21,22] Contact lens wear is well established as a risk factor for bacterial keratitis.[23] The evidence of amoeba isolation from swimming pool

251

water is supported by research carried out in Poland by Górnik and Kuzna-Grygiel,[24] who concluded that the risk of contacting virulent strains of free-living amoebae by humans is higher in the open-air bathing pools compared to indoor swimming pools.

A study conducted by Vesaluoma *et al*[22] on the microbiological quality in Finnish public swimming pools demonstrated that there is a theoretical risk of amoebic and bacterial keratitis associated with swimming. A study investigating whether hydrophilic contact lenses worn while swimming accumulate bacteria present in water was carried out by Choo *et al*.[25] They reported that swimming increased micro-organisms present on the contact lenses.

A multicentre survey carried out in England between 1992-1996[26] investigating *Acanthamoeba* keratitis concluded that 91 per cent of the soft contact lens wearers who presented with *Acanthamoeba* keratitis could have prevented the risk of the disease by effective disinfection and/or refraining from swimming while wearing lenses. Swimming, therefore, is still considered a contraindication to soft contact lens wear.[27]

One may wonder why swimmers need sharp acuity. Spinnell[4] suggests that, although it may seem unnecessary for swimmers to have sharp acuity to actually swim, during high speed turns knowing exactly when to begin the turn can save fractions of seconds that can be a margin for victory.

In addition, the ability to recognise faces or to track your child in a busy swimming pool are important social and safety aspects to be considered.

Quevedo *et al*[28] demonstrated that swimmers presented with a statistically significant reduction in tear film quality and quantity after aerobic training in an indoor swimming pool. The swimmers constantly wore protective goggles. They indicate the reduction in tear volume may have been due to body dehydration.

Salt water and chlorine can impair the adhesion properties of soft contact lenses.[29] In a hypotonic environment, soft contact lenses can flatten and enlarge,[30] whereas in the hypertonic environment lenses are more likely to tighten.[6] However, it has been shown in both environments soft contact lenses are more likely to adhere.[5]

Further to this, the International Association of Contact Lens Educators (IACLE) advises rinsing the eyes with sterile water or saline immediately after leaving the water after water sports and then waiting 20-30 minutes before removing the lenses.[6] Whether the practitioner decides to fit contact lenses for water sports or not they should always consider the use of goggles for all water activities.[4]

The literature is very contradictory at present and it is evident that there is not enough research in this area and more investigation is needed in evaluating the effect of swimming while wearing contact lenses.

Due to the risks associated with contact lens wear and swimming, a safer way of correcting the ametropic swimmer is by the use of prescription swimming goggles. A survey published by Loran[1] in 2003, demonstrated that 76 per cent of practitioners stocked such an optical appliance.

Track athletes

Running is a dynamic sport that utilises a great amount of body movement and energy. During this sport an increase in lactic acid and a lack of glucose can develop, causing corneal oedema, regardless of the running distance: short, medium or long.[20]

Quevedo *et al*[28] demonstrated that the quality and quantity of the tear film in track athletes showed no significant difference before and after training. They were surprised with the result as track athletes are exposed to many environmental factors – such as changes in air velocity and temperature – but this study only examined a small number of athletes which may have affected their results and conclusion.

Owing to running being a dynamic sport, IACLE[5] recommends that contact lenses require extra stability on the eye, thus giving minimal movement on the eye when blinking.

Ultra-violet protection is also an important consideration due to exposure to sunlight if running outdoors.[27] The potential damage caused to the eye by long-term exposure to ultra-violet light is well documented.[30,31]

Shooting

Marksmen and women require high levels of visual acuity. Eye protection is essential and is advised over contact lenses.[32]

In this sport, Quevedo *et al*[28] demonstrated a statistically significant difference before and after training of the quality and quantity of tear film, believed to have arisen from the reduction in blinking rate. They suggest that high water contact lenses should be avoided and that the use of artificial tear substitutes would be advisable.

Although contact lenses are the correction of choice for many sports, marksmen require intense concentration and small movements of the contact lenses on blinking can be unacceptably off-putting and impede the performance of the shooter.[33]

RGP contact lenses, although providing the quality of vision required when centred, may cause unwanted visual effects on blinking. Soft lenses may not produce the crispness of vision desired, so careful consideration is required when fitting for such a sport.

Racquet and ball sports

When looking at the tear film of tennis players after training, Quevedo *et al*[28] showed a statistically significant difference in the tear meniscus height after training. They assumed that environmental conditions played a major role with visual effect indicating general body dehydration and sympathetically activated reduction in tear flow.

Soft contact lenses for tennis have been recommended as they have better corneal coverage, less vertical and horizontal lag, and therefore better stability and centration when the player is looking up.[35]

Eye protection when participating in racquet sports and hockey should always be worn over contact lenses.

Contact sports

For contact sports such as football and rugby, impact to the head can occur frequently. The IACLE[5] recommends that RGP lenses should be avoided ►

Table 1 Benefits of CLs over spectacles[8-3]

Wider field of view	Limitation on edge of spectacle lens design, restricted visual field
Less magnification	Object size is more constant 'real-world'
Contact lens stability	CLs do not slip down the nose
Enhances depth perception	CLs allow more stable vision and enhanced depth perception due to less magnification difference between the eyes
Fewer aberrations	CLs move with the eyes
Fewer reflections	CLs are in contact with tears
Do not fog up or become covered in rain	CLs are in contact with tears and not exposed
Reduced ocular injury	Reduced risk of ocular injury from broken frames or lens (exclude protective spectacles and RGP contact lenses)
Wearing protective glasses	The bulk of the frame frequently interferes with the wearing of protective goggles

as they may be dislodged by such occurrences or cause trauma to the adnexa. It also recommends fitting soft lenses that have good centration, good stability and minimal movement.

Motor sports

The Motor Sports Association UK is a division of The Royal Automobile Club Motor Sports Association. It is responsible for medical standards in most motor sports in the UK. For motor sports it recommends that if contact lenses are to be worn, they should be of the 'soft' variety. It also states that contact lenses can be worn for motor cycling, but only under a full-face visor or goggles.[34]

THE SIGHT TEST

The standard testing of visual acuity is on a Snellen chart, but only a small number of sports, such as archery and shooting, involve high contrast targets and backgrounds.[36]

Studies carried out by Reichow and Coffey [37] have demonstrated that when testing contrast sensitivity athletes exhibit better acuity at higher spatial frequencies and achieve a higher contrast sensitivity function overall than non-athletes.[35]

Therefore it is also important to test contrast sensitivity in athletes wearing contact lenses as this may be reduced even though Snellen acuity is normal.[35]

CLs AND EYE PROTECTION

Contact lenses, although one of the corrections of choice for many sports, provide little or no eye protection.

When prescribing contact lenses for such activities, they can be combined with a plano polycarbonate lens in a sports appliance.[38] The advantages of plano lenses over prescription contact lenses for eye protection include the lack of prismatic effect and reduced aberrations (Table 1).

Sports have been identified as the most common cause of severe eye injury.[39] A study in Scotland[40] reported that the incidence of eye injury due to sport was 12.5 per cent, with football being the most common cause.

Research carried out in Portugal[41] demonstrated that squash, paintball, bungee jumping and soccer injuries have resulted in an alarming number of severe ocular injuries. The athlete may bring a legal claim against an optometrist, claiming that the practitioner did not provide them with the correct eyewear, so exposing them to an increased risk of eye injury.[42] Polycarbonate lenses for ocular protection are well known and are clearly the lens of choice.[38,42]

While it is important to remember that contact lenses provide no ocular protection from injury, a report by Tang *et al*[43] in 2005 reported two cases where rigid gas-permeable contact lenses protected eyes from serious foreign body-related injury, but concluded they are not recommended for protective purposes.

Soft lenses are recommended for motor sports

SPORTS CONTACT LENSES

New performance-enhancing contact lenses have been designed and developed for athletes. The Nike MaxSight sports tinted contact lenses are made by Bausch & Lomb. The tint covers the entire cornea, eliminating stray light. They use what has been termed 'Light architecture optics' to filter out specific wavelengths (90 per cent of blue light). This is claimed to improve key visual elements, such as seeing a ball or background, while reducing sunglare. The lens is available in two tints, one is grey/green (which reduces blue and orange-yellow light), for sporting activities in bright environments, such as golf and running.

The other tint is amber (allowing for more efficient transition between sun and shade), designed for use with fast-moving ball sports in variable light, such as football, tennis, and hockey.

These lenses also filter out over 95 per cent of UVA and UVB, although UV-absorbing contact lenses are not substitutes for protective UV-absorbing eyewear, such as UV-absorbing goggles or sunglasses.[44]

Key points

What to consider when fitting contact lenses for sports

- Always use and advise patients on protective eyewear over contact lenses where necessary, especially for contact sports and those with orbit size projectiles
- Whether the practitioner decides to fit contact lenses for water sports or not, if the patient insists on wearing them or has competitive requirements they must consider the use of water-tight fitting goggles over the contact lenses. It should be noted that more investigation is needed in evaluating the effect of swimming while wearing contact lenses to establish safe criteria. Due to the lack of research and the associated risk of swimming in contact lenses, a safe alternative is prescription swimming goggles
- Examine the athlete's visual environmental factors when fitting contact lenses, for example UV exposure and drying
- Measure contrast sensitivity as well as high contrast visual acuity to more fully evaluate the vision of athletes in contact lenses

CONCLUSION

With the Olympics coming to Britain in 2012, optometrists have a role to ensure that athletes receive the best visual correction to enhance their sporting ability. The aim of this article is to give an insight into the use of contact lenses in sports. However, it is clear that much research is needed in this area to make sports refractive prescribing more evidence-based.

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• *Martin Cardall is an optometrist currently undertaking a PhD at Aston University on the use of contact lenses in sport and is a member of the Sports Vision Association*

MULTIPLE-CHOICE QUESTIONS

1 For which sport may contact lenses be a disadvantage?
A Football
B Running
C Shooting
D Tennis

2 What happens to the tear film in swimmers after aerobic training in an indoor pool?
A The quality and quantity after exercise is increased
B The quality and quantity after exercise reduced
C The tear prism is greater
D The quality and quantity after exercise is the same as before exercise

3 The estimated population of gym members in the UK in 2003 had:
A Risen by 1 per cent compared to 2001
B Stayed the same compared to 2001
C Decreased by 1 per cent compared to 2001
D Decreased by 1.5 per cent compared to 2001

4 What happens to IOPs as a result of exercise?
A Elevated
B Reduced
C No change
D Unknown

5 Which of the following statements regarding the use of contact lenses during water sports is untrue?
A Chlorine and other contaminants may remain in contact lenses after swimming
B Generally contact lens manufacturers recommend contact lenses for water sports
C Salt water and chlorine can impair the adhesion properties of soft contact lenses
D Due to the lack of research and the associated risk of swimming in contact lenses, a safe alternative is prescription swimming goggles

6 Which of the following statements regarding contact lens use for sports is true?
A Contact lenses provide adequate eye protection during sporting activities
B Contrast sensitivity testing is important in athletes wearing contact lenses
C RGP lenses should be fitted to contact sport athletes
D CR39 lenses is the lens material of choice for protective sports eyewear.

The deadline for response is February 9

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Contact lens fitting trends in sport

Part 1: The patient's experience

Martin Cardall BSc MCOptom; Nathanael Anguige BSc; Shehzad A Naroo PhD, MCOptom; James S Wolffsohn PhD, MCOptom

Australia rugby World Cup star Daniel Vickerman receives assistance with his contact lens

Introduction

The sports and leisure market is now considered to be the second largest industry worldwide[1]. It therefore comes as no surprise that, for many people, exercise and sport are everyday activities. The large variety of contact lenses on the market today would suggest they are an ideal form of vision correction for people involved in sporting activities[2]. The limitations that can be imposed by spectacles and spectacle lenses are outlined in Table 1 (opposite). Research carried out by Gupta et al. identified sport as a primary motivating factor for over a quarter of all patients choosing to wear contact lenses[3]. Furthermore, Bowden and Harknett found that 45% of female and 65% of male contact lens patients participated in sporting activities, of which 94% wore their contact lenses to play their sport[4].

In 2002, the National Statistics survey found that 75% of the UK adult population had regularly participated in some form of sport, game or physical activity in the twelve months prior to the survey[5]. Their results showed that swimming was the most popular activity, with over 7 million participants; this was followed by rambling/hiking. In addition, they found that participation in a sport, game or physical activity was likely to reduce with increasing age.

As previously stated, whilst swimming is regarded as one of the most popular recreational activities, in general, contact lens manufacturers do not generally recommend contact lens wear for water sport activities[2]. This is primarily due to the risk of contaminants within the water binding with the contact lens matrix, which therefore gives rise to the potential for further complications such as punctate keratitis[6]. There is also evidence to suggest that acanthamoebal infection has also been associated with swimming and contact lens wear[7, 8].

In order to investigate the patient's own experiences of wearing contact lenses for sport, a questionnaire was designed to determine the refractive correction, level of participation in sport and recreational activity and any associated visual problems.

Results

The questionnaire was distributed to 225 first-year undergraduate optometry students during the first week of term at Aston University, Birmingham in 2005 and in 2006. The response rate was 100%.

The average age of the subjects in this study was 20 ± 4 years (range 18-51 years). The male to female ratio was 2:3. Figure 1 represents the choice of visual correction amongst this cohort. The study highlighted that 59% wore a vision correction; this is slightly lower than the national average of 68%[9], although the data were not age or sex matched. In total, 35% of the subjects wore contact lenses, however only 2% wore contact lenses as their only form of visual correction, not wearing spectacles at all.

Figure 2 (page 42) highlights that males participate in sports and sporting activity for significantly ($p<0.05$) more time (5.3 ± 2.9 hours) on average per week compared to females (3.1 ± 2.5 hours).

Overall, 89% of subjects who wore contact lenses participated in sports, and of these 96% wore them during sport. This supports the findings of Bowden & Harknett[4], who found that over 94% of lens-wearing patients wore contact lenses during sport. It is unsurprising that a high number of patients wear contact lenses for sport with the numerous advantages they have over spectacles, highlighted in Table 1.

The respondents were questioned with regard to the amount of time that they used their contact lenses when participating in sport (Figure 3, page 42). A total of 58% were found to wear their contact lenses most of the time (75-100%). It should be highlighted that this result may well vary according to the type of sport participated in and the degree of visual correction required. Whilst males tend to participate in more sport than females (Figure 2), there was no

Benefits of contact lenses over spectacles	Reason
Wider field of view	Edge of spectacle lens and frame design may limit field
Less magnification	Object size is more constant "real-world"
Contact lens stability	CL do not slip down the nose
Enhances depth perception	Less anisometropia
Less aberrations	CL moves with the eye
Less reflections	CL is in contact with tears
No fogging / misting	Spectacles may fog or become obscured
Reduced ocular injury	Ocular injury from broken frames or lens (excluding protective spectacles and RGP CL)
Can wear eye protectors over CL	The frame from spectacles may interfere with the wearing of protective goggles/eye wear

Table 1: Benefits of contact lenses versus spectacles[2,6]

evident difference in the amount of time males and females contact lens wearers used their contact lenses for sport (ChiSquared test $p=0.96$).

When fitting contact lenses for any sport or sporting activity, it is important to consider both the type and modality of contact lens wear. It is generally not recommended to wear rigid gas permeable lenses for contact sports[2]. Lenses with high oxygen transmissibility, such as silicone hydrogels, have been suggested for altitudinal sports such as skiing or snow boarding[10].

This study highlighted that many different contact lens wear modalities are worn for sports, the most common of those being the monthly soft replacement contact lens. Clearly, this result depends upon the individual's visual correction and ocular findings as different modalities have different parameters and not all parameters are available in all the different types of modalities. Overall, 31% of patients wore daily disposable lenses whilst 77% wore monthly soft replacement contact lenses to participate in sporting activity (Figure 4, page 42). It is interesting to note that none of the cohort examined wore rigid gas permeable lenses for sports. No statistical difference was shown for the modality of contact lenses worn for sport between both males and females (ChiSquared test $p=0.56$).

Figure 5 (page 43) shows common problems that are encountered by the respondents whilst wearing their contact lenses for sports. In total 84 problems were reported, although 35% of all subjects who wore contact lenses during their sporting activity reported no adverse symptoms. The most common symptom experienced is dry eyes (39%). In a study on athletes in the USA[11], the most common contact lens problems experienced were irritation and loss of the lens itself. Despite the symptoms, highlighted in figure 5, only 10% of our respondents removed their contact lenses immediately after sport (Figure 6). It is not surprising that over a third of our respondents reported dry eye symptoms, as a study by Quevedo et al[12] demonstrated a statistically significant decrease in both tear film quality and quantity after swimming, tennis and shooting. Research conducted by Ridder et al[13] examined whether or not artificial tear substitutes stabilised the tear film and improved contact lens wear in those wearers who exhibited dry eyes. They found that there is a benefit to using certain tear supplements on visual performance in those subjects with an evaporative dry eye condition.

In general, contact lens manufacturers do not recommend

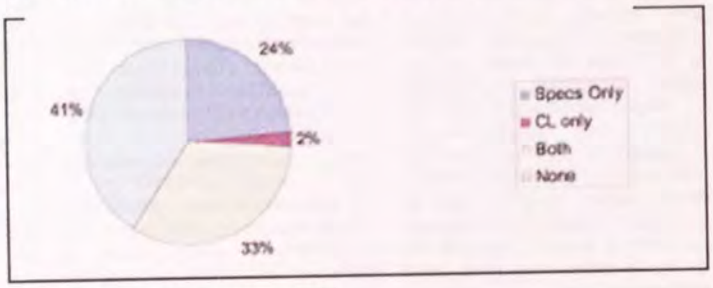

Figure 1: Choice of visual correction

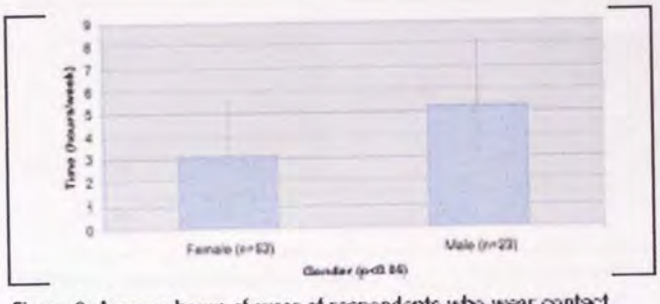

Figure 2: Average hours of wear of respondents who wear contact lenses and participate in sport

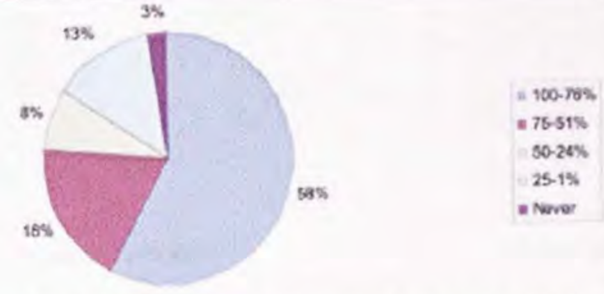

Figure 3: Amount of time subjects wear contact lenses when playing sport

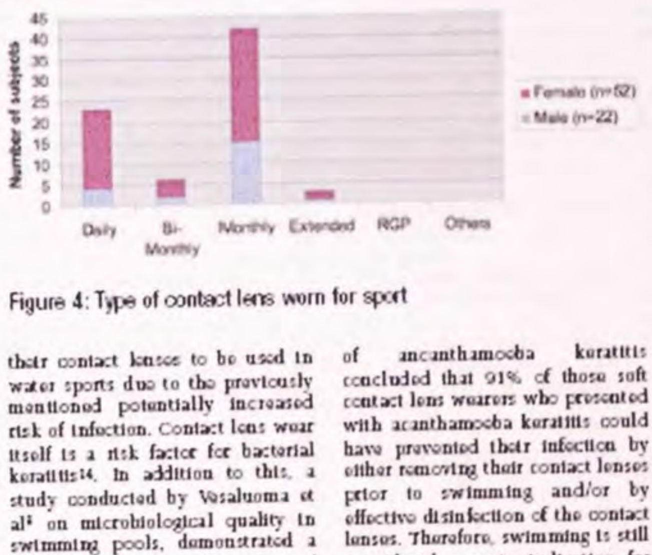

Figure 4: Type of contact lens worn for sport

their contact lenses to be used in water sports due to the previously mentioned potentially increased risk of infection. Contact lens wear itself is a risk factor for bacterial keratitis[14]. In addition to this, a study conducted by Vesaluoma et al[3] on microbiological quality in swimming pools, demonstrated a theoretical increased risk of amoebic and bacterial keratitis if contact lenses were worn for swimming.

A multi-centre survey carried out in England between 1992 and 1996[15] investigating the incidence of ancanthamoeba keratitis concluded that 91% of those soft contact lens wearers who presented with acanthamoeba keratitis could have prevented their infection by either removing their contact lenses prior to swimming and/or by effective disinfection of the contact lenses. Therefore, swimming is still considered a contra-indication for successful soft contact lens wear[15]. It was, perhaps, surprising to discover that whilst there is clearly a risk of infection associated with contact lens wear and swimming, 23% of the participants in this study were their contact lenses to swim in, although 17% of them did wear swimming goggles over their contact lenses (Figure 7, page 43). The literature available on the use of contact lenses in swimming is often contradictory[15,16], but a clearer and safer alternative that should be considered is the use of prescription swimming goggles. Loran reported that 76% of optical practices stock such devices for the public to purchase[1].

Figure 8 (page 43) highlights the wide variety of sports and recreational activities played whilst wearing contact lenses. Amongst our cohort the most common sport, played by a third of the participants, was football. Interestingly, football is the commonest sport reported to cause ocular injury, and active involvement in sports is regarded as the commonest cause of severe eye injury[17]; which raises the question as to the importance of eye protectors to playing sport. However, it is not clear whether the increased risk of eye injury associated with football is simply because there are more people engaged in the sport.

Conclusion

As contact lenses have major advantages to provide visual correction during sport (Table 1) it was not surprising to find out that 58% of subjects who wore contact lenses in this study (Figure 3) used them 'most of the time' for their sporting activities. These results certainly seem to highlight that contact lenses are the visual correction of choice for sports and sporting activity.

Considering the aforementioned risks of swimming associated with contact lens wear, it was a worrying, unexpected, result to find that some of contact lens wearers swim without protective swimming goggles. Despite the risks, 23% of subjects are swimming whilst wearing contact lenses (Figure 7). The information here correlates well with the study by Bowden & Harknett, which suggested that 20% of their subjects swam whilst wearing contact lenses[4]. This raises the question whether patients are being given the correct advice, or the risks are being emphasised enough to them, on swimming whilst wearing contact lenses by

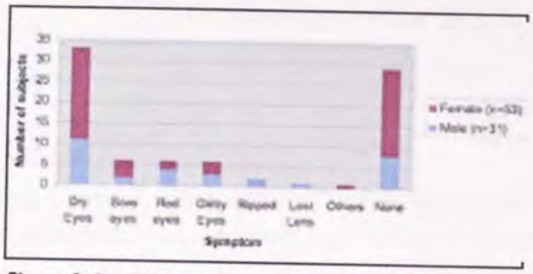

Figure 5: Symptoms reported during sport when wearing contact lenses

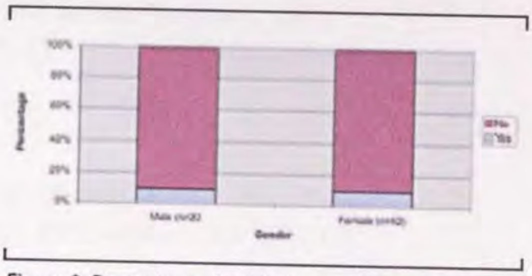

Figure 6: Percentage of subjects removing contact lenses after sport

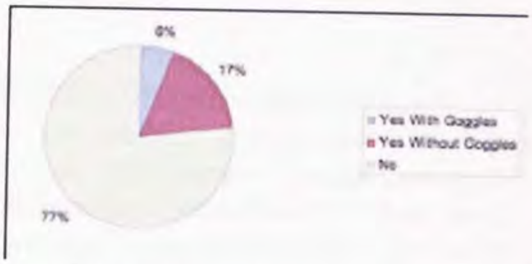

Figure 7: Contact lens in swimming

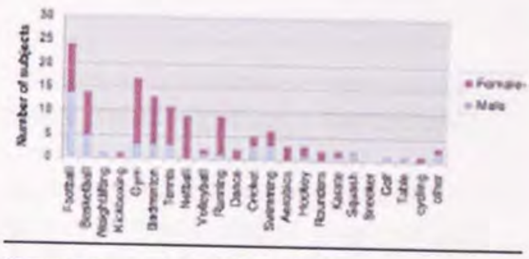

Figure 8: Types of sport played in contact lenses

their optometrist or contact lens fitter.

This study highlights that there is clearly a market for sports vision and contact lenses. Loran demonstrated that only 60% of all optical practitioners all ask their patients about hobbies, sports or recreational activities[1]. With such a high proportion of a patient base likely to be participating in sport it is essential that practitioners ask such questions not only to educate patients about their contact lenses and their application to the sports that they play, but also for the practitioner to advise the patient about suitable eye protection. Over a third of those questioned for this study reported dry eye as their primary complaint when wearing their contact lenses. With correct instruction of contact lens wear and the implementation of artificial tear substitutes, this problem has the potential to be reduced.

Part two of this work will investigate advice given to patients by eyecare practitioners for wearing CL for sports.

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2008: DALLOS AWARD 2008: Corneal oxygen consumption measured by a novel non-contact method

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PURPOSE: The physiological integrity of the cornea is dependant on the amount of oxygen available to its surfaces. Wearing contact lenses can disrupt the diffusion of oxygen to the cornea. Despite the importance of oxygen measurements, techniques have been limited by their invasive nature and small corneal area of assessment. In a previous study a new technique was demonstrated to assess whole eye oxygen consumption. Using this technology, this study further assesses the relative effect of contact lens wear on corneal oxygen consumption and the normal range of corneal oxygen consumption in the population.
METHOD: An oxygen sensitive material was mounted within an air-sealed goggle positioned over the left cornea (open, regularly blinking eye) of 50 healthy young subjects (mean age 22.5 ± 5.1 years, 1:1 male:female) to assess the range of normal corneal oxygen consumption in the open eye condition. In addition, the left eyes of 25 subjects (mean age 25.0 ± 6.3 years, 1:1 male:female) were assessed wearing a high Dk/t (Dk/t=110; Balafilcon A) and a low Dk/t (Dk/t =14; Polymacon) contact lens compared to not wearing contact lenses. The measurements were taken in real-time from the sensors using a fibre optic system.
RESULTS: The change in oxygen depletion measured in this population over 3 minutes varied from -0.14% to -1.00%, with an average of -0.53 ±0.24% O_2 during open eye condition. Eyes wearing the low transmissibility lens showed a similar result to the open eye (change of -0.50 ± 0.32% observed compared to open eye conditions -0.56 ± 0.24 %, p=0.35). Corneal oxygen consumption was slightly greater with the high transmissibility lens (-0.67 ± 0.29) and was significantly difference to the Low Dk/t lens at 3 minutes (p=0.005).**CONCLUSIONS:** There is a wide range of corneal oxygen consumption in even the young population, which may affect the risk factors of adverse responses to contact lens wear. On average, even Low DK/t contact lenses allow oxygen consumption levels to be maintained in open eye conditions, but silicone-hydrogels appear to allow corneal physiology to be enhanced.

	Volume wearing Low Dk/t** Lens (mm^3)	Volume wearing High Dk/t** Lens (mm^3)	Volume when not wearing lenses (mm^3)
Subject 1	64.73	65.10	64.53
Subject 2	62.63	62.97	61.37
Subject 3	56.37	55.87	55.67
Subject 4	60.70	60.73	60.90
Subject5	55.77	55.73	56.80
Subject 6	57.60	57.63	58.10
Subject 7	59.23	59.60	58.77
Subject 8	61.97	62.96	61.97
Subject 9	60.43	60.70	60.77
Subject 10	60.40	60.50	60.10

Table Appendix 1
The average corneal volume for each subject

	Area whilst wearing Low Dk/t** lens (mm^2)	Area whilst wearing High Dk/t** lens (mm^2)	Area whilst not wearing lenses (mm^2)
Subject 1	104.02	104.56	105.05
Subject 2	92.96	91.35	92.05
Subject 3	92.90	97.32	114.59
Subject 4	104.59	106.02	103.19
Subject 5	94.47	103.73	100.60
Subject 6	101.54	97.30	98.03
Subject 7	87.22	101.99	94.03
Subject 8	106.03	100.73	95.48
Subject 9	138.17	126.28	118.01
Subject 10	113.38	111.35	123.28

Table Appendix 2
The individual subject's average exposed cornea when the eye was open

	Volume (ml)	Volume (ml)	Volume (ml)	Mean (ml)
	Measure 1	**Measure 2**	**Measure 3**	
Subject 1	12.7	13.1	12.6	**12.8**
Subject 2	8.4	8.4	8.5	**8.4**
Subject 3	6.8	8.0	7.7	**7.5**
Subject 4	6.4	6.3	6.6	**6.4**
Subject 5	9.4	9.3	9.5	**9.4**
Subject 6	8.4	8.3	8.5	**8.4**
Subject 7	8.3	8.4	8.3	**8.3**
Subject 8	8.7	9.5	9.0	**9.1**
Subject 9	8.2	8.2	8.5	**8.3**
Subject 10	8.4	8.3	8.4	**8.4**

Table Appendix 3
The average goggle volume for the ten subjects used in the repeatability experiment