THE OXYGEN PERFORMANCE OF A CONTACT LENS ON THE HUMAN EYE.

KRISHNACHAND POSTUM

SUBMITTED IN PART FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF OPTOMETRY IN THE DEPARTMENT OF OPTOMETRY IN THE FACULTY OF HEALTH SCIENCES AT THE UNIVERSITY OF DURBAN - WESTVILLE.

SUBMITTED IN DECEMBER 1989

SUPERVISOR: PROFESSOR D.K.TURNBULL, HEAD OF THE DEPARTMENT OF OPTOMETRY.

JOINT SUPERVISOR: PROFESSOR H.S GOVINDEN, DEAN OF THE FACULTY OF SCIENCE.

This work is dedicated to Zain and Zahra, to my tutors, to my students and to the science and profession of Optometry for better patient care.

"TO MEASURE, IS TO KNOW"

Lord Kelvin

CONTENTS

CHAPTER 1 : LITERATURE SURVEY AND FORMULATION OF THIS STUDY

CHAPTER 2 : CONSTRUCTION OF MEASURING CELL AND IN VITRO CHARACTERIZATION OF OXYGEN PERFORMANCE OF RIGID CONTACT LENSES.

CHAPTER 3 : CONSTRUCTION OF CONTACT LENS MICROELECTRODES AND IN VIVO DETERMINATION OF OXYGEN PERFORMANCE OF THE CONTACT LENS MICROELECTRODES.

CHAPTER 4 : DISCUSSION

ACKNOWLEDGEMENTS:

I wish to express my sincere thanks and appreciation to :

Professor D.K. Turnbull, for promoting this project and for his encouragement and enthusiasm throughout this project.

Professor H.S. Govinden, for promoting this project and his advice in the preparation of this project.

Dr. Zainub Khan, for her enduring patience, encouragement and support, and for typing and proof-reading the thesis.

Mr. Rashid Khan, for his support, and for proof-reading the thesis.

Charmaine Coetzee, for assistance in sorting out the references.

Mr Doug Adams, Arthur van Heerden and Allergan Hydron for supporting this project by donating the Philips digital multimeter used in this study.

Jack Bernard Contact Lens Laboratory, Ford Contact Lens Laboratory and S.A Vision Care, for supplying the contact lenses.

Mr G. LeRoux and Mr V.Krishna (Dept. of Engineering, U.D.W.), for their assistance with the electronics.

ABSTRACT OF THESIS

There is considerable evidence to indicate that most gas permeable contact lenses do not transmit sufficient oxygen to supply all the corneal oxygen requirement. This problem is further exacerbated by non-valid methods of characterizing the oxygen performance of such lenses. The current methods of using oxygen permeability (Dk) and oxygen transmissibility (Dk/L) as indices of oxygen performance of contact lenses is completely erroneous. Dk and Dk/L pertain to contact lens materials in flat sheet form having uniform thickness and equal diffusion path at all points on the surface. Finished contact lenses, of necessity, are curved surfaces and of varying thickness. Consequently the concept of Dk and Dk/L cannot be applied to contact lenses.

To date there are no studies to determine the absolute oxygen tension under gas permeable contact lenses on the human eye. All attempts to quantify the oxygen tension under a lens have been by indirect methods or by predicting the pO_2 from Dk values, using mathematical equations. These results do not match the clinical findings. This study was done to show that oxygen flux through a contact lens, measured _in vitro_, is a better determinant of the _in vivo_ oxygen performance of gas permeable contact lenses. A special cell was designed to measure the oxygen flux, _in vitro_ under standardised conditions. Contact lens microelectrodes were designed to measure the oxygen tension _in vivo_. The data obtained was used to develop a model for the oxygen performance of rigid gas permeable lenses on the human eye.

ABBREVIATIONS AND DEFINITIONS

BASAL METABOLIC RATE : the minimal energy expenditure to maintain the basic body functions, expressed in terms of oxygen consumption.

D : diffusion coefficient.

FAD : flavin adenine dinucleotide, a coenzyme and electron acceptor in the oxidation of fuel molecules in biochemical reactions.

L : centre thickness of contact lens in centimeters.

k : solubility coefficient.

NAD^+ : nicotinamide adenine dinucleotide, a coenzyme and major electron acceptor in the oxidation of fuel molecules in biological reactions.

NADPH : nicotinamide adenine dinucleotide phosphate, electron donor in most reductive biosyntheses.

OXYGENATION : the process of supplying oxygen to the cornea.

OXYGEN PERFORMANCE : the ability of a contact lens to oxygenate the cornea as the result of blinking and/or lens permeability.

PERCENTAGE OXYGEN : ($\%O_2$) : the concentration of oxygen expressed as a percentage of atmospheric air (normally atmospheric air has 20.93% oxygen). The minimal corneal oxygen requirement is often expressed as a percentage of oxygen relative to atmospheric air.

PMMA : polymethyl methacrylate (optical quality "PERSPEX").

pO_2 : partial pressure of oxygen in atmospheric air, used synonymously with oxygen tension. The oxygen tension can be be converted to percentage oxygen and vise versa only when the atmospheric pressure is known.

Radiometer PHM 73 : Commercially available instrument that measures pH, pO_2, and pCO_2 in blood.

μl : microlitre.

CHAPTER 1

1.1 INTRODUCTION

Contact lenses undoubtedly provide state-of-the-art correction for refractive errors of the eye and in some cases, such as keratoconus, the only satisfactory correction. Since the cornea obtains most of its oxygen from the atmosphere, the successful wear of contact lenses depends on an adequate supply of oxygen to the cornea. This supply of oxygen to the cornea may be exclusively around and under the periphery in the case of non gas-permeable lenses and through the material as well, in the case of gas permeable lenses (Sarver et al., 1977). Therefore, there are two essential considerations for successful contact lens wear. Firstly, the fit of the lens must be considered. This encompasses the relationship between the posterior radius of the contact lens and the radius of the cornea itself. Secondly, the oxygen permeability of the contact lens itself must be considered. The fit of the rigid contact lens affects the gas exchange of the tear pool under the contact lens and consequently the oxygenation of the cornea (Fatt et al., 1969). Tightly fitted contact lenses "strangle" the cornea and loose lenses abrade the cornea due to excessive movement and friction. The practitioner aims for a compromise fit that eliminates excessive lens movement but at the same time allows adequate oxygenation of the cornea (Goldberg, 1979). Sometimes, even with the best fitted lens, the oxygenation of the cornea is compromised. Practitioners have then reverted to using gas permeable lenses to overcome the oxygenation problem caused by the non-gas permeable lenses. Bennett et al. (1983) found that gas permeable lenses did not inhibit the recovery of the cornea after anoxic stress caused by PMMA lenses. Clinical results have shown that, contrary to the oxygen performance data supplied by the manufacturers, many of these gas permeable lenses do not perform satisfactorily on the human cornea. To overcome the problems of oxygen deficit of the gas permeable contact lenses to the cornea, newer generationsof materials, specifying higher oxygen permeability, have been developed (Fatt, 1984; Schnider, 1987).

1.2 OXYGEN UTILIZATION BY THE CORNEA

The cornea, being avascular, receives most of its oxygen directly from the atmosphere. A small amount of oxygen is derived from the aqueous humour, the limbal blood vessels and conjunctival vessels. Smelser (1952) showed that the uptake of atmospheric oxygen through the tear film is essential for normal corneal metabolism, which, in turn, is essential for maintenance of the normal detergescent state of the cornea. Mishima (1965) made a detailed study of the precorneal tear film and by the "glass filament method", measured the fluid film in the rabbit eye to be 7.5µ thick. This film is governed by all the laws of thin film physics and is essential for oxygenation of the cornea and makes contact lens wear possible.

Fatt and Bieber (1968) reported the pO_2 of the in vivo precorneal film to be the same as atmospheric pO_2 and that of the closed eye to have dropped to 55 mm Hg. Using modified scleral lenses to accept oxygen electrodes the rate of corneal oxygen uptake was calculated to be 4.8 µl/cm^2/hr (Hill et al, 1963 a,b). Larke et al. (1981) measured corneal oxygen uptake in 68 subjects and found a range from 3 to 9 µl/cm^2/hr. Sarver et al. (1983) reported that there was a wide inter-subject difference in the corneal response to reduced oxygen. This seems to indicate that there is a wide variation in oxygen requirement.

1.3 CORNEAL OEDEMA OR CORNEAL THICKENING WITH CONTACT LENS WEAR

It has long been recognized that the ideal contact lens would not produce corneal oedema. Smelser and co-workers (1952, 1953, 1955) were the first to show that the corneal oedema caused by contact lens wear was due to oxygen deprivation. This was subsequently confirmed by other researchers (Langham et al., 1956; Harris et al., 1969; O'Neal et al., 1985). However, oxygen tension as low as 11,9 mm to 19 mm was sufficient to prevent corneal swelling (Polse and Mandell, 1970; Mandell, 1979). In individuals who do not wear contact lenses most of the oxygen available to the cornea is dissolved in the precorneal tear film and is spread over the cornea. When the eyes are open, oxygen is dissolved in the tear fluid directly from the atmosphere. In the closed eye the oxygen is made available to the cornea via the arterioles lining the peripheral conjunctiva (Langham, 1956). A contact lens on the eye reduces the availability of atmospheric oxygen to the cornea. Thus, oxygen has to be transported under the contact lens, in the tear fluid as a result of lid action (blinking). Alternatively, oxygen must pass through the lens itself. The PMMA lens, being non gas-permeable, will cause oedema after being worn for a fairly short period if stationery (as in a tight fit). The lens must therefore be designed and fitted in such a way that the lid action will transport enough oxygen bearing tears beneath the lens to satisfy the minimum or critical oxygen tension at the corneal surface (Hill _et al_., 1970). Jauregui and co-workers (1972) have shown that the precorneal tear film under a lens which has been properly fitted, according to the accepted clinical criteria, will provide an oxygen tension of 20 mm Hg. Polse and Mandell (1970) have theorized that failing to achieve this condition will result in corneal oedema.

It has been shown that most hydrogel lenses allow the passage of a certain amount of oxygen, but not enough to satisfy the requirements of the cornea (Fatt and St. Helen, 1971; Holden et al., 1983, 1985 a,b). This means that the hydrogel lenses must also be designed and fitted such that the tear pump created by blinking will provide sufficient oxygen in the tears to prevent corneal oedema. Despite this, it has been shown that many hydrogel lenses still do not achieve adequate oxygenation of the cornea (Bailey et al., 1977; Polse et al, 1975). Wagner et al. (1980) showed that there was only 1.3% to 2.2% tear replenishment per blink. According to the calculations of Fatt and Lin (1976), the change in tear pO_2 would be 1.1 mm Hg to 2.9 mm Hg.

Variations in PMMA lens geometry has been devised in an attempt to provide adequate oxygenation of the cornea. These lenses have been fitted flatter, smaller, thinner, aspherical, multicurved, and/or fenestrated. Hydrogel lens geometry has also been varied to provide flatter, smaller and/or thinner lenses. Although these fitting techniques have met some of the corneal oxygen requirements, they have not eliminated corneal oedema in all patients.

There are several desirable properties which make PMMA the lens material of choice for correction of many refractive conditions. However, contact lenses with similar properties, but with the added feature of adequate gas permeability, would provide the cornea with a more favourable physiologic environment.

In recent years several new materials have been developed and tested in the hope of increasing the oxygen permeability of the lenses to meet the corneal requirements (Sarver et al., 1983; Stahl, 1984;). Fatt and co-workers (1971) have reported silicone polymers to have high gas permeability. However, these lenses have proved to be unsuitable because of the inherent hydrophobic surface properties, poor optics and consequent poor patient comfort. Other type of lens materials, copolymers of methylmethacrylate and silicone have also been tested. These material have improved gas permeability and good optical features. In addition it was reported to have produced no corneal oedema and minimal corneal thickening.

1.4 THE CRITICAL OXYGEN REQUIREMENT DURING CONTACT LENS WEAR

In view of the emphasis on providing minimal physiological stress to the cornea during contact lens wear, a precise determination of the critical oxygen requirement during lens wear is desirable for practitioners and contact lens designers. The literature abounds in the estimates of critical oxygen requirements of the cornea, determined by different methodologies (Efron et al.,(1986). Holden and co-workers (1984) have proposed that a Dk/L of

$$24 \times 10^{-9} \text{ (cm / sec) (ml } O_2 \text{ / ml x mm Hg)}$$

is required to prevent corneal swelling during open-eye lens wear. According to Roscoe and co-workers (1984) this corresponds to 16.7% oxygen concentration. Yet the minimal level of oxygen concentration to avoid corneal swelling in response to gaseous hypoxia was found to be 10.1% (Holden et al., 1984).

1.5 CORNEAL METABOLISM

Most of the glucose utilized by the cornea (65%) is metabolized via the hexose monophosphate shunt pathway (Devlin, 1986). This is the highest amount of glucose reported to be metabolized via this pathway compared to any other mammalian tissue. Thirty percent of the glucose in the cornea is metabolized via the glycolytic pathway. The cornea is also characterized by a high rate of oxygen consumption. This is essential because the end product of glucose metabolism in the stroma is lactate, which is passed on to the corneal epithelium for oxidation to carbon dioxide and water by the enzymes of the Citric Acid Cycle. A deficiency in oxygen supply to the cornea, which can occur with poorly fitted contact lenses, will result in damage to the stroma as a result of lactic acid accumulation (Klyce, 1981).

One end product of the hexose monophosphate shunt pathway is NADPH, which is used for reductive biosynthesis as well as for protection of the cornea against injury by oxidizing agents such

as oxygen, ozone and superoxide radicals (Devlin, 1986).
The most efficient mechanism for energy production is via the Embden Meyerhof pathway and Citric Acid Cycle, leading to the production of carbon dioxide, water and ATP. Anaerobic metabolism of glucose, accompanied by the production of lactic acid, also releases energy, but the amount is very small.

In most biosynthetic reactions, the precursors are more oxidized than the products, hence the need for reductive power in addition to ATP. NADPH, formed during metabolism of glucose via the hexose monophosphate pathway, is used almost exclusively for reductive biosyntheses. In addition, the hexose monophosphate pathway generates ribose which is utilized for RNA, ATP and coenzymes for the constantly regenerating corneal epithelium.

The crucial need for atmospheric oxygen by the corneal epithelium is linked to corneal metabolism and the generation of high energy intermediates for cell function as well as for rapid regeneration of the epithelial layer.

Three stages have been described for the aerobic generation of energy from oxidation of dietary foods, as outlined in Figure 1.1 (Stryer, 1981). The first stage leads to the production of fuel molecules (sugars, fatty acids, amino acids) but no useful energy is generated. The second stage involves the degradation of fuel molecules to a few simple units (mainly the acetyl unit of acetyl

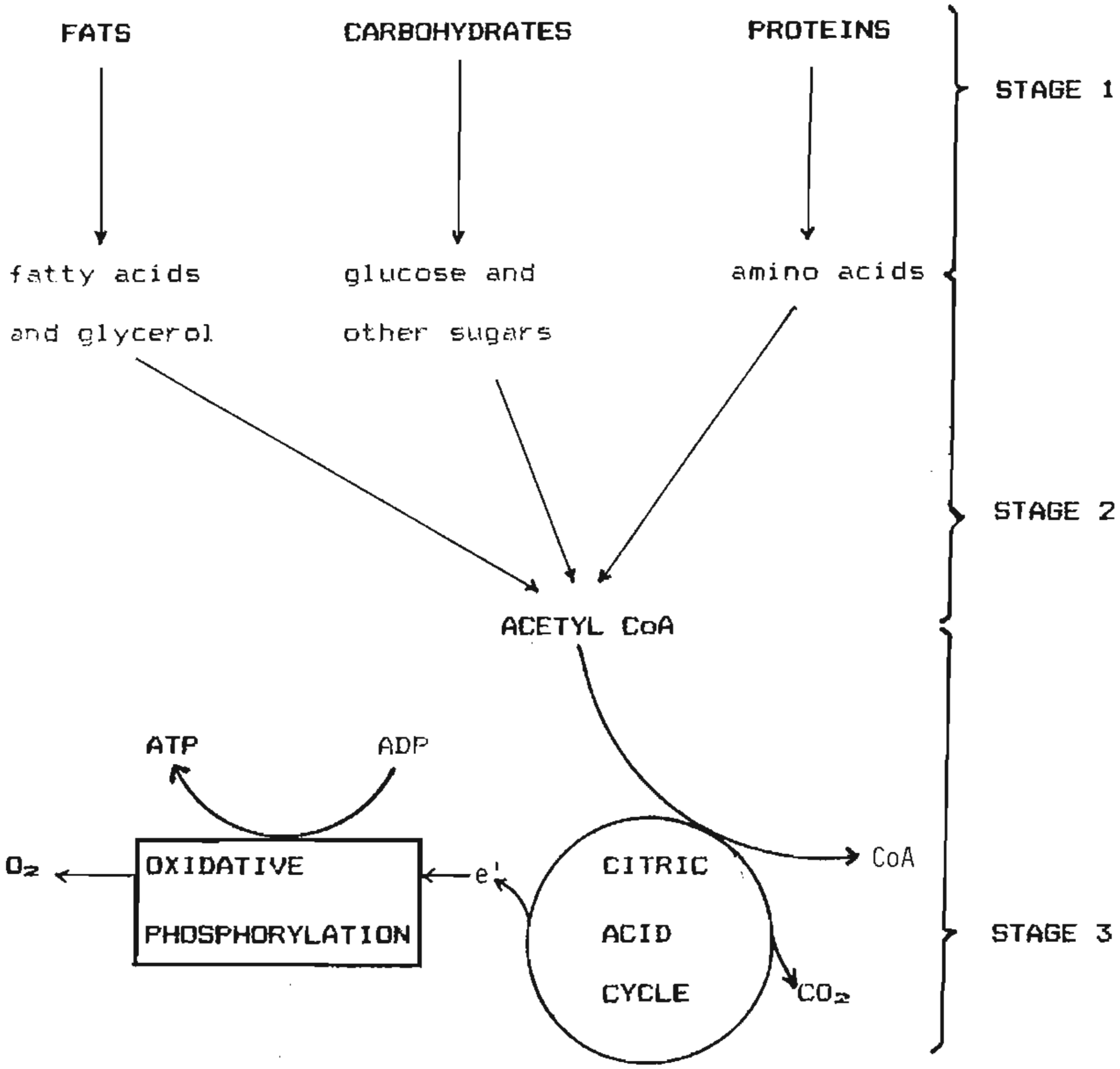

Figure 1.1 : Stages in the aerobic generation of energy from oxidation of fuel molecules showing the need for oxygen in the final stages of metabolism.

coenzyme A) with a small amount of ATP being produced. The third stage consists of the citric acid cycle and oxidative phosphorylation, which are the final common pathways in the oxidation of fuel molecules. The acetyl units are completely oxidized to CO_2, yielding four pairs of electrons (e′) per unit (Lehninger, 1975). The electrons are transferred to NAD^+ and FAD during citric acid cycle metabolism (Fig. 1.1). Thus most of the useful energy is produced in the third stage of the degradative pathway.

The electrons transferred to NAD^+ and FAD have a high energy potential (E_o'), which is converted into phosphate transfer potential ($G^{o\prime}$) of ATP, as electrons are passed on to oxygen.

The standard free energy change ($\Delta G^{o\prime}$), is related to the change in electron transfer potential (redox potential, $\Delta E_0'$) by the following equation

$$\Delta\ G^{o\prime} = \Delta\ -nF\ \ E^{o\prime}$$

where n is the number of electrons transferred, and F is the caloric equivalent of the Faraday constant (23.062 kcal V^{-1} mol $^{-1}$ (Stryer, 1981).

The driving force of oxidative phosphorylation is the electron transfer potential of NADH or $FADH_2$. A deficit of oxygen to the cornea, such as that caused by contact lens wear, will result in reduced corneal oxidative phosphorylation and thereby reduce ATP synthesis in these cells. This, in turn, would affect the biochemical and physiological integrity of the corneal epithelium.

Anaerobic metabolism and lactate production would be the alternative to the above. During anaerobic glycolysis pyruvate is converted to lactate by the enzyme lactate dehydrogenase, and NAD^+ is regenerated in the process; thus glycolysis can continue, albeit at a reduced rate. However, there is an accumulation of lactate (Langham, 1952). From muscle, lactate is passed via the circulatory system to the liver to be re-synthesized into glucose. Since the cornea lacks blood vessels, the lactate cannot be removed effectively. In addition, the energy produced by anaerobic glycolysis is fairly low (Lehninger, 1975).

1.6 OXYGEN UPTAKE BY THE HUMAN CORNEA

Before evaluating the oxygen performance of contact lenses, it is necessary to establish the oxygen uptake profile of the human cornea. This means that one has to establish corneal oxygen requirements before determining whether a contact lens can supply this demand or not. Smelser and co-workers (1952) have shown that atmospheric oxygen is essential for normal corneal metabolism.

Hill and Fatt (1963 a,b) were the first to determine the oxygen flux across the cornea-atmosphere boundary in vivo. They used a modified scleral lens fitted with a modified Clarke type polarographic electrode. The electrode-lens system enclosed a limited volume of air-saturated saline. By recording the change in pO_2, the corneal oxygen uptake was deduced. (The flux into the cornea is known to be only a part of the total supply of oxygen to the cornea). From this study it was found that the rate of oxygen uptake by the cornea was $4.8 \mu l/cm^2$ /hour. Schoessler (1981) used a membrane-covered polarographic electrode held on the cornea and recorded an oxygen uptake of $2 \mu l/cm^2/hr$. Quinn and Schoessler (1983, 1984) observed variations in individual corneal requirements. Morris and Ruben (1981) used a polarographic electrode over a soft lens and reported that patients with keratoplastic eyes and eyes with bullous keratopathy had lower than normal oxygen uptake. Rasson and Fatt (1982) used a Clarke-type electrode over a soft lens to determine the oxygen flux into the cornea and oxygen tension under the lens. They presented a series of curves and a polynomial equation describing the oxygen flux into the cornea.

A polarographic oxygen sensor was used to measure corneal oxygen uptake at various points across the cornea (Fitzgerald et al., 1986; Fatt, 1976; Efron et al., 1981, 1983, 1985). These studies demonstrated that, within the sensitivity of the technique, there was no significant difference in the oxygen uptake rates between the central and peripheral points of the cornea. The central corneal uptake was determined to be 6.23 ± 0.25 μl / cm^2 / hour. Mandell (1982), on the other hand, postulated that the minimal corneal needs were between 2% and 5% oxygen at the anterior surface of the cornea.

1.7 CURRENT METHODOLOGIES FOR ASSESSING OXYGEN PERFORMANCE

At present there are three procedures for assessing corneal oxygen supply during contact lens wear: oxygen transmissibility (Dk/L) (Fatt, 1984; Fatt and Chaston, 1981), equivalent oxygen percentage (EOP) (Hill, 1977; Flynn et al., 1984) and corneal swelling (Brennan et al., 1988). These three methods relate to different aspects of the lens-cornea system. Dk/L describes the the ease with which oxygen passes through a gas-permeable material in vitro. EOP is a measure of the apparent oxygen concentration on the corneal surface after a lens has been worn on the eye. Corneal swelling is one of the physiological responses to wearing a contact lens on the eye.

A precise description of the above three procedures is essential in developing a comprehensive model for predicting the corneal response to a given oxygen concentration during contact lens wear. Clear definition of the inter-relationships between these procedures is also crucial for the interpretation of apparently conflicting results obtained when the corneal response to contact lens wear was studied. Each of the above procedures for assessing oxygen performance is examined (Sections 1.8, 1.9 and 1.10) individually.

1.8 EQUIVALENT OXYGEN PERCENTAGE (EOP) MEASUREMENTS

EOP is regarded as the in vivo measure of contact lens oxygen performance. The procedure attempts to establish the pO_2 or percent oxygen at the anterior corneal surface during contact lens wear. However, this is an indirect method which actually measures oxygen debt after a lens has been worn on the eye. The recovery rate is then expressed relative to atmospheric pO_2 or percent oxygen ($\%O_2$). The procedure involves two stages.

The first stage entails the determination of a calibration curve for each cornea under study (Hill, 1977; Roscoe et al., 1982, 1984, 1985). The patient is then fitted with air-tight goggles that isolate the eye and the adnexa from the air in the atmosphere. The goggles are fitted with inlet and outlet taps. Gas mixtures containing different percentages of oxygen (in nitrogen) are passed through the goggles. The cornea is exposed to each concentration of oxygen for a specific period of time, which allows the cornea to equilibrate with the gas mixture in the goggles. The time for equilibration is between 30 minutes and 3 hours. The goggles are removed and a polarographic oxygen probe, which has been standing in 100% oxygen-aerated water, is pressed lightly on to the cornea. The initial reading on the recording paper is assumed to be 100% oxygen. As the cornea presumably takes up oxygen from the tear layer between the cornea and the electrode membrane, the recorded pO_2 falls. The rate of fall in pO_2 or the percent oxygen is proportional to the corneal oxygen debt. The reasoning behind this method is that if the cornea had been exposed, previously, to a very low percentage of oxygen, the resultant oxygen debt would be high and consequently a rapid fall in the pO_2 recorded would be noted. If, on the other hand, the cornea had been exposed to a high percentage of oxygen, the oxygen debt would be smaller and the consequent rate of decrease in pO_2 would be small. Thus, a number of recovery curves are obtained for different percentages of oxygen introduced into the goggles.

In the second stage of EOP measurement, the contact lens is placed on the cornea for a given length of time. The lens is then removed and the polarographic electrode is pressed onto the cornea. The recovery rate of the O_2 debt caused by the contact lens is then recorded.

The profile obtained with a contact lens is compared with that obtained in the first stage. The oxygen performance of the contact lens is determined in terms of the percentage oxygen in the goggles that produced a similar recovery curve, hence the term equivalent oxygen performance (EOP).

At present the EOP technique is the most popular technique cited in the literature for the evaluation of oxygen performance of contact lenses on the eye *in vivo*. Numerous studies have been carried out relating EOP to corneal swelling and to transmissibility (Dk/L). These relationships are discussed in Section 1.10). Nevertheless, the EOP technique is an indirect estimation of oxygen performance of contact lenses on the eye.

1.9 CORNEAL THICKNESS MEASUREMENT AS AN INDEX OF OXYGEN PERFORMANCE

One of the first observed physiological changes in the cornea induced by contact lenses is corneal haze. It has been shown experimentally that these optical changes in the human cornea were attributed to contact lenses which deprived the cornea of its normal access to oxygen (Smelser and Ozanics, 1952; Smelser, 1952). It has been suggested that the cornea maintains its normal water balance by an active metabolic process which requires oxygen. Contact lenses which interfere with the normal availability of oxygen to the cornea, cause corneal hydration which is represented by the observed increase in corneal thickness and turbidity (Smelser and Chen, 1955). Experiments carried out in rabbits show that there is also an increase in corneal lactic acid content with contact lens wear (Langham, 1952). This was also found to be the case in guinea pigs (Smelser and Chen, 1952).

Unaike and co-workers (1972) have shown that changes in glycogen content, LDH (lactate dehydrogenase) concentration and corneal thickness were related to the subjection of the cornea to an oxygen deficient atmosphere. The relationship to corneal thickness was later confirmed in humans also, when hard contact lenses were worn (El Hage et al., 1974; Unaike et al., 1972). The significant increase in corneal thickness was attributed to an osmolarity effect, a decrease in corneal glycogen content and a decrease in trans-corneal potential.

Under normal conditions a constant de-hydration is maintained in the cornea. Under conditions of epithelial or endothelial damage, or interference with normal metabolism, or changes in tonicity, there is corneal swelling. Such swelling results in thickening of the cornea and is related to stromal hydration (Hedbys et al., 1966). The mechanism by which corneal thickness is controlled is not known. It is believed that water is pumped out of the stroma by an active pump mechanism (Mandell, 1981).

Small changes in thichness of the normal cornea have been reported under closed-eye conditions (Mishima and Maurice, 1961). The human cornea swells during overnight sleep. However, the magnitude of swelling is reported to be variable. Mandell and Fatt (1965) have reported an increase of 3.06% following 6 hours sleep. The corneal thickness returned to baseline one hour after exposure to atmosphere. Mertz (1980) has reported the overnight corneal swelling after 7 hours sleep to be 4.5%, with logarithmetic recovery to baseline within one hour. Unaike and co-workers (1971), on the other hand, have reported 20% corneal epithelial swelling per hour in response to oxygen-free atmosphere.

A reduction in temperature of isolated corneas, and possibly a reduction in the rate of metabolism, has been reported to cause corneal oedema, determined from measurements of corneal thickness (Davson, 1955). Smelser and Ozanics (1955) showed that similar thickening could be obtained by reducing the supply of oxygen to the anterior surface of the cornea in a living animal.

In order to relate the cornea's oxygen consumption to corneal thickness two factors must be considered. Investigations have shown that during sleep there is approximately 4% thickening of the cornea, which is reversed during the first few hours after waking. This is a normal phenomenon and therefore cannot be regarded as a cause of corneal problems. Corneal thickening during sleep is due to the lowering of the osmolarity of the tear film (Mishima and Maurice, 1961). When the eye is open, water evaporates from the precorneal fluid resulting in a 10% higher concentration of solutes than that present in freshly produced tear fluid. Hence the cornea under open-eye conditions is bathed in a hypertonic solution, whereas, during sleep (closed-eye conditions) the cornea is covered in an isotonic tear layer. This reduction in salt concentration in the tear fluid, during sleep causes thickening of the cornea by osmotic process. The diurnal thickening and the thinning of the cornea during the awake-sleep cycle is a normal event and can be described as an osmolarity effect without relation to the oxygen supply to the cornea and is not harmful to the cornea (Sarver and Staroba, 1978).

It is well known that most contact lenses restrict the supply of oxygen to the cornea (Parrish and Larke, 1981). If the restriction is prolonged and severe then the normal metabolic activity is adversely affected, causing the cornea to swell (Smelser and Ozanics, 1952; Maurice, 1957; Cogan, 1962; Dufin _et al_. 1982). Even hydrogel lenses have been reported to cause corneal swelling (Polse, Sarver and Harris, 1976). However, wearing of contact lenses is generally considered acceptable on daily wear basis provided the degree of corneal swelling is not greater than the physiological swelling occurring during overnight sleep. This response is about 3% to 4% increase in corneal thickness, as discussed earlier. Extended wear contact lenses may impose continuous corneal hypoxia without periodic restoration of normal atmospheric levels of oxygen to allow corneal recovery. Therefore a measure of corneal thickness is used as an index of the oxygen performance of contact lenses on the human eye (Decker et al., (1978), Korb et al., (1980). Terry et al. (1978) reported that variation in osmotic pressure may have a detectable effect on the corneal thickness.

Procedures for the measurement of corneal thickness:

1) Slitlamp pachometry.

A specialized slitlamp or a modified biomicroscope is used in this procedure (Sarver et al, 1978, 1979). The objective is focussed on the anterior corneal surface and the focus is shifted to the posterior surface. The distance travelled by the biomicroscope to achieve focussing from one surface to the other is converted to read corneal thickness.

2) Ultrasonic pachometry

Ultrasonic waves are bounced off the anterior and posterior corneal surfaces. By measuring the time taken to record the echo and utilising the velocity of sound waves in the human cornea, between 1502 m/sec and 1610 m/sec (Chen and Holden, 1982), the absolute corneal thickness is determined.

1.10 OXYGEN PERMEABILITY (Dk) AND OXYGEN TRANSMISSIBILITY (Dk/L) AS MEASURES OF THE OXYGEN PERFORMANCE OF CONTACT LENSES

Oxygen permeability may be defined as a description of the ease or difficulty with which a gas can pass through a material. This concept can best be described as a phenomenological process (Yasuda, 1967). Fatt (1968) has defined the oxygen permeability of contact lens materials as $P = D.k$; where P is the oxygen permeabiliy, D is the diffusion coefficient and k is the solubility coefficient. Researchers in the field of contact lenses believe that an <u>in vitro</u> measure of oxygen permeability would indicate the possible performance of the lens on the eye. Permeability is defined as an intrinsic property of the material. As certain conditions have to be satisfied when defining permeability, these will be discussed further.

1) The material must be of uniform thickness at all points at which diffusion will take place. This ensures that the diffusing molecules will encounter the same resistance at all points. Since contact lenses are optical elements, negative lenses are thinner at the centre while positive lenses are thicker at the centre than at the periphery.

2) The material must be homogenous at all points. Since contact lenses are largely polymeric in nature, the conformation of the

polymer chains will affect the Dk values depending on the path through the material. Dk measured "with the grain" may differ from Dk measured "against the grain". There is no evidence in the literature with regards orientation of polymer chains due to manufacturing process, gravity or electrochemical charge.

3) The surfaces through which diffusion takes place must be parallel and diffusion must be normal to the surface. Again, of necessity, contact lenses have curved surfaces and diffusion does not always take place normal to the surface (Fatt, 1979).

4) The diffusion path must be equal at all points of diffusion. Since a contact lens varies in thickness from centre to periphery, the diffusion path is not equal at all points.

It must be pointed out at this stage that the permeability equation is derived from Fick's law. The gas laws define diffusion from one point to another where the only driving force is the pressure gradient and the diffusion process is achieved by the kinetic energy of the gas molecules. Boundary effects are not considered and other forces like surface charge of the boundary and the diffusing molecules are also not considered.

The diffusion process does not fully describe the passage of oxygen molecules through a contact lens on the human eye. The permeation of oxygen through a contact lens on the eye is affected at least by the following forces : the electronegativity of the oxygen molecule , the surface charge of the contact lens, the electrolytes in the tear layer, the surface tension and the interfacial tension of the tear layer and the polymer material, and the oxygen concentration gradient. Not all of these factors are accounted for in the permeability equation.

In as far as the contact lens industry is concerned neither D nor k is measured. The oxygen permeability of materials is determined by indirect procedures and relative values are obtained, i.e., relative to the permeability indices of materials for which D and k values have been determined. The method of Fatt is widely used in the contact lens field and will be described.

In the field of contact lenses, the polarographic method of determining oxygen permeability has become very popular (Petersen and Fatt, 1973; Estabrook, 1967; Freeman and Fatt, 1972; Refojo et al., 1977; Fatt, 1978; Wilson, 1979). The original polarographic method was developed by Fatt and St. Helen in 1971. The electrode consisted of a flat platinum cathode and a cylindrical silver anode in an annular well surrounding the post that supported the cathode. This cell could only be used to measure flat samples or soft lenses that had to be flattened against the flat cathode (Morris et al, 1977). Fatt (1984) reported several problems associated with determining transmissibility for gas permeable rigid lenses from measurements done on flat samples. The buttons used are of uniform thickness, whereas the lenses vary in thickness from centre to periphery. Also the cutting and polishing of a lens in the lens-making process could give a permeability value different from that of a flat disc of the same material. Consequently Fatt developed a polarographic oxygen cell with a curved surface that could be used to measure permeability of a contact lens. The system is reported to be a modification of Eberhard's coplanar electrodes.

The modified polarographic cell (Fatt, 1984), which is now widely used in the contact lens field (Ruben, 1982; Hill et al., 1984), will be described. The cathode is a solid cylinder of gold or platinum. The anode is a hollow cylinder of pure silver. The cathode and anode are cast concentrically in an epoxy cylinder. Thermistors are cast into the unit to monitor the cell temperature and control the temperature of the incubator. When the assembly is cured, the measuring surface is lathed to a convex spherical surface. Fatt (1984 a,b) cut the spherical surface to 7.80 mm radius, since this figure lies at the centre of most trial sets. A special holder was designed to hold the polarographic cell. The cell holder consisted of a clamp to hold the cell and a moveable vertical open cylinder, covered at the lower end with a piece of nylon mesh (a piece of nylon stocking boiled in saline to soften it). This mesh was pressed onto the electrode head without blocking the diffusion of oxygen to the upper lens surface. Thermistors were used to monitor both electrode and incubator temperature. The polarographic current was amplified and recorded.

For rigid lenses it was necessary to use a water-bearing membrane interposed between the lens and the electrode surface. Fatt and Chaston (1981) introduced the use of saline-saturated cigarette paper as the membrane. Fatt (1984) and Brennan et al. (1986) also used ultrathin HEMA lenses of low power as the membrane. Apparently the HEMA lenses gave more reproducible and highly precise results. It was necessary to determine the transmissibility of saline-saturated cigarette paper before transmissibility of the sample could be measured, because the cigarette paper and sample are in series during a measurement.

The polarographic cell shows a small current flow in the absence of oxygen. This current called the "dark current" must be subtracted from the total current measured when oxygen transmissibility of a lens is being determined. The dark current was measured using a non-gas permeable material as sample. Some researchers have used pure nitrogen (Refojo, 1984) to determine the dark current. The dark current in Fatt's system was found to be 0.07 uA.   Fatt and St.Helen (1971) gave the following equation for calculating Dk/L from the measured current:-

$$(Dk / L)t = i / nFA$$

where i is the measured current

n is the number of electrons involved in the reduction of oxygen to hydroxyl ions. (in this case n=4).

F is the Faraday constant

A is the area of the cathode

P is the pO_2 at the open surface of the sample.

t refers to the total transmissibility of the contact lens and the cigarette paper in series.

Fatt and St. Helen reasoned that since transmissibility is the equivalent of resistance, and that the layers are in series, the total resistance is the sum of the resistances of the layers.

Therefore

$$(L/Dk)_T = (L/Dk)_P + (L/Dk)_{CL}$$

where P refers to cigarette paper and CL to contact lens.

By rearranging the equation we get

$$(L/Dk)_{CL} = (L/Dk)_T - (L/Dk)_P$$

The permeability of the material is obtained by multiplying the transmissibility by the thickness (L) of the material.

An alternative method of calculating the permeability is given by Refojo (1984) in the CLAO journal. The measuring polarographic cell is calibrated by using materials of known Dk values, often Teflon membranes. A constant for the cell is calculated from the current, area of the material, thickness of the material, the oxygen pressure gradient and the Dk of the material. For an unknown sample, Dk is calculated using the following equation:-

$$DK = \frac{(\text{current} \times \text{thickness of the material} \times \text{cell constant})}{\text{oxygen gradient}}$$

where the current is in milliamperes, the thickness in centimeters and oxygen gradient in millimeters mercury.

The Dk is then expressed in the following units:-

$$Dk = Z \times 10^{-11} \text{cm}^3.\text{cm}/\text{cm}^2.\text{sec.mm Hg at cell temperature.}$$

In this procedure, transmissibility is then calculated by dividing the permeability by the thickness of the sample, i.e. Dk/L.

Fatt (1979) and Brennan (1984) report that the center thickness should not be used in determining Dk/L as the center thickness is not the true average thickness. These researchers have developed equations to determine the "areal" thickness which should then be used in calculating transmissibility.

Both Dk and Dk/L describe the passage of oxygen through a gas permeable contact lens material. Numerous researchers have attempted to find a relationship between oxygen permeability, EOP and corneal swelling. Fatt and Chaston (1982) plotted graphically, EOP and oxygen tension as a function of lens transmissibility (Dk/L). They found that the set of points were closely grouped around a single straight line. The relationship between EOP and Dk/L was given by the following equation:-

$$EOP = 2.26 \times 10^{8}(Dk/L) - 0.07$$

This equation predicts that a contact lens having a Dk/L value of 7×10^{-9}(cm/sec)(ml O_2/ml x mmHg) would meet the critical oxygen tension of 10 mmHg at the corneal surface as found by Polse and Mandell (1970). It is to be noted that this study did not take into account the effects of blinking.

Weissman (1982) mathematically analysed his data and came up with the following relationship:-

$$P_t = P_a(Dk/L)/(9.7 \times 10^{-8} + [Dk/L])$$

where P_t is the tear layer oxygen tension and P_a is the oxygen tension at the anterior lens surface.

Solving the equation for P_a for oxygen tension values from 50 to 155 mmHg and Dk/L values from 5 to 30 x 10^{-9}cm.ml O_2/sec ml.mmHg, Weissman concluded that corneal swelling begins when the oxygen tension in the precorneal film decreases below 3% to 5% and when the oxygen flux into the cornea decreases below 6 to 7 µl oxygen per cm^2/hr.

O'Neal et al. (1983) measured Dk/L of several hard lens materials and they predicted that lenses having Dk values from 4.5 to 19.10 x 10^{-11} (cm^2/sec)(ml oxygen.mm Hg) would result in an oxygen tension under the lens from 18 to 70 mm Hg in the open-eye state and 1 to 12 mm Hg in the closed eye state. For a +3.00 dioptre lens they predicted an oxygen tension of 14 to 35 mm Hg in the open eye and 0 to 4 mm Hg in the closed eye state. They predicted that lenses having a Dk/L of 17.6 x 10^{-9} cm.ml O_2/sec ml . mm Hg would satisfy the corneal requirements.

Decker, Polse and Fatt (1978) investigated the relationship between oxygen transmissibility of a soft contact lens on the eye and corneal swelling. Their study showed that the higher the oxygen transmissibility the less the corneal swelling under the lens. The soft contact lens apparently causes the oxygen tension at the interface between the lens and the cornea to be lower than in the open eye state without a contact lens. The lens with a higher transmissibility allows a higher oxygen tension at the lens cornea interface. Fatt (1981) states that the soft contact lenses can be ranked in order of oxygen transmissibility by measurement of oxygen uptake by the rabbit cornea immediately after a lens is removed from the eye (EOP method). Lenses of low oxygen transmissibility cause a greater oxygen deprivation of the cornea and a correspondingly greater oxygen uptake rate when the lens is removed. Fatt also points out that this method is not very precise since small differences in oxygen transmissibility amongst different contact lenses may be buried in the uncertainty of the data.

Flynn et al. (1983) and Hill (1986) suggested the use of the "H/T index" to describe the oxygen performance of soft lenses. H is the water content and T is the thickness of the lens. The H/T index was found to have a good correlation with EOP. The H/T index was intended to be a quick and convenient way of estimating the oxygen performance of soft lenses. Several studies have shown that oxygen permeability of soft lenses is related to the water content of the lens (Refojo, et al., 1979). Ng and Tighe (1976) used a modified polarographic technique to measure the Dk of soft lenses. A hard hydrophobic, highly permeable sheet was used as support for the soft lens. The total Dk was calculated and from the known Dk of the supporting sheet, the Dk of the soft lens was calculated.

For more than fifteen years the contact lens industry has been misled by a few researchers in the field of oxygen performance through gas permeable lenses. The industry has been led to believe that oxygen permeability through the lens itself is the most important criterion in the successful wear of contact lenses. Consequently there has been rapid and continuous development in the field of polymer technology, such that the introduction of new materials is now a common occurrence.

On a clinical level, the importance of an adequate supply of oxygen to the cornea has been recognized as a prerequisite to successful lens wear. For many years practitioners have managed to obtain a satisfactory fit with PMMA lenses, which are non-gas permeable. The fact that PMMA lenses work indicates that the fit of a lens is also an important criterion in the successful wear of contact lenses. Those clinicians who found oxygenation problems have resorted to gas permeable lenses in order to solve the problems. Gasson (1981) reported that, in practice, oxygen permeability problems were not completely solved, even with new lens forms. Ewbank (1987) reported that the controversy over the Dk issue still continues with Fatt conceeding at the BCLA conference in Jersey that Dk was of more use to the industry's marketing managers than to practitioners.

1.11 FORMULATION OF PRESENT WORK

This study attempts to resolve the discrepency that exists between measured parameters of oxygen performance of contact lenses and the clinical findings of corneal swelling, caused even by the most permeable lenses. It is well known that the cornea needs a continuous supply of oxygen to its anterior surface. When the eye is open, atmospheric air with a pO_2 of about 155 mm Hg supplies this oxygen. However, there is considerable variation in the minimum oxygen tension required in the precorneal tear film to avoid corneal oedema with contact lens wear. A survey of the literature has shown that the cornea is very active metabolically with continuous synthesis occurring as indicated by the hexose monophosphate shunt and glycolysis and the citric acid cycle. This also indicates a large oxygen demand.

Thus far, determination of oxygen performance of contact lenses has largely involved indirect procedures. However, the pO_2 under the lens in successful contact lens wear can be established directly by embedding microelectrodes in the contact lens itself. This would then be indicative of the minimum pO_2 required under the lens to avoid corneal oedema.

To determine the oxygen performance of contact lenses, it is necessary to measure the actual amount of oxygen (O_2 flux) passing through a contact lens in vitro and in vivo.

In order to carry out these experiments contact lenses containing the microelectrodes had to be designed, constructed and tested in vitro. The construction involved the use of gas permeable lenses in which platinum and silver electrodes were embedded (Chapter 2). The oxygen flux, in vitro, was then measured through the lenses which were placed in an apparatus especially designed and constructed for the experiments (Chapter 2).

Dk is an intrinsic characteristic of the lens material only, and ceases to be relevant when the material is cut and polished to make a contact lens. Oxygen flux measured in vitro, on the other hand, is the only parameter that is relevant to the in vivo oxygen performance of the contact lens. Therefore, contact lenses containing carefully constructed microelectrodes (embedded in the contact lenses) were used for in vivo studies of oxygen flux through the contact lens, or permeability of the lens. In addition, the effect of blinking on the pO_2 under the lens was studied.

Previous studies have shown that lenses coated with an aqueous solution have a lower oxygen flux than dry lenses (Bhagwan et al., 1984; Turnbull et al., 1986). It was also shown that at high Dk values, the measured oxygen flux through contact lenses was not proportionally higher as might be inferred from the Dk values (Postum, 1986). This would appear to indicate a flaw in Dk measurements. Therefore, in the final analysis, this research project is concluded with a proposal for the use of another paramater, based on direct experimental measurements and mathematical calculations, which may represent oxygen performance of gas permeable contact lenses more precisely than Dk values.

CHAPTER 2

CONSTRUCTION OF MEASURING CELL AND IN VITRO CHARACTERIZATION OF OXYGEN PERFORMANCE OF RIGID CONTACT LENSES

2.1 INTRODUCTION

It has always been the desire of contact lens practitioners to have a parameter of oxygen performance of contact lenses, measured in vitro, that could be extrapolated to the in vivo situation. A survey of the literature shows that presently there is no evidence of a direct measure of oxygen performance. Fatt (1969) introduced the theoretical concept of oxygen permeability, defined by Dk, as an index of oxygen performance. According to this concept, the higher the Dk, the better the expected performance of the lenses in vivo. However, clinically, it has been found that Dk and Dk/L (discussed in Section 1.10) do not satisfactorily characterize the oxygen performance of a contact lens on the human eye (Gasson, 1981). The theoretical reasons for inapplicability of Dk will be discussed in Chapter 4.

The concept of higher Dk improving the availability of oxygen to the cornea during contact lens wear has led to the development of numerous types of polymers for the manufacture of contact lenses.

Recently the super-permeable fluorocarbon materials have become available. However, their oxygen performance is also clinically disappointing (Brennan, 1986). Dk and Dk/L are simply based on mathematical and theoretical concepts and have not been supported directly by clinical or experimental findings.

The concepts of Dk and Dk/L should therefore, be rejected as an index of oxygen performance and be replaced by measurements of oxygen flux, in vitro, under carefully controlled conditions. The data obtained should then be used to define the index of oxygen performance of each contact lens type. Oxygen flux, measured in vitro, can be related directly to the corneal oxygen requirement as both are expressed in the same units of measurement viz. µl oxygen/cm^2/hour.

Oxygen flux is defined as the amount of oxygen passing through the contact lens in a given time. The driving force is the pressure gradient between the front and back surfaces of the lenses. Oxygen flux is dependent on this pressure gradient (pO_2) and temperature, both of which can be accurately measured. Oxygen flux is independent of the form (i.e., design and thickness) of contact lenses.

A measurement of oxygen flux is the desired and relevant index of oxygen performance since this in vitro measurement can be equated to in vivo measurements and to corneal oxygen uptake.

A cell was specially designed to hold contact lenses, one at a time, and allow the permeation of oxygen through the lens to be measured directly, with suitable measuring and monitoring devices. The in vivo conditions were simulated as closely as possible. For instance, the boundary effects play an important role in the passage of oxygen from the atmosphere to the cornea. Thus, similar conditions were simulated by maintaining fluid layers on both sides of the lens being tested.

2.2 METHODS

2.2.1 MATERIALS AND EQUIPMENT

Five trial sets of contact lenses were obtained from contact lens laboratories. The lens types were PMMA, SM 38, Polycon I, Boston IV and a fluoropolymer. The latter four were gas-permeable materials which ranged in Dk values as low, medium, high and super-permeable respectively. Each trial set comprised ten lenses ranging in base curves from 7.30 mm to 7.75 mm in 0.5 mm steps. The base curves chosen covered the range required by all the subjects in this study. Each lens had the basic specifications of:

base curve/7.00 mm optic zone/standard flattening factor/ 9.20 mm diameter/-3.00 DS.

All the lenses had centre thicknesses of 0.19 mm. This centre thickness was chosen so that there would be enough stock material to construct the microelectrodes (as described in section 3.2.2). All the lenses were of the single cut, aspheric design.

As no commercially-made equipment was available for measuring oxygen flux of contact lenses, a measuring cell was designed to hold the various contact lenses as well as fit the Radiometer E5047 pO_2 electrode. The cell was constructed from a 10.0cm "Perspex" cube into which a cylindrical chamber of precisely measured diameters was drilled to accommodate the pO_2 electrode and the contact lens. Rubber O-rings were fitted to form gas-tight seals and ensure that there was no exchange with the atmosphere. The electrode tip (sensor) was exposed to the measuring chamber (Figure 2.1) and was not influenced by atmospheric conditions. The contact lens under test was clamped into position by a tight-fitting collar and an O-ring, thus forming an air-tight barrier between the atmosphere and the measuring chamber. Two 16-guage hypodermic needles were also fitted in the "Perspex" block to form the inlet and outlet lines from the measuring chamber. The Radiometer PHM 73 pH/blood gas analyser and J-J Instruments recorder were also used for monitoring and recording results. A constant-temperature air-bath incubator and a digital thermometer were used to maintain the temperature of the measuring cell at 34^0C.

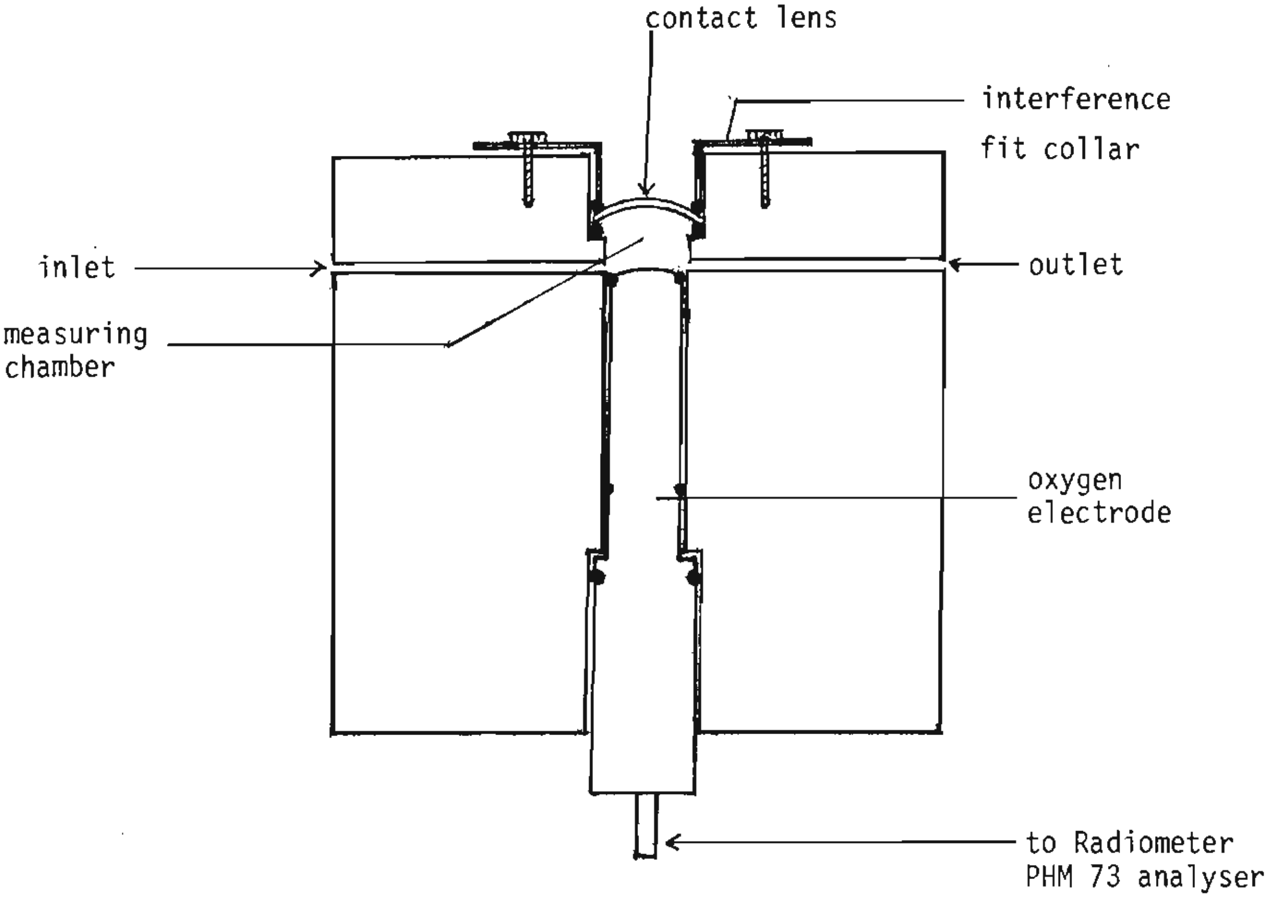

Figure 2.1: The pO_2 measuring cell for in vitro studies. The cell is described in Section 2.2.1.

2.2.2 CALIBRATION OF EQUIPMENT

In this *in vitro* study conditions were set to mimic, as closely as possible, the *in vivo* conditions. Chambers on both sides of the lens were filled with fluid. The system was calibrated by clamping a non-gas permeable PMMA lens *in situ*. Oxygen-deficient saline,i.e., 0.9% saline, through which pure N_2 gas was bubbled for two hours to purge the solution of oxygen, was introduced into the measuring chamber. When the analyser reading had stabilized, the instrument was adjusted to read zero pO_2. This was followed by the introduction of saline through which atmospheric air had been bubbled. The instrument was thus set to read atmospheric pO_2, calculated from the following formula:

Barometer reading - barometer correction factor
= corrected barometer pressure

(The correction was made for expansion of glass in the barometer.) The corrected barometric pressure was then used in the following equation (from Ciba-Geigy Scientific Tables) to calculate atmospheric pO_2.

Atmospheric pO_2 = (corrected barometric pressure

- water vapour pressure) x 20,93/100

Typical values were:-

Atmospheric pressure:	747 mm Hg
Ambient temperature:	25^0C
Barometer correction factor:	3.23
Corrected barometric pressure:	743.7 mm Hg
Water vapour pressure:	23.7mm Hg

Atmospheric pO2 = (20,93/100) x (743.7 - 23.7)

= 150.7mm Hg

2.2.3 USE OF CELL FOR MEASUREMENT OF OXYGEN FLUX THROUGH CONTACT LENS

A lens under study was cleaned thoroughly with a propietary cleaner (Clens, Alcon Labs) and rinsed with saline. The lens was then allowed to soak in a soaking and wetting solution (Soaclens, Alcon Labs) for at least 48 hours. This ensured complete hydration of the lens. The lens was then clamped in the measuring cell using the rubber O-rings. The convex surface (front surface) of the lens faced atmospheric air. A hypodermic syringe was used to place 0.01ml saline (0.9%) over the front surface of the lens. Saline (0.9%) saturated with pure nitrogen was introduced into the measuring chamber and when the system had stabilised the zero baseline was recorded. This ensured that there was fluid on both surfaces of the lens to simulate the condition of the lens on the cornea. The inlet and outlet taps were closed, atmospheric air was then allowed to diffuse through the lens into the measuring chamber. The resultant change in pO_2 with time was recorded. The change in pO_2 was recorded for at least 30 minutes for each lens. During the recording time, the temperature was maintained constant at 34^0C in the air-bath incubator and no fluctuation in temperature was noted. Each lens was run three times and the averaged value was used in the calculation of the oxygen flux through the lens.

The volume of the measuring chamber (v_1) was measured by placing a flat "Perspex" disc instead of the contact lens in the measuring chamber. The inlet and outlet taps were closed and a 0.2mm hole drilled in the disc allowed the measuring chamber to be filled with saline using a micro-syringe. Air bubbles were eliminated by filling the chamber slowly and frequent tapping of the measuring cell to expell air bubbles.

The volume due to the sag (v_2) of the contact lens was calculated using the formula

$$v_2 = (0.33\pi h^2) x (3r - h)$$

where h is the sag of the lens and r is the base curve.

Total volume (V) = $v_1 + v_2$

The area of the front surface of the contact lens was calculated using the formula:

$$A = \pi (0.5d^2 + h^2)$$

where d is the diameter of the lens (9.20mm in this study) and h is the sag (Figure 2.2).

The sag of the contact lens was calculated using the formula:

$$h = r - \sqrt{r^2 - (d/2)^2}$$

2.3 **RESULTS**

2.3.1 **MEASUREMENT OF pO_2 AND USE OF DATA**

A typical profile for the pO_2 recorded for a contact lens in the measuring cell is presented in Figure 2.3. Measurements were made in triplicate for each lens type and each base curve. Each pO_2 measurement was used to calculate oxygen flux, which was then corrected to STPD (standard temperature and pressure [dry]) for each base curve. Average values and standard deviations of

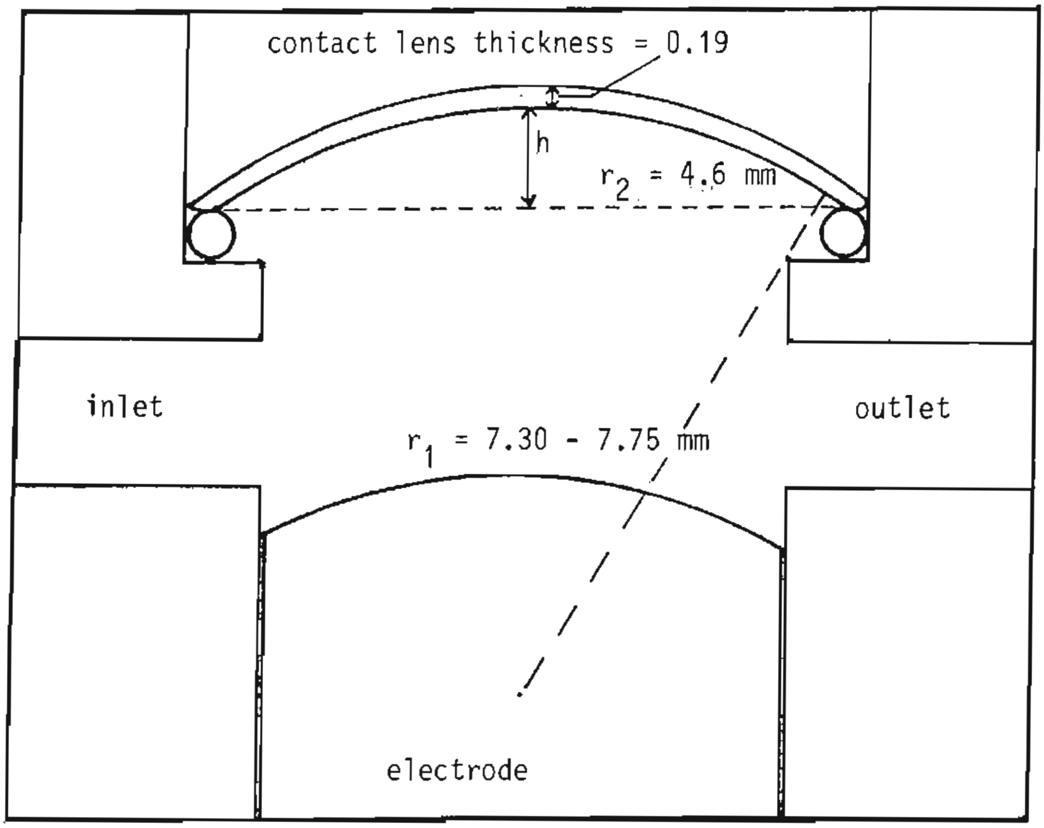

Figure 2.2: Enlarged view of the pO_2 measuring cell. The volume under the contact lens was calculated as described in the text.

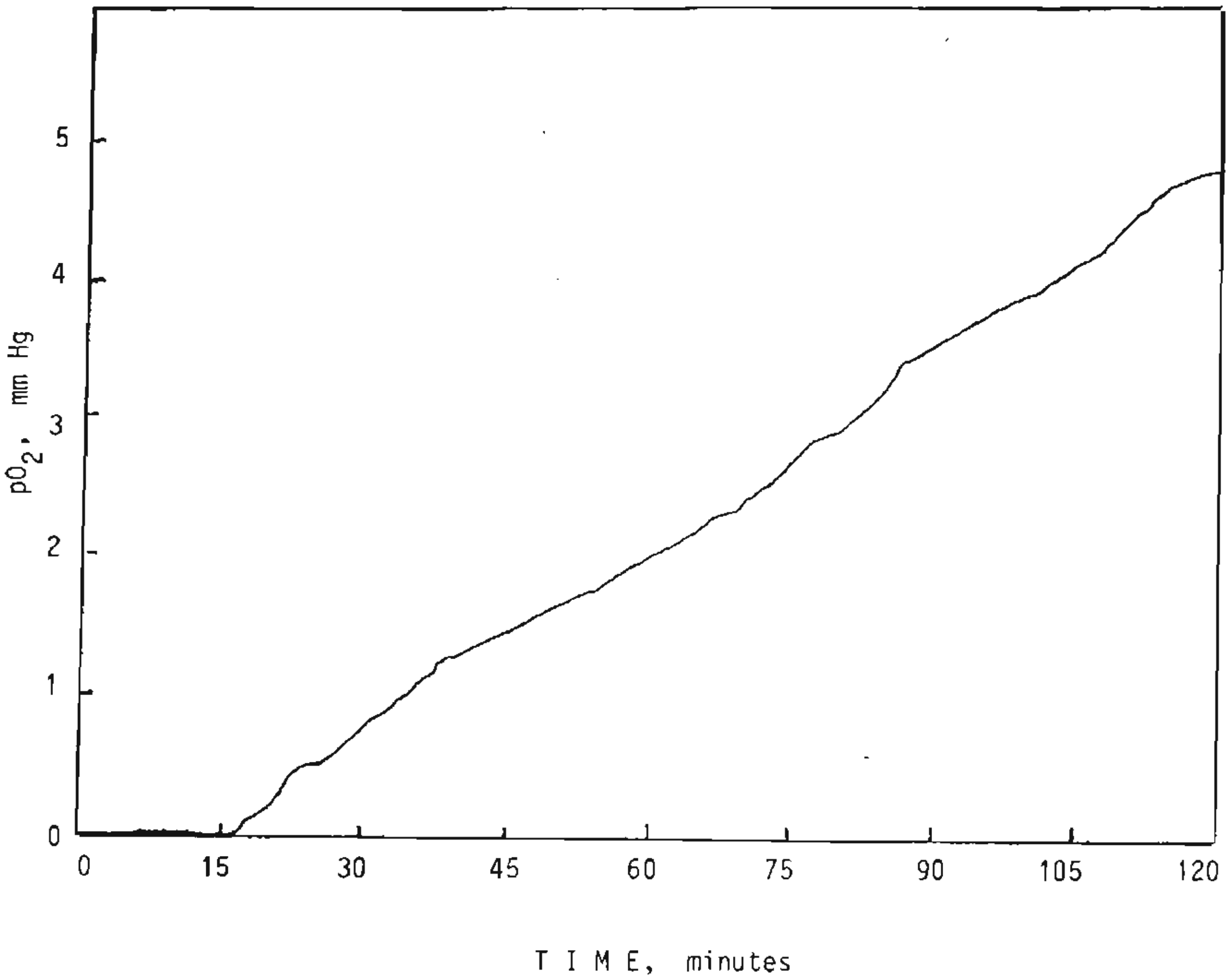

Figure 2.3: Typical pO_2 profile obtaines for contact lenses used in *in vitro* studies. Oxygen flux was calculated from such recordings after correcting to STPD. Data obtained from the recordings are presented in Tables 2.1, 2.2, 2.3 and 2.4.

oxygen flux at STPD were also calculated. Results are presented in Tables 2.1, 2.2, 2.3, and 2.4. The standard temperature and pressure (dry) was determined as shown in Section 2.3.2. Oxygen flux was calculated as described in Section 2.3.3.

2.3.2 **CONVERSION OF DATA TO STPD CONDITIONS (STANDARD TEMPERATURE AND PRESSURE, DRY)**

Since pO_2 measurements differ under variations of temperature and pressure, standardized procedures for handling of gasometric data of contact lenses were adopted. For a given barometric pressure and temperature reading, a correction factor was obtained from Geigy Scientific Tables. Subtraction of the correction factor from the barometric pressure yielded the corrected barometric pressure. The corrected barometric pressure and the cell temperature of 34^0C were used to obtain a second factor (gas reduction factor) for the conversion of pO_2 readings to gas volumes at STPD. The gas volumes were multiplied by the second factor to obtain corrected gas volumes.

2.3.3 **CALCULATION OF OXYGEN FLUX**

The change in pO_2 with time was recorded. Using the recorded data, the calculation of oxygen passing through the contact lens in a given time can be calculated as follows:

$$\text{OXYGEN FLUX} = \frac{[pO_2\ (\text{final}) - pO_2\ (\text{initial})] \times V \times 1000}{\text{corrected atmospheric pressure}} \times \frac{1}{A}$$

where A is the area of the contact lens and V represents the total volume of the measuring chamber. Since the initial pO_2 is equal to zero (pure nitrogen in the measuring chamber) and A and V are determined by calculation, oxygen flux was calculated.

In this study, the oxygen flux of PMMA lenses was found to be negligible over the measuring period (30 minutes).

POLYCON I

Oxygen flux, µl /cm^2 / hr (STPD)

BC	T_1	T_2	T_3	Ave	S D
7.30	1.29	1.39	1.19	1.29	0.10
7.35	1.37	1.39	1.19	1.32	0.11
7.40	1.19	1.37	1.27	1.28	0.09
7.45	1.15	1.41	1.29	1.28	0.13
7.50	1.22	1.24	1.39	1.28	0.09
7.55	1.24	1.27	1.41	1.31	0.09
7.60	1.27	1.31	1.32	1.30	0.07
7.65	1.31	1.19	1.27	1.26	0.07
7.70	1.35	1.18	1.29	1.27	0.09
7.75	1.39	1.19	1.30	1.29	0.10
				1.29	0.09

TABLE 2.1 : Oxygen flux determined for the Polycon I contact lenses measured under in vitro conditions. T_1, T_2, T_3 represent values obtained in three tests for lenses of different base curves (BC). Average values (Ave) and standard deviations (SD) are indicated. Studies were carried out at 34^{0}C. Correction for STPD is described in Section 2.3.2.

SM38

Oxygen flux, μl / cm^2 / hr (STPD)

BC	T_1	T_2	T_3	Ave	S D
7.30	1.74	1.85	1.65	1.75	1.10
7.35	1.78	1.98	1.16	1.81	0.16
7.40	1.82	1.72	1.62	1.72	0.10
7.45	1.66	1.60	1.92	1.73	0.17
7.50	1.60	1.65	1.91	1.72	0.17
7.55	1.95	1.72	1.66	1.78	0.15
7.60	1.72	1.66	1.95	1.78	0.15
7.65	1.72	1.75	1.82	1.76	0.05
7.70	1.75	1.82	1.55	1.71	0.14
7.75	1.78	1.91	1.55	1.75	0.18
				1.75	0.14

TABLE 2.2 : Oxygen flux determination of SM 38 lenses in vitro. T_1, T_2 and T_3 represent values obtained in three tests for lenses of different base curves (BC). Average values (Ave) and standard deviations (S D) are indicated. Studies were carried out at 34^{0}C. STPD calculations and other parameters are described in the text.

BOSTON IV

Oxygen flux, µl / cm^2 / hr (STPD)

BC	T_1	T_2	T_3	Ave	S D
7.30	2.60	2.89	2.99	2.83	0.20
7.35	2.70	2.47	2.90	2.69	0.22
7.40	2.90	2.87	3.04	2.94	0.09
7.45	2.92	2.32	3.00	2.75	0.37
7.50	2.99	3.02	2.87	2.96	0.08
7.55	2.32	2.87	3.00	2.73	0.36
7.60	3.02	2.97	2.99	2.99	0.03
7.65	2.87	3.04	2.97	2.96	0.09
7.70	3.02	2.92	3.00	2.98	0.05
7.75	2.87	2.98	3.07	2.97	0.10
				2.88	0.16

TABLE 2.3 : In vitro measurements of oxygen performance of the Boston IV contact lenses of base curves (BC) ranging from 7.35 to 7.75. Three measurements (T_1, T_2, T_3) were averaged (Ave) and the standard deviation (SD) was determined. STPD calculations are described in the text. Experiments were carried out at 34°C.

FLUOROPOLYMER

Oxygen Flux, µl / cm^2 / hr (STPD)

Base curve	T_1	T_2	T_3	Ave	S D
7.30	3.20	3.82	3.47	3.50	0.31
7.35	3.37	3.58	3.92	3.62	0.28
7.40	3.88	3.27	3.48	3.54	0.30
7.45	3.02	3.92	3.37	3.44	0.45
7.50	3.84	3.47	3.67	3.66	0.19
7.55	3.50	3.86	3.78	3.71	0.19
7.60	3.62	3.42	3.91	3.65	0.25
7.65	3.88	3.78	3.57	3.72	0.13
7.70	3.84	3.84	3.92	3.87	0.05
7.75	3.19	3.76	3.58	3.51	0.29
				3.62	0.24

TABLE 2.4 : Oxygen flux determination of Fluoropolymer contact lenses. The average of three measurements (T_1, T_2, T_3) and standard deviation (SD) were calculated. Experiments were carried out at 34^{0}C at STPD as described in the text.

MATERIAL	C_t	Dk	**Av O_2 flux (S.D)** $\mu l/cm^2/hr$(STPD)	**AVE O2 FLUX** (34^0C,747mmHg)
PMMA	0.19	0	0	0
Polycon I	0.19	5	1.29 + 0.09	1.56
SM 38	0.19	12	1.75 + 0.14	2.12
Boston IV	0.19	24	2.88 + 0.16	3.48
fluoropolymer	0.19	72	3.62 + 0.24	4.38

TABLE 2.5 : Average oxygen flux, Dk values given by manufacturers and STPD are tabulated for the different contact lenses under study. Centre thickness (C_t) of all the lenses were the same. Dk values are supplier's values.

The data presented above indicates that the oxygen flux ranges from 1.56 to 4.38 $\mu l/cm^2/hr$ for the different lenses studied. Even the super-permeable lenses do not transmit sufficient oxygen under the test condition to satisfy the minimum corneal oxygen requirement as stated by Mandell (1984).

CHAPTER 3

CONSTRUCTION OF CONTACT LENS MICROELECTRODES AND IN VIVO DETERMINATION OF OXYGEN PERFORMANCE OF THE CONTACT LENS MICROELECTRODES

3.1 INTRODUCTION

The most direct method of determining oxygen performance of contact lenses is to measure the pO_2 under the lens in situ in the human eye. Hill and Fatt (1963) have used large scleral flange lenses in an attempt to measure oxygen performance. Hamano et al. (1986 a,b) have attempted to make direct measurements by recording the pO_2 in the conjunctival sac. However, this is not a true reflection of the pO_2 under the contact lens, and the effects of blinking have not been quantified.

A study of the literature shows that none of the methods employed to study oxygen performance of contact lenses are direct methods of assessment. It was decided that the only possible direct method of measuring oxygen performance was to implant microelectrodes into the contact lenses. Since no such contact lenses were available commercially, these had to be designed, constructed, rigorously tested and then utilized for in vivo studies. Geddes (1968, 1972) and Fatt (1964) have proposed that the most appropriate electrode materials are gold or platinum for cathode and silver-silver chloride for anode. The reduction of oxygen at a cathode gives rise to a current which is proportional to the oxygen tension in the solution, provided that a constant polarising voltage of 0.5 to 0.8 volt is applied across the electrodes. Using a platinum electrode as cathode and a silver-silver chloride anode, four electrons are generated at the anode (Geddes,1972), which are used to reduce a molecule at the cathode. The oxygen tension at the cathode drops to zero and this acts as a "sink" so that oxygen diffuses towards it to make up the deficit (Fatt, 1976). The reactions that occur (Wilson and Goulding, 1986) are:

$$O_2 + 2H_2O + 2e' \longrightarrow H_2O_2 + 2OH^-$$

$$H_2O_2 + 2e' \longrightarrow 2OH^-$$

In this study it was decided to use platinum and silver electrodes for the cathode and anode, respectively, for the microelectrodes implanted into the various types of contact lenses. Construction of such electrodes has not been cited in the literature. Thus the contact lens micro-electrodes were designed from first principles of oxygen measurements (Geddes, 1972), leading to the development of microelectrodes embedded in contact lenses which could be worn directly on the cornea by human subjects who were accustomed to prolonged contact lens wear. The cornea was carefully examined to ensure that there was no corneal damage following contact lens microelectrode wear by the volunteers.

3.2 MATERIALS AND METHODS

3.2.1 DESIGNING THE CATHODE AND ANODE

Fine platinum and silver wire stock, of 0.1 mm diameter, was obtained under special permit. The wires were cut into 10 mm pieces. The tip of each silver wire was heated in a bunsen flame to form a rounded beaded tip. Wire pieces with bead diameter between 0.2mm and 0.3mm were selected for use in construction of microelectrodes. Bead diameters were measured by means of a Loupe magnifyer with a graticule (Peak 7x). Platinum wires were treated in the same way as the silver wires, except that the tips of the platinum wires had to be heated with an oxyacetylene flame to form the beaded tips.

The beaded tips of the platinum and silver wires were again carefully examined for uniformity and smoothness. Irregularly formed beads and beads with protrusions were discarded. A binocular magnifying microscope was utilized for examining the beads. Each selected wire with the correct dimensioned bead was then cleaned with hydrochloric acid, washed thoroughly with distilled water, dried and finally covered with an even spread of lacquer to form an insulation. A surgical blade was subsequently used to cut each beaded tip in half. This resulted in the formation of a hemisphere at the end of each insulated wire, with a flat, uninsulated surface of diameter between 0.2 mm and 0.3 mm (Figure 3.1). Each flat, uninsulated surface constituted the measuring surface of the fully constructed microelectrode (Section 3.2.3).

3.2.2 PREPARATION OF CONTACT LENSES FOR THE CONSTRUCTION OF MICROELECTRODES

The platinum and silver microelectrodes were built into contact lenses that subjects wore on the cornea during the study. Trial lens sets in five different materials were used: PMMA, Polycon I, SM 38, Boston IV and a Fluoropolymer. The base curves ranged from 7.30 mm to 7.75 mm in 0.5 mm steps. All the subjects in this study could be fitted with a lens from this range of base curves. All the lenses had a diameter of 9.20 mm and were of the aspheric design, with a standard flattening factor. All the lenses had a power of -3.00 DS. Aspheric lens design was chosen

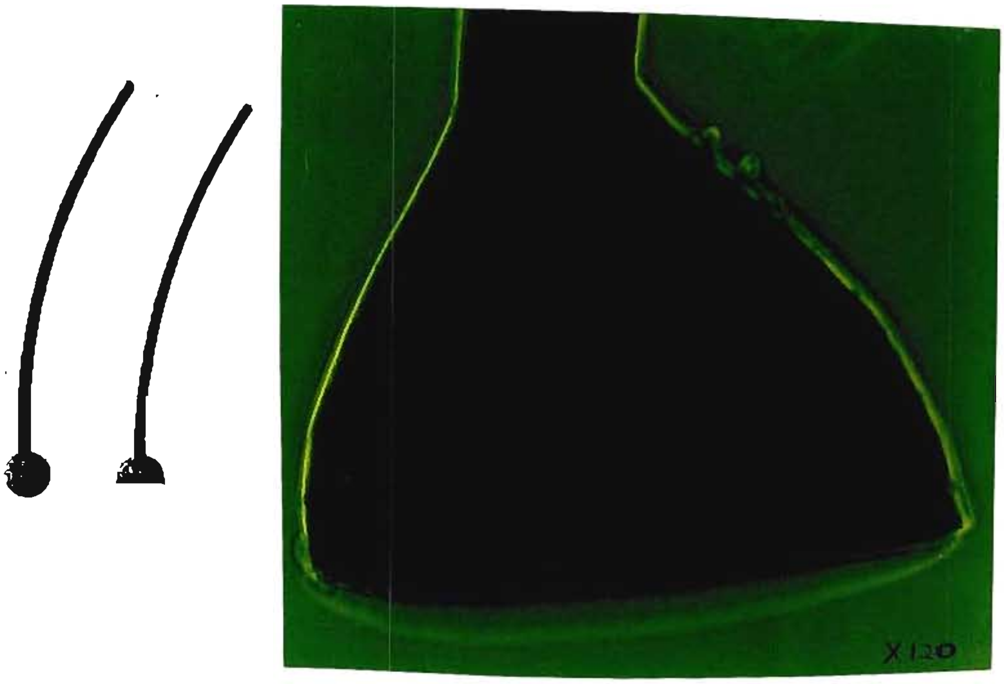

Figure 3.1: Platinum and silver electrodes were made as described in Section 3.2.1. After insulation of the microelectrodes, the beads were cut to expose an uninsulated flat surface (right).

because of the good fit obtained with this type of lens at the University of Durban-Westville Optometric clinic. Ames and Erikson (1987) reported that aspheric lenses were less sensitive to fitting relationships and that they showed less tendency to decentre vertically.

Each trial lens was fenestrated at two points, 5 mm apart, within the optic zone. A 0.2 mm drill bit, held in a pin vice, was used for the fenestration, which was made from the posterior surface of the lens, towards the anterior surface. This ensured that any distortion or break in the lens surface occurred on the anterior surface, away from the cornea. A 0.3 mm bit was then used to further enlarge the fenestration from the anterior surface, penetrating two-thirds of the lens thickness only. Thus each contact lens had two fenestrations of 0.3 mm diameter from the anterior surface, narrowing to 0.2 mm at the posterior surface. The edge of the fenestration at the posterior surface was lightly polished. A toothpick dipped into a finely abrasive polish (Silvo) diluted with Soaclens was used for this purpose.

3.2.3 ASSEMBLY OF THE CONTACT LENS ELECTRODES

The electrodes (silver and platinum prepared as described in Section 3.2.1) were carefully placed in the fenestrations of the contact lenses from the anterior surface, such that each bead rested in the 0.3 mm diameter orifice without reaching the posterior surface of the lens (Figure 3.2). Each electrode was fixed in position with the use of liquid acrylic which was applied by means of a micropipette attached to a blow-tube. The silver electrode was chlorided in situ as described by Geddes (1972), using a 0.9% saline solution and a voltage of 1.5V for 30 seconds. The contact lens electrode was then cleaned with Clens (a proprietary contact lens surface cleaner) and distilled water. Each microelectrode was then aged for 48 hours in Soaclens (a hard contact lens wetting and storage solution) to stabilize the electrodes (Geddes, 1972).

3.2.4 FINAL ASSEMBLY OF IN VIVO SYSTEM FOR THE MEASUREMENT OF OXYGEN PERFORMANCE OF CONTACT LENSES

For use on subjects each contact lens microelectrode was attached to a module containing an integrated circuit, which was included in series to combat and regulate any voltage drop of the batteries used in the circuit. This device was mounted on a spectacle frame for easy use on the subjects as well as to reduce the length of the wires from the contact lenses and thus reduce electrical noise. The batteries for the voltage regulator were

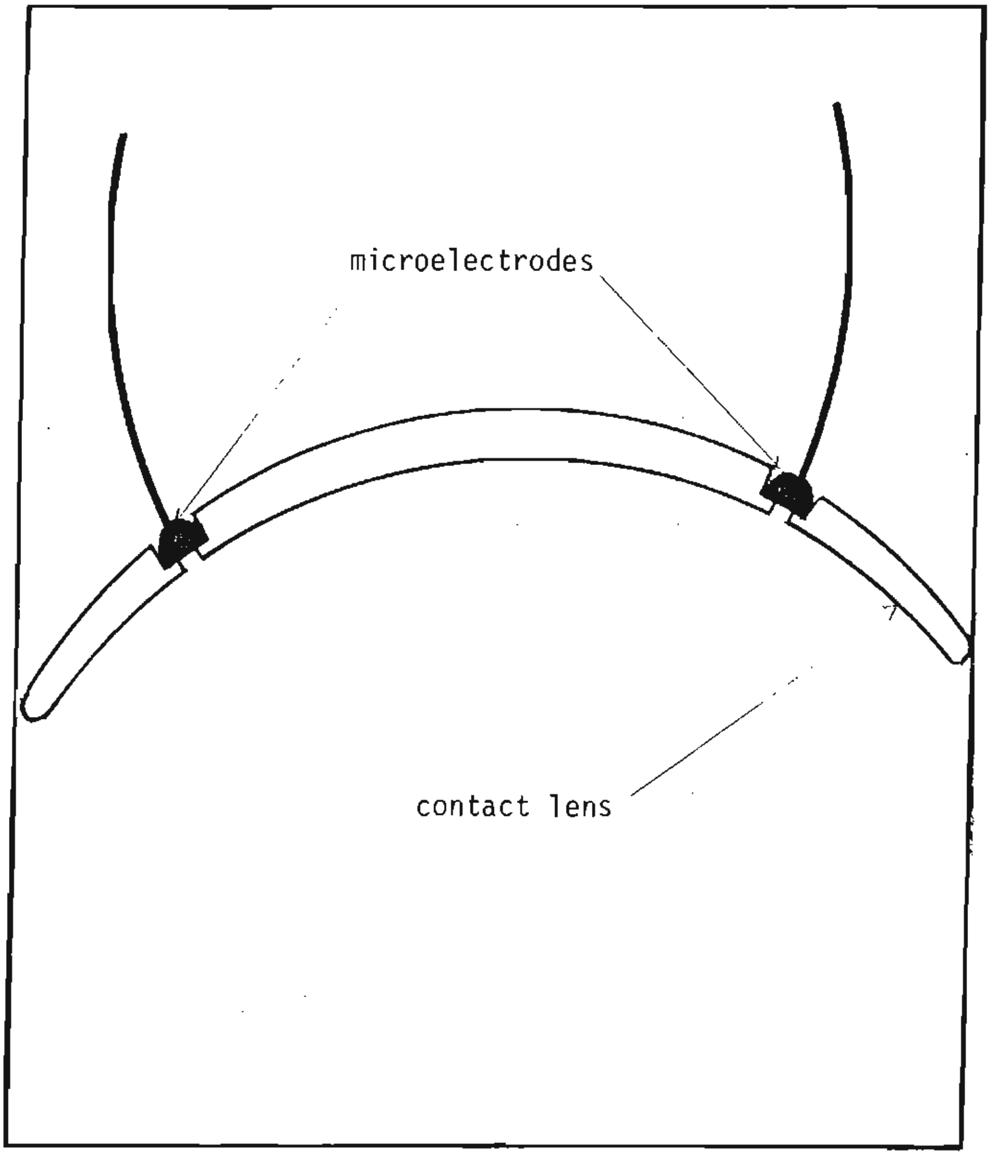

Figure 3.2 Contact lens microelectrode constructed as described in Section 2.3.2.

also mounted on the spectacles. The in vivo oxygen performance of each contact lens on the human cornea was monitored by means of a Philips digital multimeter. All data was subsequently analysed with the aid of a computer. A photograph of the assembled measuring devices is given in Figure 3.3.

3.2.5 CALIBRATION OF THE CONTACT LENS MICROELECTRODE SYSTEM

Since each electrode system varied slightly with respect to area and consequent output current, each system had to be calibrated individually. A cell was designed for calibrating each contact lens microelectrode system. The cell was constructed from a block of Perspex of dimensions 5.0cm (thickness) x 5.0cm (width) x 10cm (length). A hole of 7.00 mm was drilled through the length of the Perspex block and enlarged to 9.20 mm to a depth of 2.5cm (Figure 3.4). Two holes (2.0 mm) were drilled at right angles to and passing through the 9.00 mm bore, to serve as inlet and outlet, respectively, for gasses. A third hole was drilled to enter at the 7.00 mm main bore for flushing N_2 through. An O-ring was fitted to the ledge of the main bore to form a gas-tight seal when the contact lens microelectrode was placed on the ledge, between the 9.0 mm (upper) and the 7.00 mm (lower) chambers.

The contact lens electrode to be calibrated was placed with the

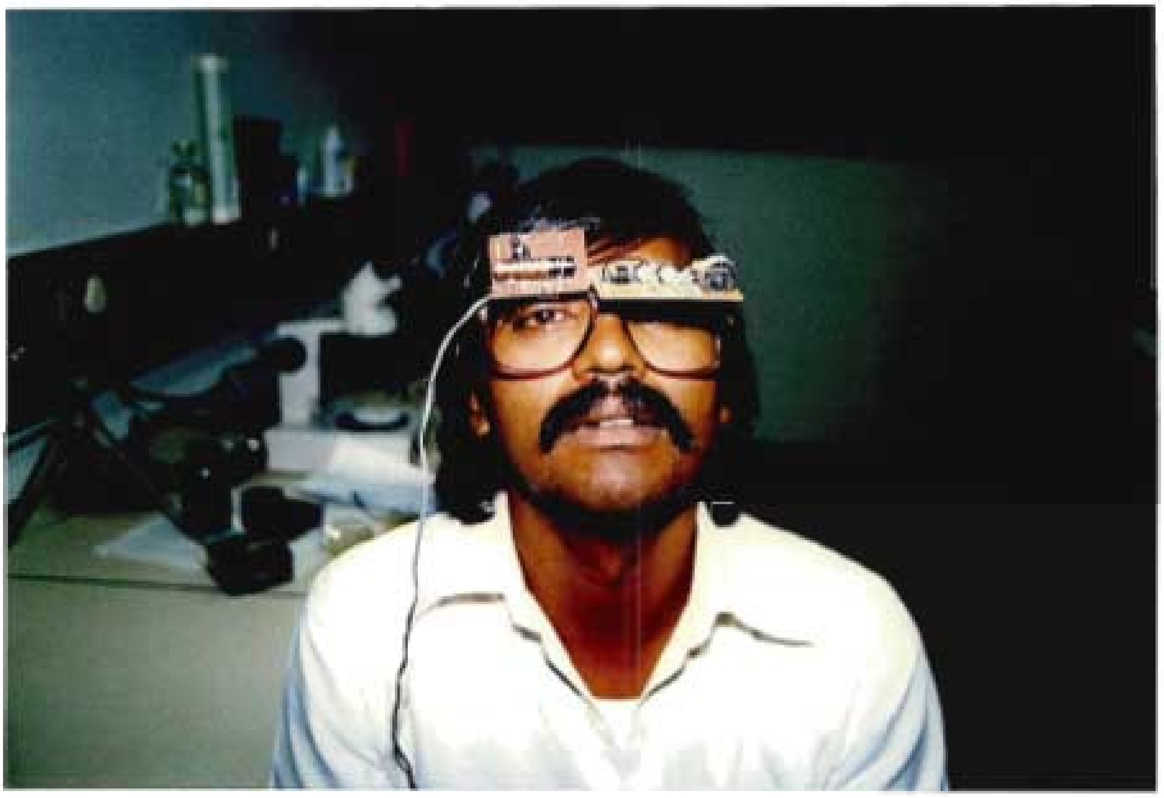

Figure 3.3: Contact lens microelectrode assembly worn by subject. The microelectrode was worn in the right eye. The electronics were mounted on the spectacle frame (Section 3.2.4).

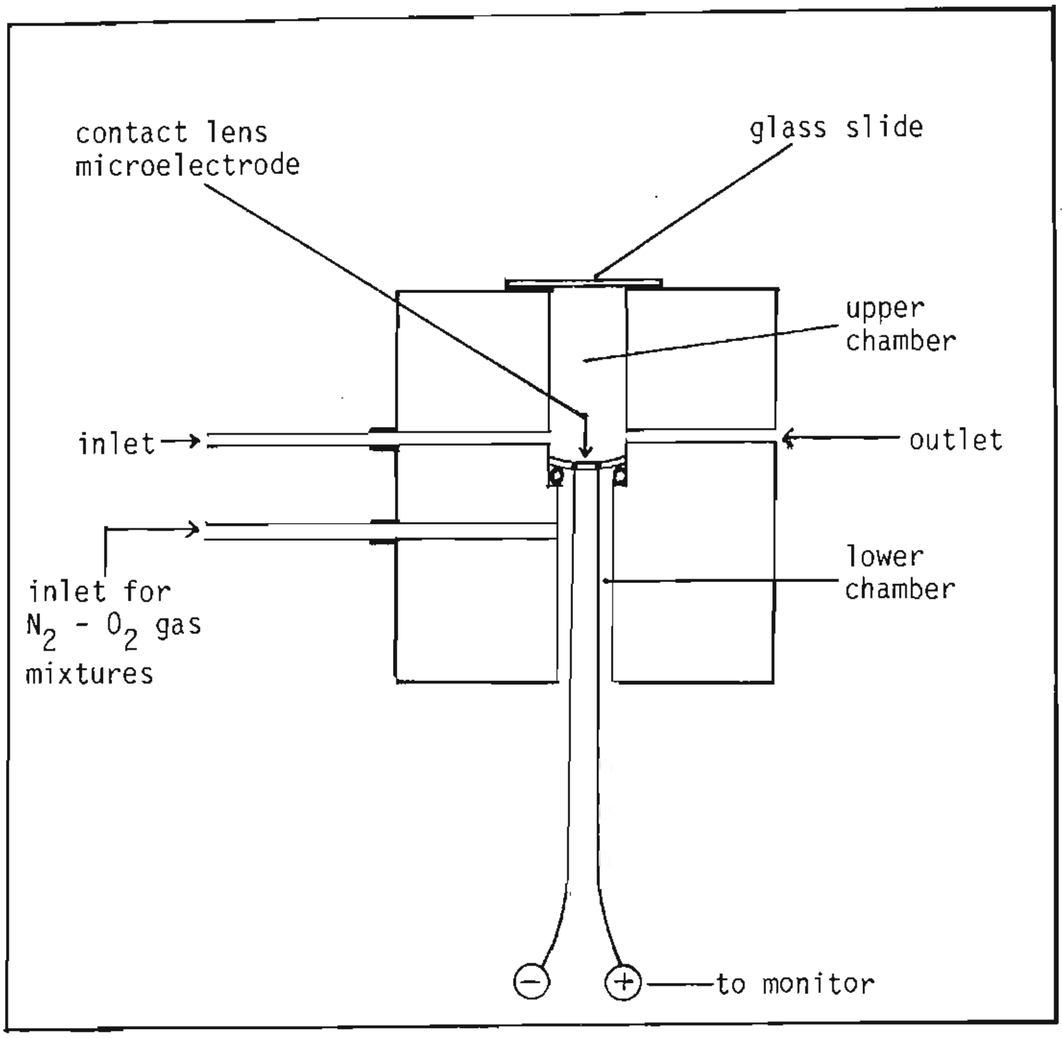

Figure 3.4: Measuring cell for calibration of contact lens microelectrodes used in *in vivo* studies.

back (posterior) surface of the contact lens and electrodes exposed to the upper chamber of the cell. A glass slide was used to seal the upper chamber to eliminate interference from atmospheric air during the calibration. The lower chamber was flushed with a continuous stream of nitrogen gas throughout the calibration procedure, to prevent diffusion of oxygen from the anterior surface or lower chamber. Air-saturated saline (0.9%) was introduced into the upper chamber via the inlet and bathed the posterior surface of the contact lens and the electrodes.

Nitrogen-aerated saline, which had been previously boiled to remove all gasses, including oxygen, was introduced into the upper chamber. The contact lens microelectrode was connected to the polarizing voltage circuit and the current was recorded. This current, recorded in the absence of oxygen, is known as the dark current (approximately 7.0 to 20.0 nA). Then, specially mixed gasses consisting of pure nitrogen gas containing 2.5% O_2, 5% O_2, 7.5% O_2, 10% O_2, and 15% O_2 respectively were introduced into the upper chamber and the concomitant current recorded. An extra point on the calibration was obtained by passing atmospheric air (20.93% oxygen) through the upper chamber. A calibration curve of O_2 versus current was plotted for each contact lens electrode.

The calibration of each contact lens electrode was carried out before, and rechecked after each contact lens electrode was used to determine pO_2 on the human cornea. The calibration was carried out at atmospheric pressure (recorded), at 34^0C, to correspond to the mean corneal temperature.

3.2.6 **MEASUREMENT OF pO_2 UNDER A LENS IN VIVO**

Each subject was an adapted contact lens wearer. A contact lens-electrode having the same base curve, diameter and design as his habitual lens was constructed for the study. Each contact lens electrode used was thus the best fit for each subject. Each contact lens electrode (cleaned as described in Section 3.2.3) was placed on the right cornea of the subject. The electrode wires were connected to the electronics on the spectacles described in Section 3.2.4, with the silver-silver chloride electrode attached to the positive terminal and the platinum electrode connected to the negative terminal. The reduction current was measured by means of the Philips Digital Multimeter. This instrument has the necessary sensitivity and stability to measure current down to 0.1 nA.

Each subject was asked to blink normally (about 18 to 22 blinks per minute). The recordings obtained were a summation of pO_2 under the lens, the effect of blinking and the change in mean pO_2 with time. The subject was then asked to stop blinking for as long as possible (up to two minutes in some subjects) so that the rate of oxygen uptake could be recorded. The above procedures were repeated three times.

Subjects were allowed to wear contact lens electrodes for a maximum of 30 minutes. During this time all the necessary data was obtained and the cornea was not unnecessarily traumatized.

3.3 **RESULTS**

3.3.1 **CALIBRATION OF THE CONTACT LENS ELECTRODES**

Tables 3.2 to 3.6 show the oxygen reduction current recorded with the various gas mixtures. The values shown are the recorded current minus the dark current. A calibration curve was drawn for each contact lens electrode. This curve would give the oxygen tension under the contact lens when the oxygen current was recorded (Section 3.2.6). A typical calibration curve is presented in Figure 3.5.

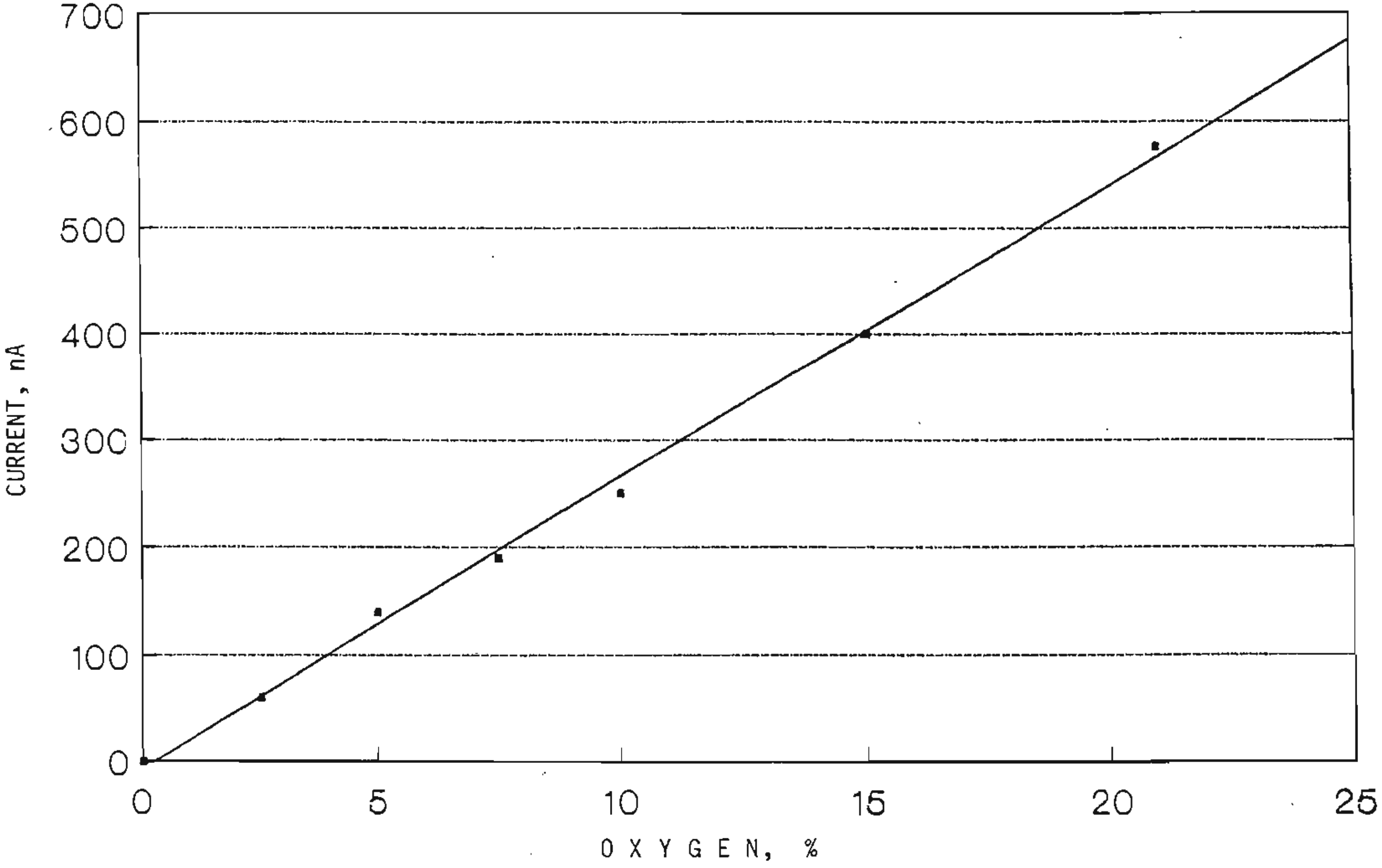

Figure 3.5: Calibration curve for the contact lens microelectrode.

3.3.2 THE OXYGEN REDUCTION CURRENT RECORDED IN VIVO AND THE DETERMINATION OF THE OXYGEN TENSION UNDER THE LENS THEREOF

A hardcopy recording of oxygen reduction current was obtained for each lens on each subject. Ten baseline readings of current were taken off the recording and converted to oxygen tension by referring to the calibration curve (obtained in section 3.3.1) for the lens under test. Similarly the peak current due to blinking was recorded and converted to oxygen tension. The averaged value and standard deviation for each test was determined. The two-tailed t-test was done to test the validity of the sampling. The average values were used in all the calculations and discussion that follow. The data obtained in the *in vivo* experiments and the results of the statistical analysis is presented in the appendix. A typical profile obtained during *in vivo* experiments is presented in Figure 3.6.

3.4 DISCUSSION OF THE METHODOLOGY

3.4.1 SUBJECTS USED AND TYPES OF CONTACT LENSES USED

Fifteen subjects volunteered for this study. The subjects were either rigid contact lens wearers or those who wished to wear

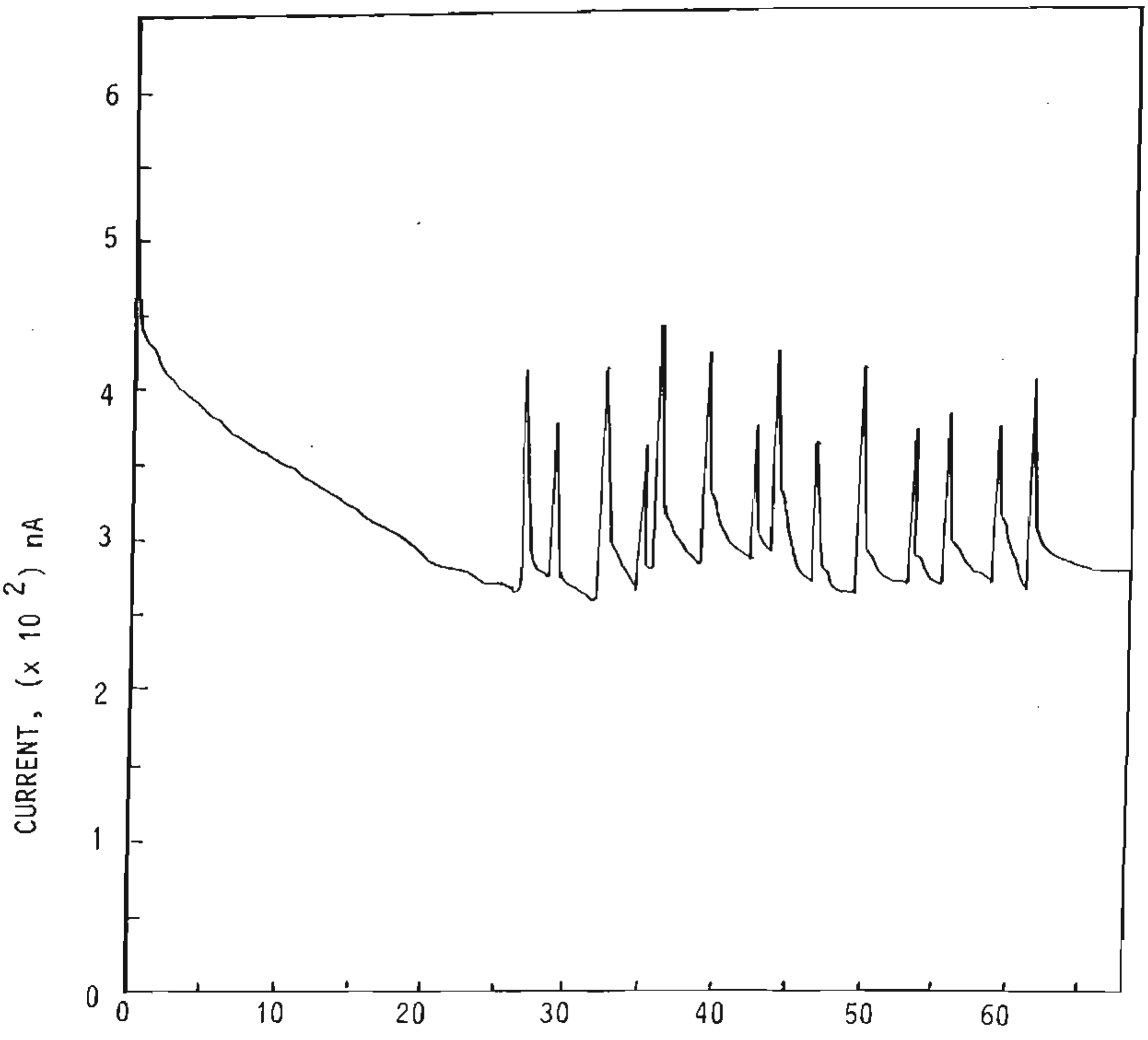

Figure 3.6: A typical profile obtained in the *in vivo* experiments.

rigid contact lenses. Informed consent was obtained from each subject. All subjects agreed to wear PMMA lenses for the correction of their refractive error. Prior lens wearers were reassessed and supplied with a free pair of lenses. New lens wearers were assessed and lenses of best fit determined by the standard clinical procedures. These patients were also supplied with free lenses. The subjects chosen had spherical or near spherical corneas. The average "K" readings were 43H/V44 and the average Rx was -2.75 D. The subjects were assessed regularly for the next three months to ensure that the lens of best fit had been obtained.

Only adapted subjects were used in this study because the microelectrode wires caused slight irritation (tickling sensation) of the lashes which was well tolerated by adapted contact lens wearers. Because of the flexibility of the wires a good fit and centration of the contact lens microelectrodes was maintained on the cornea. Blinking did not traumatize the cornea or the subject. Recordings of oxygen performance with and without blinking were thus made with ease. Reaction to the same stimuli elicited the usual violent blinking and tearing response in a few unadapted volunteers and resulted in breakages of the fine electrode wires. Unadapted subjects (non contact lens wearers) were therefore not used in this study. Lenses of the five different materials used in this study and corresponding to the same refractive correction for each subject's right eye were used. The lenses had the following specifications:

BC / 7.00 / StFF / 9.20 / -3.00 DS.

The types of lenses used are discussed in Section 3.2.2. The Dk values of the lens materials is indicated in Table 3.1. After-care examination of subjects was carried out (fluorescein and slit lamp examination) to ensure that there was no corneal damage.

3.4.2 THE CONTACT LENS MICROELECTRODES

Construction of the contact lens microelectrodes was carried out with the utmost care thus ensuring that the use of the microelectrodes would be safe for the subjects. Fenestrations in the contact lenses were properly polished so as not to damage the cornea. The microelectrodes did not touch the cornea but were recessed to further protect the cornea and ensure that a tear film existed between the cornea and the microelectrodes (Figure 3.2). The silver microelectrodes were chlorided according to standard procedure as described by Geddes (1972). Successful chloriding was seen as a fine black coating of the cut surface of the electrodes. Silver-silver chloride electrodes have been reported to have lower impedence and greater stability than any other polarographic electrodes (Geddes, 1972). In addition, chloriding the electrodes reduced the spontaneous noise. Thus the output current during measurements was larger because impedence was reduced and the surface area was increased. The aging process (Section 3.2.3), on the other hand, was carried out to stabilize the electrodes and remove any impurities that might have been trapped on the electrode surface during the chloriding process. The method followed in the preparation of the electrodes ensured that high fidelity recordings could be obtained. The high sensitivity and low noise of the system also enabled the author to detect the small differences in oxygen permeability of the lenses under test.

An interesting phenomenon noted was that on placing the electrode on the subject's cornea, the whole system was electrically damped. Noise that was present during the calibration procedure was absent in the <u>in vivo</u> experiments. This may be explained by an optimal combination of inductances and resistances in the system that produced a high signal to noise ratio (Geddes, 1972).

A survey of the literature has shown that a number of factors have to be considered for the construction of the oxygen microelectrodes. The polarographic electrodes have to be encased and oxygen is measured through an oxygen permeable membrane at the base of the electrode. This, in the long term, prevents contamination of the anode and cathode. In this study, however, short-term recordings were done, thus eliminating the problems of contamination. Also the design of the contact lens microelectrode was such that a "recessed" electrode was obtained. According to Lessler and Brierley (1969) the recessed electrode gave accurate measurements of oxygen content with a calibrated electrode and there was excellent current linearity with oxygen tension. This type of electrode is relatively free of movement artifact since the solution in the recess is protected from convection.

Fatt (1976) has recommended the use of polarizing voltages of 0.5V to 1.2V for polarographic electrodes. Most researchers use dry cells or button type mercury cells to provide the voltage. However, it was found that, in the calibration procedures, the battery voltage dropped during usage and the recorded current was related to the falling voltage. A special circuit was designed and built by an electronics technician in the Department of Engineering, University of Durban-Westville, to control and regulate the voltage supply. This circuit maintained the voltage at a constant 0.72 volt. It is apparent from the literature that studies carried out do not take into account the fall in battery voltage. Hence results presented in the literature may therefore represent falling battery voltages rather than the oxygen concentration. Calculations of Dk values cited in the literature have also been made with the use of batteries, and correction of falling battery voltage has not been indicated.

LENS MATERIAL	**Dk**(supplier's data)
PMMA	0
POLYCON I	5
SM 38	13
BOSTON IV	23
FLUOROPOLYMER	72

TABLE 3.1: Dk values of different lens materials used to make microelectrodes.

PMMA

		Current in nA at Specific Calibration Gasses(%)					
BC	DC	2.5%	5.0%	7.5%	10%	15%	21%
7.30	11	60	140	190	250	400	576
7.35	16	61	138	189	257	387	544
7.40	12	65	144	187	248	324	538
7.45	9	58	141	169	241	421	570
7.50	11	57	142	174	253	407	557
7.55	13	61	138	198	254	416	549
7.60	20	61	135	178	255	402	555
7.65	16	63	138	178	250	405	557
7.70	8	61	145	189	241	421	571
7.75	7	58	140	192	249	399	548

TABLE 3.2 : Oxygen reduction currents of PMMA contact lens electrodes of different base curves (BC) at various gas mixtures. The dark current (DC) was recorded in the absence of oxygen. Values tabulated are averages of three determinations.

POLYCON I

		Current in nA at Specific Calibration Gasses					
BC	DC	2.5%	5.0%	7.5%	10%	15%	21%
7.30	16	61	143	193	253	402	570
7.35	16	60	145	187	248	394	553
7.40	15	58	139	185	245	416	571
7.45	11	58	141	190	153	388	548
7.50	9	63	149	192	261	391	550
7.55	7	57	145	181	267	398	561
7.60	9	59	137	185	248	401	562
7.65	11	59	142	192	248	416	576
7.70	13	61	137	187	251	409	549
7.75	17	62	145	183	253	401	563

TABLE 3.3 : Oxygen reduction currents of Polycon I contact lens electrodes, of different base curves (BC), at gas mixtures containing between 2.5% and 21% oxygen. The dark current (DC) was recorded in the absence of oxygen. Values tabulated are averages of three separate experiments.

SM 38

		Current in nA at Specific Calibration Gasses					
BC	DC	2.5%	5.0%	7.5%	10%	15%	21%
7.30	11	57	142	187	248	409	579
7.35	13	61	142	189	240	400	569
7.40	17	60	138	178	248	399	573
7.45	9	55	148	191	245	408	591
7.50	8	65	142	187	263	392	563
7.55	17	63	148	179	240	398	564
7.60	14	63	148	192	241	400	579
7.65	13	58	139	169	250	400	581
7.70	12	59	138	178	249	409	582
7.75	16	63	141	190	261	384	569

TABLE 3.4 : Oxygen reduction current of SM 38 contact lens electrodes for different base curves (BC) at different gas mixtures. The dark current (DC) was recorded in the absence of oxygen. Values tabulated are averages of three recordings.

BOSTON IV

		Current in nA at Specific Calibration Gasses					
BC	DC	2.5%	5.0%	7.5%	10%	15%	21%
7.30	17	59	138	169	248	402	581
7.35	12	63	142	160	263	410	580
7.40	10	65	148	179	239	400	565
7.45	7	55	138	187	145	397	572
7.50	15	60	141	155	241	387	599
7.55	12	67	148	161	249	391	591
7.60	19	64	139	187	249	399	573
7.65	13	60	142	178	261	397	574
7.70	13	61	141	189	257	410	565
7.75	11	63	140	187	254	412	578

TABLE 3.5 : Oxygen reduction currents of Boston IV contact lens electrodes, for different base curves (BC) at different gas mixtures. The dark current (DC) was recorded in the absence of oxygen. Values tabulated are averages of three recordings.

FLUOROPOLYMER

		Current in nA at Specific Calibration Gasses					
BC	DC	2.5%	5.0%	7.5%	10%	15%	21%
7.30	13	61	122	168	248	351	592
7.35	12	58	127	173	255	348	587
7.40	19	55	126	184	261	361	563
7.45	16	59	127	186	239	359	584
7.50	13	62	125	185	240	342	564
7.55	9	63	128	172	261	363	585
7.60	11	58	129	179	242	359	590
7.65	10	57	124	184	240	359	584
7.70	12	61	128	181	254	351	576
7.75	13	61	127	182	255	345	570

TABLE 3.6 : Oxygen reduction currents of Fluoropolymer contact lens electrodes, for different base curves (BC) at different gas mixtures. The dark current (DC) was recorded in the absence of oxygen. Values tabulated are averages of three recordings.

CHAPTER 4

DISCUSSION

4.1 IN VITRO STUDIES

Various methods have been used to determine the oxygen performance of gas permeable contact lenses on the human eye. As discussed in Chapter 1 (Sections 1.8, 1.9, 1.10) these methods are very imprecise or too indirect to be of scientific value. A direct method of measurement would be more relevant to contact lens fitting.

In this study a direct method was used to determine the oxygen performance of contact lenses in vitro (Chapter 2), the results of which can be directly related to the oxygen requirement of the cornea. As yet the oxygen requirement of the intact cornea has not been accurately established. Estimates of corneal oxygen requirements vary from 4.6 (Mandell, 1982) to 15.0 $\mu l/cm^2/hr$ (Holden et al., 1984). Recently it has become common practise to express corneal oxygen requirement in terms of the tear pO_2 necessary to maintain corneal integrity.

This study showed that the in vitro measurement of oxygen flux can be related directly to corneal oxygen requirement. Measurement of oxygen flux circumvents the problems associated with measurements of Dk and Dk/L. Lens thickness, lens design and gasometric parameters are all accounted for. The final value can be correlated to corneal requirements as the values are at STPD.

The results show that even a material with a Dk of 72 will not allow sufficient oxygen to pass through the lens and satisfy the corneal oxygen requirement (Holden et al., 1984). Oxygen flux is a measure of the net amount of oxygen passing through the material.

It is well documented that contact lenses interfere with the physiology of the cornea. This is evident from resultant corneal oedema and corneal haze (Chapter 1, Section 1.3) which slowly disappear when the contact lenses are removed. Studies of the mechanisms of these changes indicate that contact lenses prevent access of atmospheric oxygen to the cornea (Smelser and Ozanics, 1952). Thus, the present study has attempted to quantify the oxygen performance of the contact lenses in vitro that can be related to the in vivo situation.

In vitro studies (Chapter 2) show that none of the lenses studied would be able to supply oxygen to the cornea in the absence of blinking. The oxygen flux measured varies from 1.29 $\mu l/cm^2/hr$ for the low permeability materials to 3.6 $\mu l/cm^2/hr$ for the high permeability materials. These oxygen flux figures are far less than the minimum corneal oxygen requirement of 15 $\mu l/cm^2/hr$ (Holden, 1984). The values obtained (Chapter 2) are much lower than those obtained by indirect measurements carried out by other researchers (Fatt and St.Helen,1971; Hill,1977) as discussed in Chapter 1. This discrepency may be explained by considering the factors discussed below.

(1) Almost all previous studies have followed the procedure of measuring DK first and then calculating oxygen flux, using the formula :

$$Q = Dk/L\ (p_2 - p_1)$$

where Q = oxygen flux. It must be pointed out that the above expression is a "phenomenological" statement and not a mathematical equation (Yasuda,1967 and Refojo et al,1977). When first presented by Fatt (1971) it had the following form :

$$Q \simeq Dk/L\ (p_2 - p_1)$$

Later, work was done to determine the proportionality constant

(Fatt et al., 1969) so that

$$Q = a \cdot Dk/L\ (p_2 - p_1).$$

However, many researchers ignored the proportionality constant and readily used the phenomenological statement as if it was a mathematical equation.

(2) For the reasons discussed in Chapter 1, Dk and Dk/L have no relevance in the field of contact lenses. Therefore, the oxygen flux through a lens cannot be obtained by any means from Dk or Dk/L.

(3) Most of the previous studies have measured oxygen transmission through "dry" lenses where atmospheric air or calibration gas is in direct contact with the surface of the lens. It must be noted that on the cornea, the contact lens and tears form a three layered system (Figure 4.1). Thus the following have to be considered:

a) From the study of Turnbull et al.(1986) and Winterton et al.(1988) it may be inferred that the tear layers present limiting barriers to oxygen flux, where the total tear thickness

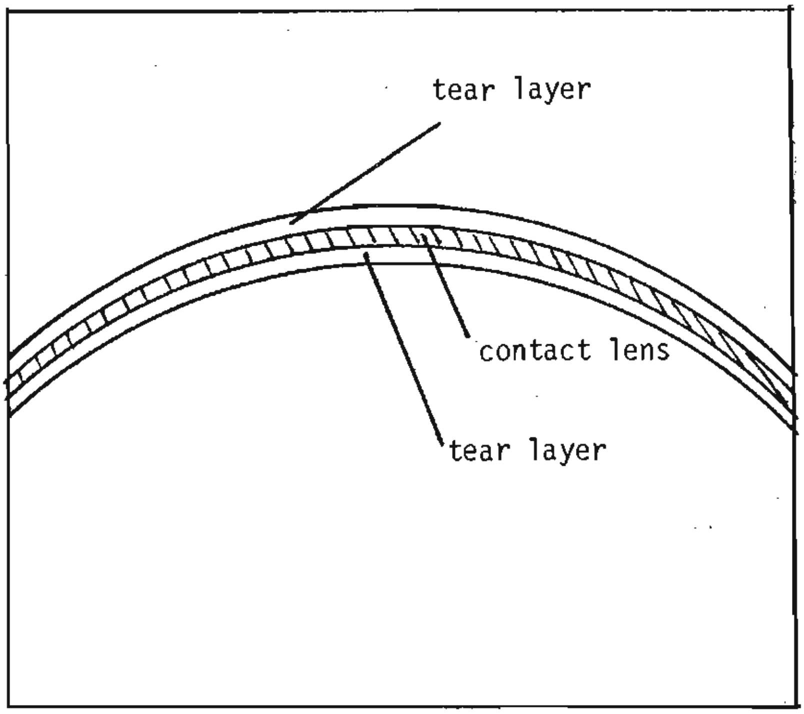

Figure 4.1: Contact lens and tears form a three-layered system.

(anterior and posterior layers) may be thicker than the central lens thickness (Figure 4.1).

b) The electrolytes in tears act on the surface of the contact lens and may bring about stereochemical changes that affect the transmission of oxygen through the lens material.

There is no acceptable theory at present that explains oxygen transmission through gas permeable materials. Some researchers tend to use the analogy of the passage of oxygen through porous material and regard the contact lens as an "oxygen sink" that attracts oxygen into its matrix (Rosenthal, 1982).

It should be noted that contact lens materials are amorphous solids with no pores. The passage of oxygen through the lens material probably depends on the electronegativity of the oxygen molecule, the surface charge of the lens material, the surface tension of the system, the type of the lens material and pressure gradient across the lens material.

It is postulated that oxygen passes through a gas permeable material by the following process: surface charges attract oxygen molecules to the surface of the material, by electrochemical reaction, the oxygen is drawn into the matrix of the lens material. The forces carrying oxygen into the lens matrix are weak van der Waal forces. Thus, the higher concentration of oxygen at the one surface and low pO_2 at the other surface causes oxygen to diffuse along a concentration gradient and pass through to the other surface.

Traditionally, permeability is expressed as Dk, where D is the diffusion coefficient and k the solubility. It is then possible to increase permeability by increasing diffusion or solubility or both. If the diffusion coefficient only is increased, then more gas will pass through the material. On the other hand, if k is increased then more gas will be bound to the lens matrix, but this does not mean that more gas will pass through the material. The current procedures of measuring permeability entail placing the material in contact with the polarographic electrode. This electrode "looks into" the material and gives a transmissibility reading when in fact there may be little or no gas passing through the lens material.

Cognisance must also be taken of the nature of the oxygen molecule. The oxygen molecule is relatively electronegative and the molecules tend to adhere to the walls of the lens material.

An electrode "looking into" the material will give a falsely high reading, by reading the concentration of oxygen along the walls, whereas in reality the nett concentration may be much lower.

4.1.1 OXYGEN PERMEABILITY AND DIFFUSION

The gas laws define diffusion under steady state equilibrium conditions. Normally diffusion is considered to be driven from one compartment to another by a pressure gradient through a diffusion barrier. This barrier does not affect the diffusion process in any way. Diffusion occurs in both directions ("free diffusion") with a net gain in one direction (Figure 4.2). When considering a contact lens, the situation is complicated by a barrier (the contact lens) that influences the diffusion. The "barrier effect" is not taken into account in many calculations that deal with permeability of contact lenses. The oxygen pressure gradient may not be the only driving force. The electrolyte tears, the electric charge of the lens surface and the micro- electrochemical processes that may occur will profoundly affect the passage of oxygen through the lens. Hence the passage of oxygen through the lens cannot be explained simply by the general diffusion theory as the oxygen pressure gradient is not the only driving force.

The purpose of the in vitro studies was to devise a reliable method of measuring the amount of oxygen passing through contact lenses. The method chosen, namely oxygen flux, is free from the constraints of Dk measurements. Furthermore, oxygen flux can readily be equated to corneal oxygen uptake. It is only neces-

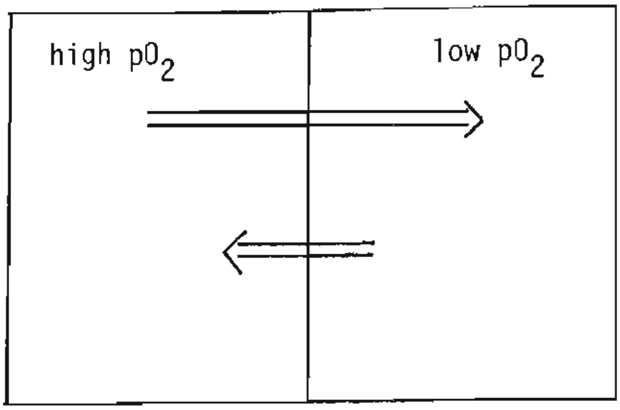

Figure 4.2: Diffusion of oxygen, through the lens, in both directions, with a net gain in one direction.

sary to comply with the gasometric standards when measuring oxygen flux. Oxygen flux measurements standardized to STPD can be compared and equated to measurements done anywhere in the world, at any time, as long as the results are standardized.

Results obtained (Chapter 2) show that even the material with the highest permeability (Fluoropolymer has a Dk of 72) cannot transmit sufficient oxygen to supply total corneal requirement. The low permeability materials transmit negligible amounts of oxygen compared to the corneal oxygen requirement of 15 $\mu l/cm^2/hr$ as quoted by Holden et al. (1984).

The in vitro oxygen flux results indicate that gas permeable lenses fitted tight with little or no tear exchange under the lens will suffocate the cornea in the absence of blinking. The technique of fitting non gas permeable (PMMA) lenses must still be adhered to when fitting gas permeable lenses, i.e., lenses fitted on flattest "K", allowing some tear pumping for exchange under the lens.

It is also notable that in previous studies (Turnbull et al., 1986; Bhagwan et al., 1984; Winterton et al.,1988) the gas transmission through wet lenses (film of liquid over both surfaces) was significantly less than oxygen transmission through "dry" lenses (air dried for 48 hours). The wet situation exists on the cornea with a bi-tear layer offering resistance to oxygen transmission. So it is expected that less oxygen passes through the lens *in situ*.

4.2 IN VIVO STUDIES

The second part of this study, involving the investigation of oxygen tension under the lens on the human cornea, showed that a well fitted PMMA lens would, in the absence of blinking, diminish the pO_2 under the lens to zero in about 20 minutes. As the gas permeability of the material increased the time to reach zero pO_2 increased. Even with the high Dk materials the pO_2 under the lens decreased.

The direct measurement of pO_2 *under* a contact lens worn on the human cornea has not been cited in the literature. Hamano and coworkers (Hamano *et al*. 1986, a,b) have studied pO_2 with the contact lens *in situ* on the human cornea. However, they measured pO_2 in the conjunctival sac of human subjects with and without contact lenses. This method, again, is an indirect procedure as it does not measure the pO_2 directly under the lens. Thus, the present *in vivo* study is the first undertaken to make direct measurements of pO_2 in situ. It is also the first to produce recordings of the effects of blinking on the tear pO_2 with the contact lens in situ on the human cornea.

The average pO_2 under PMMA lenses worn on the human cornea was found to be 55.6 mm Hg. This is much less than the minimum 10% atmospheric oxygen (pO_2 ~ 77 mm Hg; Holden et al., 1984). The recordings show that when blinking was inhibited, the pO_2 gradually dropped. The rate of fall was 6 mm Hg in 150 seconds (2.4 mm Hg in 1 minute). This would mean that the precorneal tear layer would be depleted of oxygen in about 20 to 30 minutes. This time does not take into account tear exchange taking place passively, due to tear flow or convection. With the latter consideration the depletion time to zero pO_2 would probably be 20 to 30 minutes. With a drop in precorneal pO_2, the corneal oxygen uptake will concomitantly fall and the curve will become exponential. The cornea will take up more oxygen from the aqueous humour as well as shift to anaerobic metabolism (Hill, 1977; Efron et al., 1986). Blinking replenishes the precorneal tear pO_2 by about 33%. This figure is markedly more than the 20% predicted by Mandell (1980) and Hill (1984), who determined percentage tear exchange by fluorophotometric techniques.

With the PMMA lens in situ and allowing blinking, it was found that there was a gradual drop in pO_2 over an extended time (30 minutes). The drop in pO_2 was of the order of 6 to 7 pO_2 units per hour. This implies that zero pO_2 would be reached in 10 to 12 hours. This seem to indicate that even with a well fitted PMMA lens, the cornea is starved of oxygen towards the end of the wearing period and the cornea goes into anaerobic metabolism and incurs an oxygen debt.

With the gas permeable lenses the pO_2 was found to be higher when blinking was inhibited, albeit to a small extent. Even with the higher Dk material the precorneal pO_2 was not equal to the minimum pO_2 recommended by Holden et al. (1984). Thus the cornea would eventually go into anaerobic metabolism. Blinking again increased the precorneal pO_2 by about 33%, with each blink.

The increase in precorneal pO_2 was between 7% and 25% with gas permeable lenses. Blinking increased the pO_2 by a greater amount (Table 4.6). The low pO_2 under the lenses found in the in vivo studies agrees with the findings of Hamano et al. (1986a,1986b) who also recorded lower than expected pO_2. However, their studies were carried out in the conjunctival sacs of human subjects. The values obtained in this study are compared with those of other researchers in Table 4.1. It is seen that even relatively non -permeable lens (PMMA) maintain the minimum corneal oxygen tension to prevent corneal oedema. The oxygen reaching the cornea is not through the lens but by the action of blinking and passive convection. Fitting a high gas permeable lens increases the oxygen tension by approximately 25%. This indicates

Minimum pO_2 to maintain integrity of the cornea:

Mandell, (1980) : 55 mmHg
Holden *et al*., (1984) : 70 mmHg
Hamano, et al.,(1986) : 94 mmHg

Recorded pO_2, (*in vivo*, on the human cornea):

Hamano *et al*.(1986) : 33.7 ± 7.6 mm Hg

This study : 55.6 mm Hg (PMMA) to
69.3 mm Hg (fluoropolymer)

Table 4.1: Comparison of minimum oxygen requirements predicted, by other researchers, with that of actual recorded oxygen tensions (present study).

that the "fit" of the lens is a more important factor in oxygenation of the cornea. Yasuda and Stone (1966) reported that oxygen has a molecular size close to that of water and that their diffusivities are similar in many cases. This seems to imply that since rigid gas permeable lenses do not adsorb or transmit sufficient amounts of water their adsorption and transmission of oxygen would also be low.

4.3 MATHEMATICAL MODELS FOR PRECORNEAL pO_2

The lower than expected oxygen tension values again highlight the inherent problems associated with Dk as an *in vitro* index of oxygen performance. Several attempts have been made to mathematically calculate the precorneal pO_2 under a contact lens from Dk values. The following equation has been presented (Fatt *et al*.,1969; Fatt *et al*.,1971; Fatt, 1978) that predict the precorneal pO_2 :

$$\acute{A}\,P = (Dk/L)\,(P_a - P)$$

where $\acute{A}$ = constant, P_a = atmospheric pO_2, and P = precorneal pO_2.

Hamano *et al*.,(1986) derived an equation based on conjunctival sac pO_2 measurements.

$$pO_2 = 44.0 \times \ln(Dk/L) - 96.1$$

Both the above equations are based on Dk. Using these equations, measured and calculated pO_2 obtained in the present study are compared in Table 4.2 and a graphical representation is presented in Figure 4.3. It can be seen that both mathematical models predict a linear relationship between Dk/L and precorneal pO_2. Also Fatt's equation overestimates the oxygen transmissibility of the lenses. The Hamano equation also predicts a linear relationship and overestimates the precorneal pO_2 at higher Dk values. It should be noted that both these equations are not linear at lower Dk values (Hamano, 1986). This analysis again highlights the inherent problems of using Dk/L as an index of oxygen performance.

This study indicates that oxygen flux is a more reliable prediction of the corneal oxygen tension. Table 4.3 and Figure 4.4 show the relationship between <u>in vitro</u> oxygen flux and pO_2.

The graph shows a linear relationship between oxygen flux measured <u>in vitro</u> and precorneal pO_2 measured <u>in vivo</u>. It therefore seems that oxygen flux measured <u>in vitro</u> is a better predictor of the <u>in vivo</u> performance of gas permeable contact lenses.

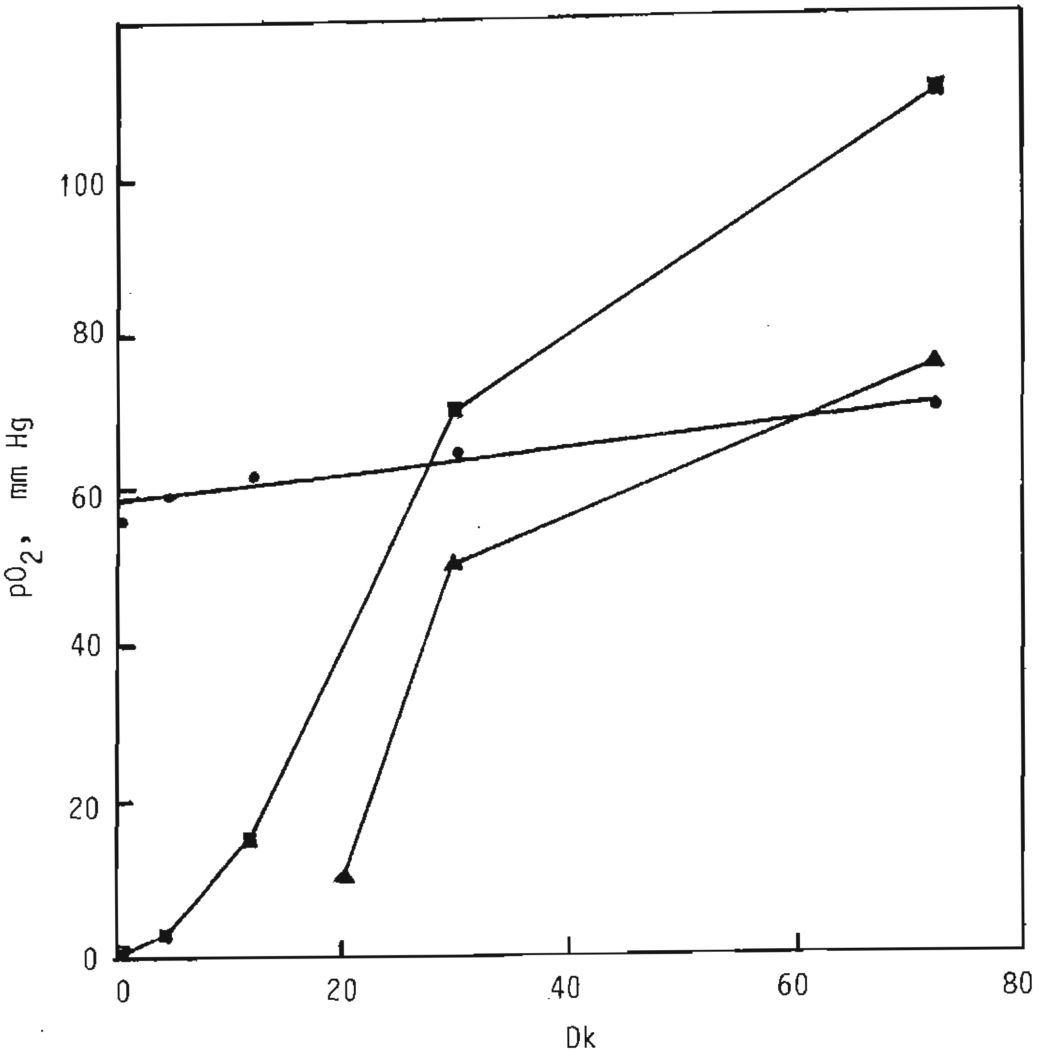

Figure 4.3: Plot of pO_2 versus Dk for the present study (●), compared with those of Hamano (▲) and Fatt (■).

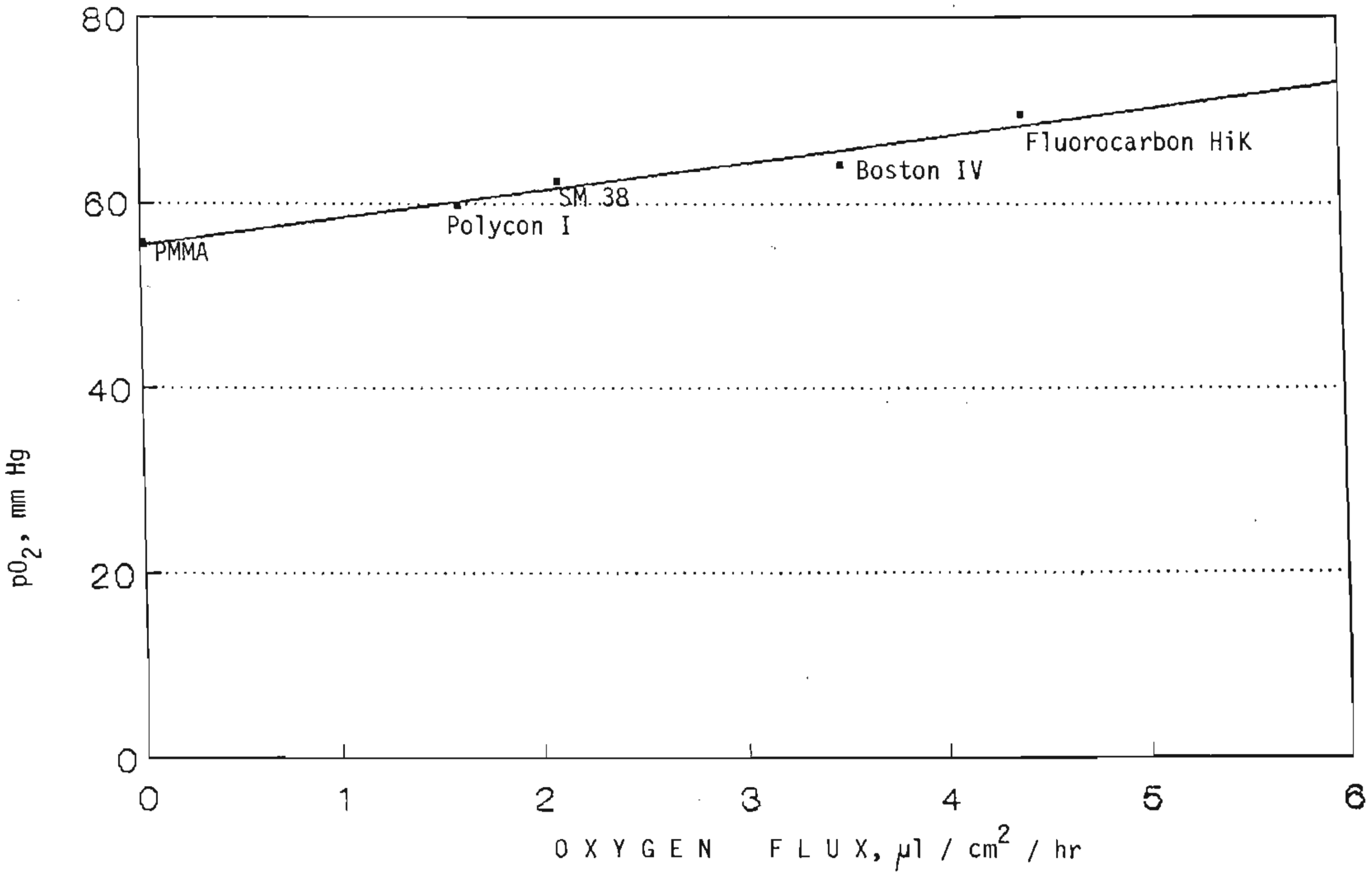

Figure 4.4: Relationship between oxygen flux values obtained from <u>in vitro</u> measurements and pO_2 measured <u>in vivo</u>.

4.4 OXYGEN UPTAKE

The method of recording precorneal pO_2 enables one to calculate the corneal oxygen uptake. The change in pO_2 over a given time with blinking suspended was measured. The only assumption to be made is the volume of the tear fluid under the lens.

Fatt (quoted by Weissman, 1984) derived the following equation to describe the relationship between oxygen flux and corneal oxygen uptake :

$$J = -(QL/2 + \Delta P \cdot DK/L)$$

where J = oxygen flux, Q = whole corneal oxygen flux, L = corneal thickness, DK = corneal permeability, P = oxygen tension difference across the cornea, and P = $P_t - P_{aq}$, where P_{aq} is the pO_2 in the aqueous. The model describes a homogeneous single layered cornea. Weissman (1984) rearranged the above equation to give

$$Q = 2\Delta P \cdot DK/L^2 - 2J / L$$

Assuming a corneal thickness of 0.5 mm, P_{aq} of 50 mm Hg and Pt of

25 mm Hg, Weissman mathematically estimated the whole corneal oxygen uptake to be 4.85×10^{-5} ml O_2/ml/sec.

For a well fitted PMMA lens the pO_2 at the cessation of blinking was 56 mm Hg (average value). After 150 seconds the pO_2 decreased to 50 mm Hg. Therefore $\triangle pO_2 = 6$ mm Hg/150 sec. or 2.4 mm Hg/min.

The tear volume under a contact lens has been postulated by Cuklanz and Hill, (1969) and Weismann (1984) to be between 0 and 47 ul. For the present study a tear volume of 47µl is assumed. The solubility coefficient for oxygen in saline at 35^0C is given as $2.5 \times 10^2 \times P_t/P_a$ ml O_2/ml tears, at a pO_2 of 66 mm Hg. Substituting the pO_2 values, the volume of oxygen in the tears is calculated to be 0.0106 ml O_2/ml. At a pO_2 of 50 mm Hg the dissolved oxygen in the tear layer is calculated to be 0.0083 ml O_2/ml of tears. Therefore the oxygen consumption (difference) is 0.0023 µl O_2/ml/min or 3.83×10^{-5} µl/ml. cornea/sec.

4.5 DEVELOPMENT OF A MODEL FOR THE OXYGEN PERFORMANCE OF RIGID GAS PERMEABLE LENSES ON THE HUMAN EYE

The *in vitro* and *in vivo* studies in this project have provided sufficient data to develop a model for the oxygen performance of gas permeable lenses on the human eye.

The cornea, being avascular, receives most of its oxygen from the atmosphere. The driving force for oxygen is the partial pressure of oxygen in atmospheric air. The average atmospheric pressure in Durban over the experimental period was 747 mm Hg and the average air temperature was 26^0C. The water vapour pressure at 747 mm Hg and 26^0C is approximately 25 mm Hg (Ciba Geigy Tables). The corrected atmospheric pressure is therefore 728 mm Hg (747 - 25 mm Hg). Since the atmospheric air contains 20.93% oxygen, the partial pressure is 152 mm Hg.

The pO_2 in the tear layer of the front surface of the lens should theoretically be the same as atmospheric air, namely, 152 mm Hg. It is expected that this value would be slightly reduced due to the boundary effects of the anterior tear layer and reflux of stale tears after blinking.

The passage of oxygen through the lens may be expressed in terms of the oxygen flux. Table 4.4 shows the averaged values of oxygen flux for the five materials used in this study. The values are for 'wet' lenses. The resulting baseline pO_2 under a 'good-fit' lens is presented in Table 4.5. The resultant baseline pO_2 under the lens is due to the oxygen flux through the gas permeable lens, blinking and tear reflux after blinking. The data presented in Tables 4.4 and 4.5 are diagrammed in Figure

4.5. A study of the typical pO_2 profile (Figure 3.6) shows that there is approximately 33% change in pO_2 (due to blinking, tear reflux and convection). Table 4.8 summarises the change in pO_2 for the lens materials studied.

Holden _et al_. (1984) and Efron _et al_. (1986) have shown that at least 10% oxygen is required at the precorneal layer to prevent oedema. From the present investigation it is evident that none of the lenses studied would supply enough oxygen to prevent oedema. It must also be pointed out that in the Holden study, one subject needed 7.5% oxygen to prevent oedema. Four subjects required 10.1% and 3 subjects required 21.4% oxygen to prevent oedema. The author of this present study postulates that corneal oxygen uptake is related to basal metabolic rate (BMR). (This is not supported by experimental evidence). He suggests that since BMR is age and sex related, the wide variation in corneal oxygen uptake would be expected. Hamano _et al_. (1983) have found that the cornea requires 13% oxygen to avoid suppression of epithelial mitosis and accumulation of lactic acid in the anterior chamber. Even in the presence of blinking none of the lenses used in this study have satisfied the criteria proposed by Hamano (1983).

The relationship between oxygen flux determined _in vitro_ and resultant baseline pO_2 was investigated, and is presented in Figure 4.4. The regression equation for the line of best fit obtained from the graph is:

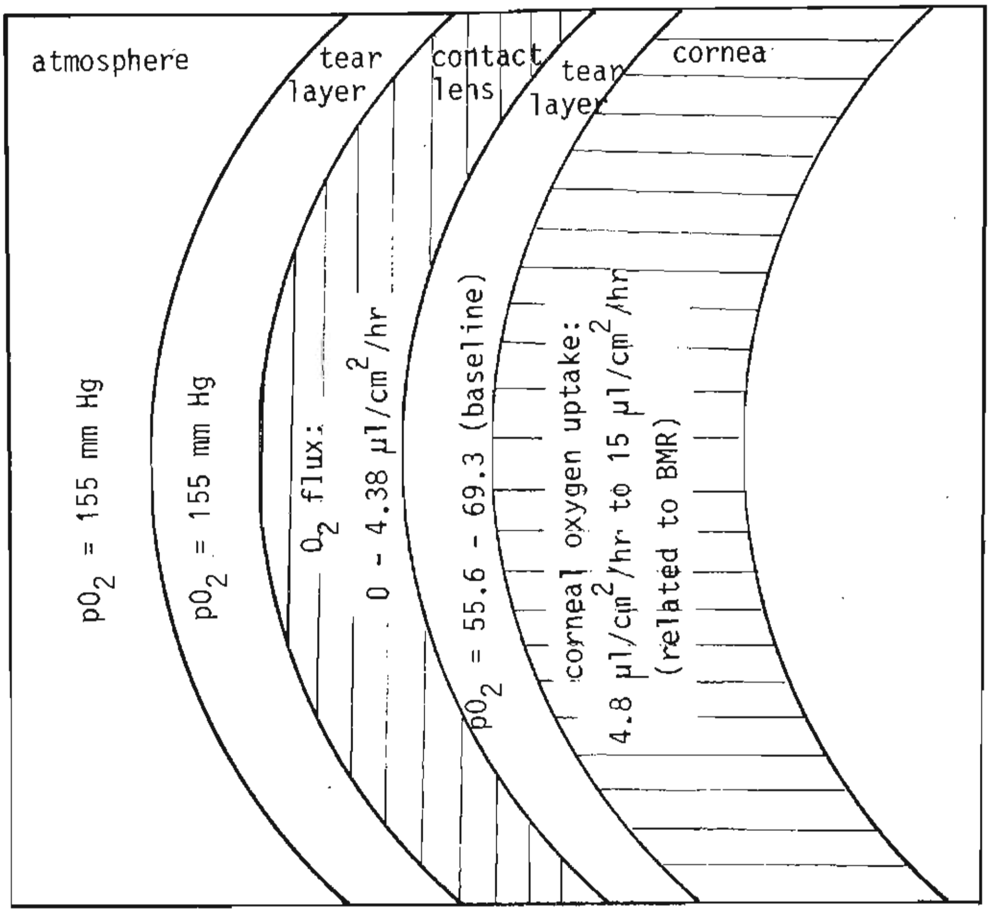

Figure 4,5: Anotated diagram of data obtained in Tables 4.4 and 4.5. Baseline pO_2 under a contact lens, due to oxygen flux through the lens, blinking and tear reflux.

$$y = 3.1x + 55.6$$

that is

$$\text{baseline } pO_2 = 3.1\ O_2 \text{ flux} + 55.6$$

and the increase in pO_2 associated with blinking 33% for the five lens types tested.

4.6 USE OF THE MODEL

Fatt and Liu (1984) have presented hypothetical graphs predicting pO_2 under the lens, with and without blinking. These graphs are calculated from their equation (Fatt and Lin, 1970). However, the graphs are based on Dk values, and inherit the problems of Dk as discussed previously.

The mathematical equation derived in this study (Section 4.5) provides a useful model for the oxygen performance of well fitted rigid contact lenses on the human cornea. The only parameter that one has to determine is oxygen flux through the lens under study (Chapter 2). Using the equation derived in this study, the pO_2 values may then be calculated from the experimentally obtained oxygen flux values (as shown in Table 4.7).

The requirement of 13% O_2 (Hamano et al., 1985) to prevent compromise of corneal physiology translates into a pO_2 value of approximately 94 mm Hg. This yields an oxygen flux of about 13 μl O_2/cm^2 /hr (Table 4.7). Thus the lens with the highest oxygen flux (fluoropolymer has an O_2 flux of 4.38 $\mu l/cm^2/hr$) produces a pO_2 of 69.3 mm Hg. Thus the model may be used to determine whether a contact lens under study will compromise the corneal integrity, simply from determining its oxygen flux and applying the proposed mathematical equation to obtain its baseline pO_2.

MATERIAL	**O_2 flux(av)**	**pO_2(measured)**	**pO_2(Fatt)***	**pO_2(Hamano)****
PMMA	0	55.6	0	not applic.
POLYCON I	1.56	59.7	~3	not applic.
SM 38	2.12	62.2	~15	~10
BOSTON IV	3.48	64	~70	~50
FLUOROPOLYMER	4.38	69.3	~110	~70

oxygen flux in $\mu l/cm^2/hr$

pO_2 in mmHg.

Table 4.2: Comparison of pO_2 values obtained from mathematical models proposed by Fatt (1979) and Hamano <u>et al.</u> (1986) with those of values obtained in this study. The values presented here have been read off the graphs presented in the literature. A graphical representation is presented in Figure 4.3.

* Fatt and St.Helen, (1971).

**Hamano et al.,(1986).

Material	**O_2 FLUX**	**PRECORNEAL pO_2**
PMMA	0	55.6
POLYCON I	1.56	59.7
SM38	2.12	62.2
BOSTON IV	3.48	64
FLUOROPOLYMER	4.38	69.3

Table 4.3: Oxygen flux(µl/cm^2/hr) measured <u>in vitro</u> and precorneal pO_2(mmHg) measured <u>in vivo</u>. A graphical representation is presented in Figure 4.4.

MATERIAL	**O_2 FLUX (STPD)**	**O_2 FLUX ($34^{o}C$/747 mm Hg)**
PMMA	0	0
Polycon I	1.29	1.56
SM 38	1.75	2.12
Boston IV	2.88	3.48
Fluoropolymer	3.62	4.38

Table 4.4: Averaged values of oxygen flux($\mu l/cm^2/hr$) for the lens types used in this study. The values are for 'wet' lenses.

MATERIAL	**pO_2 (ave)**
PMMA	55.6
Polycon I	59.7
SM 38	62.2
Boston IV	64.0
Fluoropolymer	69.3

Table 4.5: Baseline pO_2(mmHg) under a good-fit lens, due to the oxygen flux through the material, blinking and tear reflux.

LENS MATERIAL	**Baseline reading**			**Peak reading due to blink**		
	mmHg	**/**	**%O_2**	**mgHg**	**/**	**%O_2**
PMMA	55.6	/	7.66	73.90	/	10.19
Polycon I	59.7	/	8.22	79.40	/	10.93
SM 38	62.2	/	8.56	82.73	/	11.39
Boston IV	64.0	/	8.81	85.12	/	11.72
Fluoropolymer	69.3	/	9.54	92.17	/	12.69

Table 4.6: Change in pO_2 of the materials under study, due to blinking and tear reflux.

O_2 flux of gas permeable (wet) lenses (µl/cm^2/hr)	Predicted pO_2 under a well fitted lens (mmHg)
1	57.8
2	61.8
3	64.9
4	68.0
5	71.1
6	74.2
7	77.3
8	80.4
9	83.5
10	86.6
11	89.7
12	92.8
13	95.9
14	99.0
15	102.1

Table 4.7: Use of the mathematical model developed from this study to calculate pO_2 values from oxygen flux measurements.

MATERIAL	BASELINE pO_2	PEAK pO_2 DUE TO BLINK	%Atmos.
PMMA	55.6	73.9	10.1
Polycon I	59.7	79.4	10.9
SM 38	62.2	82.7	11.4
Boston IV	64	85.1	11.7
Fluoropolymer	69.3	92.1	12.7

Table 4.8: The effect of blinking on the precorneal pO_2 for the contact lenses used in this study.

CONCLUSION

The advent of gas permeable materials has offered the contact lens practitioner new possibilities in the management of refractive errors. One of the primary requisites for successful lens wear is to provide the minimum corneal oxygen requirement to avoid compromising the corneal physiology (Mandell, 1983). Hence it has become important to be able to determine the oxygen performance of contact lenses. A survey of the literature has shown that the study of oxygen performance of gas permeable contact lenses is fraught with inconsistencies and unsubstantiated assumptions. The entire theory is based around the definition of oxygen permeability. Clinical findings have shown that predictions based on Dk are incorrect.

With a measuring cell specially designed and tested in this study, oxygen flux was successfully measured *in vitro*. Contact lens microelectrodes were designed from first principles and the oxygen tension and the change in oxygen tension with blinking was recorded directly, *in vivo*. The oxygen flux determinations of "wet" lenses yielded values that were lower than the reported minimum oxygen requirement of the cornea. Thus, *in situ*, in the absence of blinking, the contact lenses used in this study would deprive the cornea of oxygen. Blinking was observed to increase the oxygen tension under the lens by approximately 33%. The material with the highest permeability (fluoropolymer) was observed to increase the oxygen tension under the lens by 25%. These findings indicate that the contact lens practitioner should attempt to obtain maximum tear exchange with blinking to oxygenate the cornea rather than depend on permeability, especially with low permeability lenses. The high permeability lenses have their own problems, viz. instability of the polymer, poor surface wettability and accumulation of deposits and warping of the lens on the cornea.

As far as it can be ascertained this has been the first study to measure the oxygen tension under a lens in vivo. Therefore the results obtained here cannot be corroborated with other studies. No attempt was made in this study to correlate either oxygen flux or precorneal pO_2 with Dk and Dk/L. For reasons discussed in Chapters 1 and 4, Dk and Dk/L, as presently defined, do not pertain satisfactorily to contact lenses and as such cannot be used as correlates of oxygen performance of contact lenses. Fatt (in Ewbank, 1987) said ".....Dk was more use to marketing managers than to practitioners".

This study has shown that:

i. The relationship between Dk and precorneal pO_2 is non-linear (figure 4.3) and that the current definition of permeability i.e P = Dk, needs to be revised so that the equation becomes independent of the constraints discussed in Chapters 1 and 4. Hence Dk/L needs to be revised also.

ii. Gas permeable lenses do not transmit sufficient oxygen to satisfy all the corneal requirement as shown by the oxygen flux determinations.

iii. The true corneal oxygen requirement has to be determined accurately by direct methods. There is no satisfactory explanation in the literature for the wide range reported ($4.8\mu l/cm^2/hr$ to $15\mu l/cm^2/hr$). It is suggested here that this wide intersubject variation may be related to the subjects' basal metabolic rates.

iv. The contact lens microelectrode described can be used to measure directly the <u>in vivo</u> precorneal oxygen tension under a contact lens. The results have been shown to be reliable and reproducible. These results cannot be corroborated with other studies because no other similar measurements have been reported.

v. The lens fit and the effect of blinking contribute significantly to oxygenation of the cornea. The amount of oxygen transmitted through the lens may be used to satisfy marginal fitting needs.

vi. The contact lens practitioner should consider lens design and fitting relationship to be of primary importance in oxygenation of the cornea during lens wear.

In this study it was shown that a direct measurement of oxygen flux through a contact lens, determined in vitro, can be used to predict the oxygen tension under a contact lens in vivo. A simple model was developed to predict the precorneal oxygen tension under a lens. It is therefore suggested that contact lens manufacturers measure, under standardised conditions, the oxygen flux values of their contact lenses, and these values should be reported together with the other parameters on their packaging. Using the model developed in this study, the contact lens practitioner would be able to predict the oxygen tension under the lens. This would allow the practitioner to achieve the highest possible oxygen tension under the lens by balancing fit parameters with oxygen permeability and blink action.

The in vitro and in vivo procedures used in this may be used for further research :

i.In this study only four gas permeable materials were evaluated. There are numerous other materials that are presently being used for which oxygen flux determinations can be done.

ii. The effect of surface preparation of the contact lens (improved wetting with special solutions and gamma irradiation) on oxygen flux needs to be evaluated.

iii. The effect of lens design on oxygen flux may be investigated.

iv. A contact lens is wearable since, in vivo, the lens may be coated with mucin. This makes the relatively hydrophobic surface of the lens wettable. The effect of mucin coating on oxygen flux has not been reported. Over a period of time protein and other deposits adhere to the lens surface. The resultant effect on oxygen flux has not been reported and can be further investigated.

This study has shown that the precorneal oxygen tension under a lens can be determined with contact lens microelectrodes. With present high technology it is possible to develop better contact lens microelectrodes which could be used to study:

i. The precorneal oxygen tension under a wide variety of lenses.

ii. The oxygen tension under tightly fitted and loosely fitted lenses.

iii. The effects of blinking quantitatively on each of the cases mentioned above.

iv. The change, if any, in precorneal oxygen tension as the patient adapts to contact lens wear, and the effects of long term contact lens wear on corneal oxygen consumption.

v. The minimum corneal oxygen requirements and establish population normals and determine the reason for the wide range reported.

This and previous studies, in the field of contact lenses, have concentrated on oxygen performance as a primary requisite for successful contact lens wear. It must be noted that there are other factors which need to be investigated, viz. the bearing relationship of the lens on the cornea and the alteration of the trans-corneal potential with the lens *in situ*. It has been reported that the surface of the lens may have a nett electric charge. Such a lens, completely covered with an electrolyte (tears), may set up an electromotive force on the cornea. It is suggested that microelectrochemical reactions take place in the vicinity of the cornea and affect the oxygen availability to the cornea since the oxygen molecule is slightly electronegative.

Recently researchers have referred to the "boundary effect" and the "edge effect" which have not been fully quantified. These phenomena need to be fully investigated.

In this study it had not been possible to study the oxygen flux through hydrogel lenses, nor had it been possible to construct hydrogel contact lens electrodes mainly due to technical problems. Procedures need to be developed to determine the oxygen performance of hydrogel lenses.

Further research in this field will result in the development of easier and more precise measurement techniques and the evolution of a more refined model of oxygen performance that may be applied over a wide variety of conditions. This study will give the researcher and contact lens practitioner further insight into the oxygen performance of rigid contact lenses and will therefore contribute to the safer and more comfortable contact lens wear.

REFERENCES

AMES, K. S. and ERIKSON , P. The CLAO Journal, 13 (3), 165 - 170, 1987.

BAILEY, N. J. and HILL, R. W. Contact Lens Forum, 2, 45, 1977.

BENNETT, E. D. and TOMLINSON, A. Am. J. Optometry and Physiol. Optics, 60 (2), 139 - 145, 1983.

BHAGWAN, I., LAMORAL, B. and POSTUM, K. University of Durban-Westville Journal, 1984.

BRENNAN, A. Am. J. of Optom. and Physiol. Optics, 61 (16), 627 - 635, 1984.

BRENNAN, A., EFRON, N. and HOLDEN, B. A. Clinical and Experimental Optom. 69 (3), 82 - 89, 1986.

BRENNAN, N.A., EFRON, N. and CARNEY, L.G. Am. J. Optometry and Physiological Optics, 66 (1), pp 19 - 24, 1988.

CHAN, T., PAYOR, S. and HOLDEN, B. A. Investigative Opthalmology and Visual Science, 24 (10), 1408 - 1410, 1983.

COGAN, D.G. Investigative Ophthalmology. 1 (253), 1962.

CUCKLANZ, M.D. and HILL, R.M. Am. J. Optom., vol. 46, 228, 1969.

DAVSON, H. Biochem. Journal, 59 (24), 1955.

DECKER, M., POLSE, K. A. and FATT, I. Am. J. Optom. and Physiol. Optics, 55 (5), 285 - 293, 1978.

DEVLIN, T. M. (ed.) in Textbook of Biochemistry with Clinical Correlations, pp 839 - 842, John Wiley and Sons, New York, 1986.

DUFFIN R. M., WEISSMAN, B. and UEDA, J. International Contact Lens Clinic, 9 (2), 101 - 104, 1982.

EFRON, N. and BRENNAN, N. A. Aust. J. Optom., 68 (1), 27 - 35, 1985.

EFRON, N. and CARNEY, L.G. Am. J. Optom. and Physiol. Optics, 58, pp 806 - 809, 1981.

EFRON, N. and CARNEY, L. G. International Contact Lens Clinic, 9 (4), 1982.

EFRON, N. and HOLDEN, B.A. Optician, pp 21 - 32, Aug.1986.

EFRON N. and SWARBRICK, H. International Eyecare, 2 (3), March,1986.

EL-HAGE, S. G., HUGHES, C. C., SCHAUER, K. R. and JARRELL, R. L. Am. J. Optom. and Physiol. Optics, 51, 24 - 33, 1974.

ESTABROOK, R. W. Methods in Enzymology, 10, 41, 1967.

EWBANK, A. Optician, pp 17 - 24, 1987.

FATT, I. J. Appl. Physiol., 19, pp 326 - 329, 1964.

FATT, I. Exptl. Eye Res., 7, 413 - 430, 1968.

FATT, I. Polarographic Oxygen Sensor, CRC Press, Ohio, 1976.

FATT, I. International Contact Lens Clinic, 11 (3), 175 - 186, 1984a.

FATT, I. International Contact Lens Clinic, 11, 648, 1984b.

FATT, I. Am. J. of Optom. and Physiol. Optics, 55 (5), 294 - 301, 1978.

FATT, I. Am. J. of Optom. and Physiol. Optics, 56 (5), 324 - 337, 1979.

FATT, I. Contact Lens Forum, 6, 29 - 33, 1981.

FATT, I. The Contact Lens Journal, 14 (6), 8 - 9, 1984.

FATT, I. and BIEBER, M.T. Exptl. Eye Res., 7, 103 - 112, 1968.

FATT, I., BIEBER, M. T. and PYE, S. D. Am. J. of Optom. and Arch. of Am. Acad. of Optom., 46 (1), 3 - 14, 1969.

FATT, I. and CHASTON, J. Journal of the British Contact Lens Assoc. 66 - 70, 1979.

FATT, I. and CHASTON, J. International Contact Lens Clinic, 9 (2), 76 - 88, 1981.

FATT, I. and CHASTON, J. International Contact Lens Clinic, 9 (2), 119 - 120, 1982.

FATT, I., FREEMAN, R. D. and LIN, D. Exp. Eye Res., 18, 357 - 365, 1974.

FATT, I. and LIN, D. Am. J. of Optom. and Physiol. Optics 53 (4), 104 - 111, 1976.

FATT, I. and LIU, S. K - M. International Contact Lens Clinic <u>11</u> (2) 93 - 105, 1984.

FATT, I. and ST. HELEN, R. Am. J. of Optom. and Arch. of Am. Acad. of Optom. <u>48</u> (7), 545 - 555, 1971.

FITZGERALD, J. P. and EFRON, N. Clinical and Experimental Optom. <u>69</u> (4), 149 - 152, 1986.

FLYNN, W. J. and HILL, R. M. Contact Lens Forum, <u>58</u>, 61 - 67, Nov., 1984.

FLYNN, W. J., QUINN, T. G. and HILL, R. M. Contact Lens Forum, <u>57</u>, 57 - 59, 1983.

FREEMAN, R.D. and FATT, I. Biophysical J., <u>12</u>, pp 273 - 247, 1972.

GASSON, A. The Opthalmic Optician, <u>19</u>, 840 - 843, 1979.

GASSON, A. The Ophthalmic Optician, pp 508 - 512, Aug., 1981.

GEDDES, L. A. Electrodes And The Measurement Of Bioelectric Events, Wiley - Interscience, U. S. A., 1972.

GEDDES, L. A. Principles Of Biomedical Instrumentation, John Wiley and Sons, Inc. N.Y., 1968.

GOLDBERG, J.B. International Contact Lens Review, reprinted from International Contact Lens clinic, pp 17 - 22, 1979.

HAMANO, H., KAWABE, H. and MITSUNAGA, S. The CLAO Journal, 11 (3), 221 - 226, 1985.

HAMANO, H., MIKAMI, M., MOHRI, H. MITSUNAGA, S. and KOTANI, S. J. of Japanese Contact Lens Society, 28, 47 - 50, 1986a.

HAMANO, H., MIKAMI, M., MITSUNAGA, S. and KOTANI, S. Journal of Japanese Contact Lens Society, 28, 51 - 57, 1986b.

HARRIS, M. G. and MANDELL, R. B. Am. J. of Optom. and Arch. of Am. Acad., 46, 196 - 202, 1969.

HEDBYS, B.O., Exp. Eye Res., 5 (221), 1966.

HILL, R.M. International Contact Lens Clinic, 4 (2), pp 34 - 36, 1977.

HILL, R.M., BREZINSKI, S. and FLYNN, W.J. Contact Lens Forum, pp 35 - 39, 1985.

HILL, R. M. International Eyecare, 2, 1986.

HILL, R. M. and FATT, I. Nature, 200, 1011 - 1012, 1963.

HILL, R.M. and FATT, I. Am. J. Optom., 47 (1), pp 50 - 55, 1970.

HILL, R. M. and FATT, I. Science, 142, 1295 - 1297, 1963.

HOLDEN, B. A. and MERTZ, G. W. Investigative Ophthalmology and Visual Science, 25 (10), 1165 - 1167, 1984.

HOLDEN, B. A., MERTZ, G. W. and McNALLY, J. J. Investigative Ophthalmology and Visual Science, 24 (2), 218 - 226, 1983.

HOLDEN, B. and SWEENY, D.F. Contax, PP 13 - 18, May, 1987.

HOLDEN, B.A., SWEENY, D.F., VANNAS, A., NILSSON< K.T. and EFRON, N. Investigative Ophthalmology and Visual Science., 26, pp 1489 - 1501, 1985a.

HOLDEN, B.A., WILLIAMS, L. and ZANTOS, S.G. Investigative Ophthalmology and Visual Science, 26, pp 1354 - 1359, 1985b.

JAUREGUI, M. J. and FATT, I. Am. J. Optom. and Arch. of Amer. Acad. of Optom. 49, 507 - 511, 1972.

KLYCE, S. D. Journal of Physiology, 321, 49 - 64, 1981.

KORB, D. R., RICHMOND, P. P. and HERMAN, J. P. Journal of Am. Optom. Assoc., 51 (3), 267 - 270, 1980.

KWAN, M., NIINIKOSKI, J. and HUNT, T. K. Investigative Ophthalmology, 11, 108 - 114, 1972.

LANGHAM, M. J. Physiology, 117, 461, 1952.

LANGHAM, M.E. J.Physiology, 26, pp 396 - 403, 1954.

LANGHAM, M.E. and TAYLOR, I. S. Br. J. Ophth., 40 (6), 326 - 340, 1956.

LARKE, J. R., PARRISH, S. T. and WIGHAM, C. E. Amer. J. of Optom. and Physiol. Optics, 58 (10), 803 - 805, 1981.

LEHNINGER, A.L. Biochemistry, 2nd ed., N.Y.,1975.

LESSER, M. A. and BRIERLEY, G. P. Methods of Biochemical Analysis, 17, 1 - 29, 1969.

MANDELL, R.B. Contact Lens Practice, 3rd edition, Charles C. Thomas, U.S.A., 1981.

MANDELL. R. B. Journal of Amer. Optom. Assoc., 53 (3), 211 - 214, 1982.

MANDELL, R. B. Journal of Amer. Optom. Assoc., 50 (3), 323 - 324, 1979.

MANDELL, R.B. J. Amer. Optom. Assoc., 53, pp 211 - 214, 1982.

MANDELL, R.B. Contacto, 26, pp 4 - 8, 1982.

MANDELL, R.B. The Contact Lens Journal, 11, (4), 1983.

MANDELL, R.B. and FATT, I. Nature, 208 (5007), pp 292 - 293, 1965.

MANDELL, R.B. and FARREL, R. Invest. Ophthalmol. and Visual Sci., 19 (6), pp 697 - 702, 1980.

MANDELL, R.B. and POLSE, K.A. Am. J. Optom. and Arch. of Am. Acad. of Optom., 46, pp 479 - 491, 1969.

MAURICE, D.M. J. Physiology, 136 (2), pp 263 - 286, 1957.

MERTZ, G.W. J. Am. Optom. Assoc., 51 (3), pp 211 - 214, 1980.

MISHIMA, S. and MAURICE, D.M. Exp. Eye Res., 1 (1), pp 46 - 52, 1961.

MISHIMA, S. Arch. of Ophthal., 73, 233 - 241, 1965.

MORRIS, J. A. and FATT, I. The Optician, 174, 27 - 36, 1977.

MORRIS, J. A. and RUBEN, M. British Journal of Ophthalmology, 65, 97 - 100, 1981.

NG, C. O. and TIGHE, B. J. The British Polymer Journal, 8, 78 - 82, 1976.

O'NEAL, M. R., POLSE, K. A. and FATT, I. International Contact Lens Clinic, 10 (4), 256 - 265, 1983.

O'NEAL, M. R., POLSE, K. A. and SARVER, M. D. Invest. Ophthal. and Visual Science, 25 (7), 837 - 842, 1985.

PARRISH, S. T. and LARKE, J. R. Am. J. of Optom. and Physiol. Optics, 58 (9), 696 - 698, 1981.

PETERSON, J.F. and FATT, I. Am. J. Optom. and Arch. Am. Acad. Optom., 50, pp 91 - 93, 1973.

POLSE, K. A. and MANDELL, R. B. Arch. Ophthal., 84, 505 - 508, 1970.

POLSE,K.A., SARVER, M.D. and HARRIS, M. Am. J. Optom., 52 (185), 1975.

POLSE, K.A. SARVER, M.D. and HARRIS, M. International Contact Lens Clinic, pp 35 - 41, 1976.

RASSON, J. E. and FATT, I. Am. J. of Optom. and Physiol. Optics, 59 (3), 203 - 212, 1982.

REFOJO, M. F. Journal Of Am. Optom. Assoc. 50 (3), 285 - 287, 1979.

REFOJO, M. F., FARRIS, R. L. and DABEZIES, O. H. Jr. Contact Lenses: The CLAO Guide to Basic Science and Clinical Practice, Grune and Stratton, U.S.A., 1984.

REFOJO, M. F., HOLLEY, F. J. and LEONG, F. L. Contact Lens, 3 (4), 27 - 33, 1977.

ROSCOE, W. R. and HILL, R. M. Am. J. of Optom. and Physiol. Optics, 59 (7), 620 - 621, 1982.

ROSCOE, W. R. and SYNDER, A. C. Am. J. of Optom. and Physiol. Optics 62 (2), 129 - 131, 1985.

ROSCOE, W. R. and WILSON, G. S. Am. J. of Optom. and Physiol.

Optics, 61 (8), 538 - 542, 1984.

ROSENTHAL, P. International Contact Lens Review, reprinted from Contact Lens Forum, pp 5 - 9, Aug., 1982.

RUBEN, M. A Colour Atlas of Contact Lenses. Wolfe Medical Publications Ltd., London, 1982.

SARVER, M. D., BROWN, L. R. and RIGGERT, R. T. Am. J. Optom. and Physiol. Optics, 56 (4), 231 - 235, 1979.

SARVER, M. D., POLSE, K. A. and BAGGETT, D. A. Am. J. of Optom. and Physiol. Optics, 60 (2), 128 - 131, 1983.

SARVER, M. D., POLSE, K. A. and HARRIS, M. G. Am. J. Optom. and Physiol. Optics, 54 (4), 195 - 200, 1977.

SARVER, M. D. and STAROBA, J. E. Am. J. Optom. and Physiol. Optics, 55 (11), 739 - 743, 1978.

SCHNIDER, C. M. Contax, pp 10 - 12, May, 1987.

SCHOESSLER, J. P. Am. J. Optom. and Physiol. Optics, 58 (8), 614 - 617, 1981.

SMELSER, G. K. A. M. A. Archives of Ophthalmology, 47, 328 - 343, 1952.

SMELSER, G. K. and CHEN, D. K. A. M. A. Arch. of Ophthalmology, 53, 676 - 679, 1955.

SMELSER, G. K. and OZANICS, V. Science, 115, 140, 1952.

SMELSER, G.K. and OZANICS, V. Arch. Ophthalmology, 49 (3), pp 335 - 340, 1953.

STAHL, N., REICH, L. and IVANI, E. J. AM. Optom. Assoc., 45 (3), pp 302 - 307, 1974. 1984

STRYER, L. Biochemistry, 2nd ed., W.H.Freeman and Co., San Francisco, 1975.

TERRY, J. E. and HILL, R. M. Arch. of Ophthalmology, 96, 120 - 122, 1978.

TURNBULL, D. K., GATHIRAM, P., BHAGWAN, I., LAMORAL, B. and POSTUM, K. Journal of the British Contact Lens Assoc., 9 (2), 75 - 84, 1986.

UNAIKE, C. A., AUGSBURGER, A. and HILL, R. M. Am. J. of Optom. and Arch. of Acad. of Optom. 48, 565 -568, 1971.

UNAIKE, C. A., HILL, R. M., GREENBERG, M. and SEWARD, S. Am. J. of Optom. and Arch. of Am. Acad. of Optom., 49, 329 - 332, 1972.

WAGNER, L., POLSE, K. and MANDELL, R. Invest. Ophthalmol. Visual Science, 19 (11), 1397 - 1400, 1980.

WEISSMAN, B. A. International Contact Lens Clinic, 9 (2), 89 - 91, 1982.

WEISSMAN, B. A. Am. J. of Optom. and Physiol. Optics, 61 (4), 291 - 292, 1984.

WEISSMAN, B. A. and FAZIO, D. T. Am. J. of Optom. and Physiol. Optics, 59 (8), 635 - 638, 1982.

WILSON, G. Am. J. of Optom. and Physiol. Optics, 56 (7), 430 - 434, 1979.

WILSON, K. and GOULDING, K.H. (ED), A Biologist's guide to Principles and Techniques of Practical Biochemistry, Edward Arnold, 1986.

WINTERTON,L.C., WHITE,J.C. and SU,K.C. International Contact Lens Clinic, 15 (4),117 - 123, April 1988.

YASUDA, H. Journal of Polymer Science, 5, 2952 - 2956, 1967.

YASUDA, H. and STONE, W. Journal of Polymer Science, 4, 1314 - 1317, 1966.

ADDITIONAL READING

ANDRASCO, G. J. Investigative Ophthalmology and Visual Sci., 27, pp 20 - 23, 1986.

ANDRASKO, G. J. AND STAHL, B. Contact Lens Forum, 50 - 51, July, 1985.

ARMITAGE, P. Statistical Methods in Medical Research, Blackwell Scientific Publication, Oxford, 1980.

BARR, J. T. and SCHOESSLER, J. P. AM. J. Optom. and Physiol. Optics, 58, pp 6 - 10, 1981.

BRENNAN, N. A. J. Optom. Physiol. Optics, 61, 627 - 634, 1984.

BRENNAN, N. A. ICLC, 10, 357 - 362, 1983.

BULL, D. The Ophthalmic Optician, 20, 523 - 532, 1980.

De DONATO, L. M. Am. J. Optom. and Physiol. Optics, 58, pp 846 - 847, 1981.

EFRON, N. AND HOLDEN, B. A. Optician, Aug., 1986.

EFRON, N. AND HOLDEN, B. A. Optician, Aug., 1986.

EFRON, N., KOTOW, M., MARTIN, D. K. AND HOLDEN, B. Am. J. Optom. Physiol. Optics, 61, 517 - 522, 1984.

FATT, I. ICLC, 11, 648, 1984.

FATT, I. Optician, 17 - 21, Dec., 1987.

FATT, I. AND CHASTON, J. J. of the BCLA, 66 - 70, 1982.

FITZGERALD, J. K. The Contact Lens Journal, 10, 16 -18, 1982.

GUILLON, M. AND LYDON, D. The Contact Lens Journal, 13, 10, 1985.

HILL, R. M. The Contact Lens Journal, 10, 19, 1982.

HILL, R. M. The Contact Lens Journal, 10, 12 - 13, 1982.

HOFER, P. The Contact Lens Journal, 7, 2 - 6, 1978.

HOFFMAN, W. C. Promotional Literature, Optacryl Incorporated.

JACOB, R. The Contact Lens Journal, 9, 21 - 24, 1980.

KERR, C. The Contact Lens Journal, 13, 6. 1985.

KO, J. H. Int. Contact Lens Clinic, 17, 1980.

KREIS-GOSSELIN, F. The Contact Lens Journal, 13, 11, 1985.

LEE, H. B., FISCHER, D. J. AND TURNER, D. T. ICLC, 17, 67 - 69, 1980.

LEEDY, P. D. Practical Research: Planning and Design. 3rd Ed.

LYDON, D. The Contact Lens Journal, 13, 10, 1985.

MAUGER, T. F. AND HILL, R. M. Invest. Ophthal. Vis. Sci., 24, 582 - 585, 1983.

PAYNE, J.P. and HILL, D.W. A Symposium On Oxygen Measurements in Blood and Tissues, J and A Churchill Ltd.,1966.

PHILLIPS, A. J. The Ophthalmic Optician, 20, 523 - 526, 1980.

POLSE, K. A. AND O'NEAL, M. R. J. of the BCLA, 19 - 20, 1986.

ROSCOE, W. R., MOLINARI, J. F. AND CAPLAN, L. The Contact Lens Journal, 10, 14 - 18, 1982.

SAMMONS, W. A. The Contact Lens Journal, 13, 6, 1985.

SHAVELSON, R. J. Statistical Reasoning for the Behavioral Sciences, Allyn and Bacon Inc., 1981.

WALKER, P. J. C. The Contact Lens Journal, 13, 9, 1985.

WILSON, G., RAFFERTY, W. B. AND LEWERENZ, D. C. ICLC, 5, 61 - 65, 1978.

YANOF, H.M. Biomesical Electronics, F.A. Davis, Philadelphia,1965.

APPENDIX

SUBJECT 1.

MATERIAL: PMMA

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	49	22	50	21	58	24
2	53	23	50	25	57	21
3	55	19	54	19	56	21
4	53	22	58	19	60	17
5	50	13	50	14	61	19
6	50	13	50	13	59	19
7	55	17	58	24	48	18
8	54	17	60	17	54	13
9	55	19	56	17	51	14
10	51	22	52	23	53	23
AVERAGE	52.5	18.7	53.8	19.2	55.7	18.9
STD.DEV	2.32	3.68	3.94	4.08	4.16	3.57

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.96$

TEST 1 / TEST 3 : $p = 0.90$

TEST 2 / TEST 3 : $p = 0.94$

SUBJECT 1

MATERIAL: POLYCON I

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	62	19	62	19	62	20
2	52	26	59	22	60	21
3	58	19	59	18	64	12
4	63	19	61	17	54	17
5	60	23	61	24	54	17
6	59	14	64	13	62	19
7	60	19	60	17	54	22
8	64	14	54	16	54	17
9	59	17	62	19	62	17
10	59	15	64	19	62	16
AVERAGE	59.6	18.5	60.6	18.4	58.8	17.8
STD.DEV	3.31	3.84	2.91	3.06	4.24	2.88

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.97$

TEST 1 / TEST 3 : $p = 0.98$

TEST 2 / TEST 3 : $p = 0.95$

SUBJECT 1

MATERIAL: SM38

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	60	25	61	19	65	23
2	64	18	65	20	64	27
3	65	21	64	21	64	17
4	65	18	69	22	69	22
5	64	19	58	19	64	21
6	64	16	64	18	66	23
7	68	16	66	17	64	17
8	58	18	64	21	65	12
9	64	18	64	21	65	17
10	72	16	64	20	69	19
AVERAGE	64.4	18.5	63.9	19.8	65.0	19.8
STD.DEV	3.84	2.76	2.88	1.55	1.96	4.26

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.99$

TEST 1 / TEST 3 : $p = 0.94$

TEST 2 / TEST 3 : $p = 0.97$

SUBJECT 1

MATERIAL: BOSTON IV

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	68	25	68	23	64	23
2	64	17	64	19	69	19
3	60	24	69	21	65	24
4	67	15	66	17	61	16
5	58	27	65	27	65	21
6	66	22	67	22	64	23
7	68	18	65	27	69	22
8	62	15	69	22	63	26
9	62	22	65	24	69	23
10	66	19	64	23	65	23
AVERAGE	64.1	20.4	66.2	22.5	65.5	22
STD.DEV	3.48	4.22	1.93	3.14	2.72	2.79

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.95$

TEST 1 / TEST 3 : $p = 0.96$

TEST 2 / TEST 3 : $p = 0.98$

SUBJECT 1

MATERIAL: FLUOROPOLYMER

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	72	27	72	17	72	17
2	77	17	69	18	72	19
3	75	21	72	19	77	18
4	70	20	67	21	74	19
5	67	19	67	23	70	27
6	72	24	64	19	67	22
7	71	22	78	27	64	14
8	78	19	72	23	71	21
9	70	21	71	21	70	29
10	71	15	70	19	77	19
AVERAGE	72.3	19.5	70.2	20.7	71.4	20.5
STD.DEV	3.40	5.82	3.82	2.98	4.06	4.53

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.95$

TEST 1 / TEST 3 : $p = 0.98$

TEST 2 / TEST 3 : $p = 0,97$

SUBJECT 2

MATERIAL: PMMA

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	56	23	49	24	49	16
2	55	23	61	25	64	14
3	51	16	52	16	59	24
4	56	16	64	24	56	15
5	57	24	58	24	58	19
6	59	19	57	17	57	27
7	58	24	60	23	62	17
8	51	19	55	21	59	22
9	55	23	56	21	57	21
10	56	21	57	22	60	17
AVERAGE	55.4	21.3	56.9	21.7	58.1	19.2
STD.DEV	2.63	2.78	4.33	3.06	4.01	4.21

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.96$

TEST 1 / TEST 3 : $p = 0.92$

TEST 2 / TEST 3 : $p = 0.97$

SUBJECT 2

MATERIAL: POLYCON 1

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	56	24	50	19	59	26
2	55	23	55	25	64	14
3	61	16	60	22	59	27
4	56	16	61	24	56	19
5	57	24	56	21	56	16
6	59	23	59	27	62	17
7	63	23	58	17	62	23
8	60	27	60	26	62	19
9	64	17	60	24	66	26
10	62	24	56	22	64	24
AVERAGE	59.3	21.7	57.5	22.7	61.0	21.1
STD.DEV	3.2	3.9	3.3	3.1	3.4	4.7

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.95$

TEST 1 / TEST 3 : $p = 0.95$

TEST 2 / TEST 3 : $p = 0.91$

SUBJECT 2

MATERIAL: SM38

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	61	23	61	24	61	16
2	61	24	61	24	64	23
3	64	18	63	16	66	23
4	68	17	66	24	58	19
5	65	19	64	17	56	23
6	64	16	58	19	57	23
7	66	24	55	24	59	24
8	64	18	58	23	61	27
9	59	24	59	22	61	19
10	68	24	58	19	64	24
AVERAGE	64.0	20.7	60.3	21.2	60,7	22.1
STD.DEV.	3.0	3.4	3.3	3.2	3.3	3.2

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.90$

TEST 1 / TEST 3 : $p = 0.91$

TEST 2 / TEST 3 : $p = 0.99$

SUBJECT 2

MATERIAL: BOSTON IV

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	64	16	62	24	67	17
2	64	26	63	14	66	23
3	62	17	64	17	61	19
4	61	29	59	21	56	18
5	59	24	58	26	67	26
6	64	23	67	24	64	24
7	66	27	56	22	60	15
8	67	26	64	27	60	24
9	65	22	63	19	64	24
10	64	24	63	24	62	24
AVERAGE	63.6	23.4	61.9	21.8	62.7	21.4
STD.DEV.	2.4	4.2	3.3	4.1	3.6	3.8

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.95$

TEST 1 / TEST 3 : $p = 0.98$

TEST 2 / TEST 3 : $p = 0.98$

SUBJECT 2

MATERIAL: FLUOROPOLYMER

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	67	23	67	26	67	26
2	66	26	64	23	68	23
3	64	24	66	24	68	23
4	62	19	62	24	64	24
5	62	24	68	26	64	24
6	66	23	56	24	62	14
7	64	16	64	17	69	17
8	62	17	59	19	69	19
9	62	17	69	19	63	19
10	64	17	70	24	69	24
AVERAGE	63.9	20.6	64.5	20.2	66.3	21.3
STD.DEV.	1.9	3.8	4.5	7.2	2.75	3.8

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.98$

TEST 1 / TEST 3 : $p = 0.94$

TEST 2 / TEST 3 : $p = 0.95$

SUBJECT 3

MATERIAL: PMMA

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	56	23	56	15	56	23
2	52	24	57	24	57	21
3	57	17	52	27	56	17
4	57	19	57	17	56	21
5	56	16	57	24	69	24
6	64	24	54	27	57	28
7	58	23	58	25	52	16
8	59	24	59	26	58	24
9	52	17	52	17	59	22
10	54	18	55	19	60	19
AVERAGE	56.5	20.5	56.2	22.1	58.0	21.5
STD.DEV.	3.5	3.4	2.0	4.6	4.4	3.6

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.99$

TEST 1 / TEST 3 : $p = 0.96$

TEST 2 / TEST 3 : $p = 0.95$

SUBJECT 3

MATERIAL: POLYCON 1

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	61	24	60	23	61	23
2	60	24	62	24	61	19
3	59	23	59	17	59	22
4	62	17	55	21	61	17
5	65	22	56	19	56	23
6	51	29	56	21	51	22
7	55	17	58	26	63	27
8	59	28	62	27	67	21
9	62	26	54	23	54	19
10	65	23	54	25	56	22
AVERAGE	59.7	23.3	57.6	22.6	58.9	21.5
STD.DEV.	4.3	4.0	3.0	3.1	4.7	2.8

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.94$

TEST 1 / TEST 3 : $p = 0.98$

TEST 2 / TEST 3 : $p = 0.96$

SUBJECT 3

MATERIAL: SM 38

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	62	23	60	22	62	22
2	59	19	60	23	60	23
3	64	59	59	17	60	24
4	66	23	60	24	59	27
5	58	26	59	26	69	14
6	54	24	64	18	64	19
7	62	17	64	16	66	21
8	63	27	64	22	64	16
9	71	22	61	22	60	19
10	66	23	62	23	60	22
AVERAGE	62.5	25.3	61.3	21.3	62.4	20.7
STD.DEV.	4.8	11.9	2.1	3.2	3.3	3.8

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.97$

TEST 1 / TEST 3 : $p = 0.99$

TEST 2 / TEST 3 : $p = 0.97$

SUBJECT 3

MATERIAL: BOSTON IV

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	64	23	70	23	70	21
2	66	16	71	19	69	17
3	58	17	64	21	64	17
4	64	17	69	24	58	16
5	66	19	58	23	69	22
6	58	23	72	22	61	24
7	66	19	61	19	64	15
8	69	23	64	64	70	17
9	69	23	64	26	64	27
10	58	17	65	19	63	19
AVERAGE	63.8	19.7	65.8	22.0	65.2	19.5
STD.DEV.	4.3	2.9	4.6	3.4	4.1	3.9

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.95$

TEST 1 / TEST 3 : $p = 0.96$

TEST 2 / TEST 3 : $p = 0.98$

SUBJECT 3

MATERIAL: FLUOROPOLYMER

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	62	23	68	17	62	17
2	66	24	68	18	59	22
3	66	27	69	27	59	22
4	68	23	64	19	60	19
5	65	19	70	16	64	17
6	64	27	69	19	71	18
7	68	16	69	21	67	24
8	69	19	66	19	66	26
9	68	17	70	24	64	24
10	68	20	69	24	64	23
AVERAGE	66.4	21.5	68.2	20.4	63.6	21.2
STD.DEV.	2.2	3.9	1.9	3.5	3.8	3.2

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.96$

TEST 1 / TEST 3 : $p = 0.93$

TEST 2 / TEST 3 : $p = 0.88$

SUBJECT 4

MATERIAL: PMMA

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	52	17	51	18	58	24
2	51	21	48	19	50	23
3	56	19	61	26	60	19
4	58	22	60	21	53	19
5	50	23	57	28	59	23
6	52	23	50	19	49	18
7	54	19	50	23	54	21
8	55	24	58	24	51	17
9	53	21	60	17	54	24
10	50	24	56	24	58	19
AVERAGE	53.1	21.3	55.1	21.9	54.6	20.7
STD.DEV.	2.6	2.4	4.9	3.7	3.9	2.6

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.94$

TEST 1 / TEST 3 : $p = 0.95$

TEST 2 / TEST 3 : $p = 0.98$

SUBJECT 4

MATERIAL: POLYCON 1

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	59	25	62	16	59	19
2	59	19	54	17	59	17
3	64	21	54	24	60	21
4	59	23	62	26	64	23
5	60	18	59	21	60	18
6	63	23	60	23	63	17
7	58	21	62	24	53	19
8	52	21	54	17	58	24
9	53	19	57	25	62	27
10	62	21	58	19	63	19
AVERAGE	58.9	21.1	58.2	21.2	60.1	20.4
STD.DEV	3.9	2.1	3.4	3.7	3.2	3.3

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.98$

TEST 1 / TEST 3 : $p = 0.97$

TEST 2 / TEST 3 : $p = 0.95$

SUBJECT 4

MATERIAL: SM 38

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	62	21	68	20	69	23
2	60	19	67	21	66	17
3	68	18	69	23	64	19
4	59	18	59	19	66	19
5	64	16	64	19	69	27
6	63	21	66	28	64	21
7	69	21	63	21	64	19
8	61	18	62	22	68	17
9	63	23	65	19	61	17
10	64	21	64	23	60	22
AVERAGE	63.3	19.6	64.7	21.5	65.1	20.1
STD.DEV.	3.2	2.2	2.9	2.8	3.1	3.2

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.96$

TEST 1 / TEST 3 : $p = 0.95$

TEST 2 / TEST 3 : $p = 0.99$

SUBJECT 4

MATERIAL: BOSTON IV

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	69	27	60	19	68	23
2	68	21	61	21	69	22
3	64	23	64	23	64	23
4	64	17	58	23	69	25
5	64	19	59	23	69	22
6	59	22	64	22	64	19
7	64	19	62	26	71	17
8	69	19	71	26	65	28
9	69	21	69	24	64	21
10	68	21	68	19	63	21
AVERAGE	65.8	20.9	63.6	22.6	66.6	22.1
STD.DEV.	3.3	2.8	4.5	2.5	2.9	3.0

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.88$

TEST 1 / TEST 3 : $p = 0.92$

TEST 2 / TEST 3 : $p = 0.96$

SUBJECT 4

MATERIAL: FLUOROPOLYMER

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	64	19	68	27	63	23
2	63	22	68	28	64	19
3	67	22	69	17	69	17
4	66	29	74	19	70	23
5	62	17	69	21	66	19
6	69	16	69	19	64	17
7	62	24	69	26	69	26
8	61	24	66	19	71	19
9	60	26	66	27	67	20
10	64	24	69	19	68	17
AVERAGE	63.8	22.3	68.7	22.2	67.1	20.0
STD.DEV	2.8	4.0	2.2	4.3	2.8	3.1

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.88$

TEST 1 / TEST 3 : $p = 0.92$

TEST 2 / TEST 3 : $p = 0.96$

SUBJECT 5

MATERIAL: PMMA

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	50	23	59	24	58	23
2	53	24	55	23	58	24
3	61	16	60	19	61	24
4	60	23	56	26	56	17
5	55	14	59	24	56	13
6	57	24	55	26	57	24
7	58	17	60	21	60	25
8	55	26	57	15	60	16
9	59	19	56	16	55	19
10	56	21	59	19	52	19
AVERAGE	56.4	20.7	57.2	21.3	57.3	20.4
STD.DEV.	3.3	4.0	2.0	3.9	2.7	4.1

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.98$

TEST 1 / TEST 3 : $p = 0.97$

TEST 2 / TEST 3 : $p = 0.99$

SUBJECT 5

MATERIAL: POLYCON 1

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	58	26	56	21	56	23
2	54	14	61	25	55	26
3	64	14	62	16	61	26
4	59	15	64	19	56	17
5	62	21	58	19	57	19
6	61	17	59	17	58	23
7	66	19	60	16	64	17
8	64	20	61	18	62	16
9	56	16	56	21	61	21
10	58	18	56	21	59	23
AVERAGE	60.2	18.0	59.3	19.3	58.9	21.1
STD.DEV.	3.9	3.7	2.8	2.8	3.0	3.7

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.97$

TEST 1 / TEST 3 : $p = 0.96$

TEST 2 / TEST 3 : $p = 0.99$

SUBJECT 5

MATERIAL: SM 38

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	61	19	58	19	61	16
2	59	16	64	23	64	18
3	62	22	55	14	58	24
4	63	22	58	19	56	13
5	68	19	59	22	57	17
6	59	21	66	24	66	19
7	59	16	64	21	62	26
8	65	25	61	22	64	28
9	64	28	61	24	59	26
10	61	27	58	22	66	23
AVERAGE	62.1	21.5	60.4	21.0	61.3	21.0
STD.DEV.	3.0	4.2	3.4	3.0	3.7	5.0

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.95$

TEST 1 / TEST 3 : $p = 0.98$

TEST 2 / TEST 3 : $p = 0.98$

SUBJECT 5

MATERIAL: BOSTON IV

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	66	24	67	24	64	19
2	67	14	66	22	64	20
3	59	17	57	21	59	21
4	56	22	59	16	61	19
5	67	26	64	18	59	17
6	64	24	60	21	67	24
7	56	21	60	21	60	22
8	58	19	64	19	60	23
9	64	17	62	18	64	26
10	68	19	58	17	62	22
AVERAGE	62.5	20.3	61.7	19.7	62.0	21.3
STD.DEV	4.8	3.8	3.4	2.5	2.7	2.7

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : p = 0.98

TEST 1 / TEST 3 : p = 0.99

TEST 2 / TEST 3 : p = 0.99

SUBJECT 5

MATERIAL: FLUOROPOLYMER

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	70	24	76	26	67	22
2	70	25	72	26	70	26
3	69	27	67	26	71	27
4	69	29	70	27	71	27
5	71	27	70	26	72	27
6	71	24	70	27	77	29
7	70	21	71	24	73	17
8	74	19	71	21	70	20
9	73	19	72	23	71	21
10	71	21	74	27	68	18
AVERAGE	70.8	23.6	71.3	25.3	71.0	23.4
STD. DEV.	1.62	3.5	2.5	2.0	2.8	4.3

t- DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.99$

TEST 1 / TEST 3 : $p = 0.99$

TEST 2 / TEST 3 : $p = 0.99$

SUBJECT 6

MATERIAL: PMMA

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	55	19	51	24	56	17
2	54	27	60	22	48	18
3	57	22	63	24	55	19
4	59	24	64	25	54	19
5	62	25	57	25	58	22
6	59	22	56	22	62	23
7	61	23	58	25	61	22
8	66	22	62	22	65	23
9	65	27	61	24	62	25
10	61	24	60	22	59	22
AVERAGE	59.9	23.5	59.2	23.5	58.0	21.0
STD.DEV.	3.9	2.5	3.9	1.4	4.9	2.6

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.98$

TEST 1 / TEST 3 : $p = 0.95$

TEST 2 / TEST 3 : $p = 0.97$

SUBJECT 6

MATERIAL: POLYCON 1

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	59	27	62	19	58	22
2	52	24	60	19	61	24
3	55	23	62	22	66	22
4	59	22	61	21	62	24
5	63	24	66	24	63	26
6	66	22	62	25	61	23
7	65	23	64	23	65	22
8	63	24	67	25	61	19
9	62	19	62	22	59	22
10	62	22	60	24	65	23
AVERAGE	60.6	23.0	62.6	20.4	62.1	22.7
STD.DEV.	4.4	2.1	2.4	6.5	2.6	1.8

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : p = 0.94

TEST 1 / TEST 3 : p = 0.96

TEST 2 / TEST 3 : p = 0.98

SUBJECT 6

MARERIAL: SM 38

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	68	24	63	26	60	22
2	68	26	61	27	64	24
3	66	22	64	23	61	25
4	68	27	61	19	61	25
5	59	22	55	21	60	20
6	55	27	62	17	61	23
7	57	22	58	23	62	24
8	61	24	60	22	56	25
9	61	23	63	24	55	25
10	61	23	62	26	59	19
AVERAGE	62.4	24.0	60.9	22.8	59.9	23.2
STD.DEV.	4.8	2.0	2.7	3.2	2.7	2.2

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.96$

TEST 1 / TEST 3 : $p = 0.93$

TEST 2 / TEST 3 : $p = 0.97$

SUBJECT 6

MATERIAL: BOSTON IV

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	63	24	69	27	69	24
2	69	23	69	23	69	23
3	68	24	69	27	68	26
4	67	21	72	24	73	22
5	69	23	69	23	72	24
6	65	27	60	22	70	22
7	69	24	62	24	63	25
8	62	19	58	24	60	22
9	61	22	61	22	56	17
10	61	24	60	17	59	21
AVERAGE	65.4	23.1	64.9	23.3	65.9	22.6
STD.DEV.	3.4	2.1	5.1	2.8	5.9	2.5

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.98$

TEST 1 / TEST 3 : $p = 0.99$

TEST 2 / TEST 3 : $p = 0.97$

SUBJECT 6

MATERIAL: FLUOROPOLYMER

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	64	27	69	24	69	24
2	72	26	72	26	71	22
3	66	23	73	25	72	19
4	67	23	75	26	77	26
5	66	21	76	24	78	23
6	64	19	68	22	69	21
7	62	17	66	21	66	21
8	69	21	63	18	64	19
9	71	23	60	22	61	20
10	73	24	61	20	76	25
AVERAGE	67.4	22.4	68.3	22.8	70.3	22.0
STD.DEV.	3.7	3.0	5.7	2.7	5.7	2.5

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.98$

TEST 1 / TEST 3 : $p = 0.93$

TEST 2 / TEST 3 : $p = 0.95$

SUBJECT 7

MATERIAL: PMMA

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	55	29	56	26	51	24
2	54	27	60	27	54	23
3	57	25	58	24	49	26
4	52	23	55	23	53	27
5	50	23	52	24	61	25
6	53	27	60	23	60	27
7	58	23	58	19	59	28
8	58	19	54	19	56	21
9	56	22	50	17	57	17
10	50	19	52	21	58	22
AVERAGE	54.3	23.7	55.5	22.3	55.8	24.0
STD.DEV.	3.0	3.3	3.5	3.2	4.0	3.4

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.96$

TEST 1 / TEST 3 : $p = 0,95$

TEST 2 / TEST 3 : $p = 0.99$

SUBJECT 7

MATERIAL: POLYCON 1

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	59	25	64	19	62	26
2	59	27	62	19	62	27
3	64	24	61	22	60	24
4	62	24	62	22	61	22
5	59	24	64	23	62	19
6	60	21	61	24	59	24
7	63	19	60	17	54	19
8	58	19	59	18	62	24
9	52	26	59	21	60	20
10	62	25	62	23	52	24
AVERAGE	59.8	23.4	61.4	20.8	59.4	22.9
STD.DEV.	3.4	2.8	1.8	2.4	3.6	2.8

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.96$

TEST 1 / TEST 3 : $p = 0.98$

TEST 2 / TEST 3 : $p = 0.94$

SUBJECT 7

MATERIAL: SM 38

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	66	24	64	24	64	28
2	64	25	63	22	61	26
3	65	21	59	29	61	23
4	61	23	61	24	62	26
5	61	24	54	24	64	27
6	59	25	58	19	66	24
7	66	24	55	24	59	23
8	64	28	61	21	61	19
9	67	25	63	22	62	22
10	63	23	62	24	61	24
AVERAGE	63.6	24.2	60.0	23.3	62.1	24.2
STD.DEV.	2.6	1.8	3.4	2.6	2.0	2.7

t- DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.90$

TEST 1 / TEST 3 : $p = 0.96$

TEST 2 / TEST 3 : $p = 0.96$

SUBJECT 7

MATERIAL: BOSTON IV

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	64	26	63	24	60	25
2	62	23	62	22	64	23
3	62	21	64	23	66	24
4	61	19	62	27	67	24
5	59	24	62	25	65	28
6	63	23	66	24	64	26
7	66	27	62	22	60	23
8	67	26	64	27	60	24
9	63	24	63	24	62	24
10	64	22	63	21	63	22
AVERAGE	63.1	23.5	64.3	23.9	65.7	24.3
STD.DEV.	2.3	2.5	2.4	2.0	2.8	1.7

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.97$

TEST 1 / TEST 3 : $p = 0.93$

TEST 2 / TEST 3 : $p = 0.96$

SUBJECT 7

MATERIAL: FLUOROPOLYMER

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	69	23	72	27	70	19
2	73	22	67	23	74	21
3	71	24	64	26	71	22
4	70	19	67	23	73	18
5	72	17	69	21	73	21
6	72	24	72	19	68	18
7	70	19	78	22	70	24
8	78	27	73	23	78	29
9	70	23	69	24	73	26
10	69	22	68	26	70	24
AVERAGE	71.4	22.0	69.9	23.4	72.0	22.2
STD.DEV.	2.7	2.9	4.0	2.5	2.8	3.6

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.96$

TEST 1 / TEST 3 : $p = 0.98$

TEST 2 / TEST 3 : $p = 0.95$

SUBJECT 8

MATERIAL: PMMA

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	54	22	50	21	58	23
2	56	23	51	22	56	21
3	57	21	54	29	55	22
4	53	19	58	29	59	18
5	51	15	56	26	52	22
6	52	19	54	24	51	25
7	50	22	53	23	55	23
8	54	24	51	25	53	21
9	53	25	51	24	51	24
10	52	26	49	24	51	23
AVERAGE	53.2	21.6	52.7	24.7	54.1	22.2
STD.DEV.	2.0	3.3	2.8	2.7	3.0	1.9

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.98$

TEST 1 / TEST 3 : $p = 0.97$

TEST 2 / TEST 3 : $p = 0.95$

SUBJECT 8

MATERIAL: POLYCON 1

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	59	18	62	22	54	25
2	59	21	61	23	58	25
3	61	24	66	23	62	27
4	62	23	65	21	61	26
5	64	21	64	19	63	25
6	63	25	61	22	62	22
7	61	27	58	25	60	24
8	60	25	62	27	62	21
9	58	25	61	26	60	17
10	58	24	60	26	61	19
AVERAGE	60.5	23.3	62.0	23.4	60.3	23.1
STD.DEV.	2.1	2.6	2.4	2.6	2.6	3.2

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.96$

TEST 1 / TEST 3 : $p = 0.99$

TEST 2 / TEST 3 : $p = 0.95$

SUBJECT 8

MATERIAL: SM 38

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	65	25	61	18	69	22
2	63	24	62	19	65	24
3	64	26	64	22	63	24
4	66	25	68	24	63	27
5	65	23	71	26	65	29
6	63	21	66	26	63	26
7	61	19	63	25	63	25
8	57	24	60	24	65	22
9	61	22	56	23	60	17
10	60	25	57	24	60	19
AVERAGE	62.5	23.4	62.8	23.1	63.6	23.5
STD.DEV.	2.8	2.2	4.7	2.9	2.6	3.6

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.99$

TEST 1 / TEST 3 : $p = 0.97$

TEST 2 / TEST 3 : $p = 0.97$

SUBJECT 8

MATERIAL: BOSTON IV

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	65	19	64	23	69	23
2	66	17	64	21	65	24
3	64	15	65	19	64	26
4	62	18	63	17	61	26
5	68	27	62	22	62	26
6	69	26	62	24	66	27
7	64	24	69	27	64	26
8	63	24	68	25	69	27
9	61	25	66	24	69	25
10	60	24	61	24	66	26
AVERAGE	64.2	21.9	64.4	22.6	65.5	25.6
STD.DEV.	2.9	4.2	2.6	3.0	2.9	1.3

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.99$

TEST 1 / TEST 3 : $p = 0.96$

TEST 2 / TEST 3 : $p = 0.97$

SUBJECT 8

MATERIAL: FLUOROPOLYMER

READIBG	TEST 1		TEST 2		TEST 3	
	pO_2	BILNK	pO_2	BLINK	pO_2	BLINK
1	70	22	75	24	72	25
2	72	23	73	24	69	23
3	74	25	74	25	65	24
4	78	26	73	24	64	21
5	77	23	79	25	67	17
6	72	20	74	22	63	14
7	70	17	71	19	67	21
8	67	17	69	23	67	19
9	69	21	64	25	65	23
10	69	23	63	24	64	23
AVERAGE	71.8	21.7	71.5	23.5	66.3	21.0
STD.DEV.	3.6	3.0	5.0	1.8	2.7	3.4

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.99$

TEST 1 / TEST 3 : $p = 0.87$

TEST 2 / TEST 3 : $p = 0.87$

SUBJECT 9

MATERIAL: PMMA

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	54	26	51	27	55	24
2	53	27	54	26	53	24
3	51	29	52	26	51	23
4	47	27	55	24	48	21
5	48	26	58	23	51	19
6	50	24	61	25	51	17
7	50	22	60	24	51	21
8	51	19	56	25	53	14
9	54	17	55	22	57	17
10	55	21	54	19	55	21
AVERAGE	51.3	23.8	55.6	24.1	52.5	20.1
STD.DEV.	2.7	3.9	3.3	2.3	2.6	3.3

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.98$

TEST 1 / TEST 3 : $p = 0.96$

TEST 2 / TEST 3 : $p = 0.99$

SUBJECT 9

MATERIAL: POLYCON 1

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	59	16	64	22	62	27
2	59	17	62	19	62	26
3	64	24	54	18	64	23
4	60	26	59	18	62	21
5	58	23	61	24	60	20
6	53	15	56	19	55	17
7	56	19	55	21	54	21
8	62	23	61	24	55	21
9	61	25	60	27	54	23
10	60	26	61	27	59	24
AVERAGE	59.2	21.4	59.3	21.9	58.7	22.3
STD.DEV.	3.1	4.3	3.3	3.5	3.9	3.0

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.99$

TEST 1 / TEST 3 : $p = 0.98$

TEST 2 / TEST 3 : $p = 0.98$

SUBJECT 9

MATERIAL: SM 38

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	65	22	61	19	65	23
2	64	19	64	22	64	25
3	62	18	69	26	65	26
4	58	16	64	27	68	27
5	60	19	64	26	66	25
6	62	21	62	26	65	24
7	61	24	62	24	65	25
8	62	27	58	23	62	21
9	61	25	60	25	57	17
10	60	24	62	22	58	19
AVERAGE	61.5	21.5	62.6	24.0	63.5	23.2
STD.DEV.	2.0	3.5	3.0	2.5	3.5	3.2

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.97$

TEST 1 / TEST 3 : $p = 0.94$

TEST 2 / TEST 3 : $p = 0.97$

SUBJECT 9

MATERIAL: BOSTON IV

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	66	25	68	23	61	17
2	68	27	67	24	59	18
3	69	29	65	27	61	21
4	67	26	62	24	64	24
5	66	23	64	23	65	23
6	62	21	63	17	64	22
7	60	19	62	19	61	19
8	59	19	60	20	61	19
9	60	21	60	22	64	21
10	61	23	60	23	61	24
AVERAGE	63.8	23.3	63.1	22.2	62.1	20.8
STD.DEV.	3.8	3.4	2.9	2.9	2.0	2.5

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.98$

TEST 1 / TEST 3 : $p = 0.95$

TEST 2 / TEST 3 : $p = 0.97$

SUBJECT 9

MATERIAL; FLUOROPOLYMER

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	70	27	70	22	77	24
2	72	26	69	18	73	25
3	75	27	67	19	71	24
4	78	25	69	22	70	17
5	75	21	67	24	67	15
6	71	19	64	23	65	17
7	70	20	67	23	65	21
8	70	19	64	23	70	20
9	72	21	70	25	71	23
10	71	23	70	27	71	23
AVERAGE	72.4	22.8	67.7	22.6	70.0	20.9
STD.DEV.	2.7	3.2	2.3	2.6	3.7	3.5

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.89$

TEST 1 / TEST 3 : $p = 0.94$

TEST 2 / TEST 3 : $p = 0.94$

SUBJECT 10

MATERIAL: PMMA

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	51	24	55	19	54	21
2	52	25	52	17	51	18
3	54	27	50	15	50	14
4	58	28	50	15	51	18
5	57	29	52	17	48	21
6	55	26	51	20	50	24
7	54	25	52	23	52	25
8	57	25	53	26	55	27
9	56	23	56	29	53	27
10	53	21	51	27	51	26
AVERAGE	54.7	25.3	52.2	20.8	51.5	22.1
STD.DEV.	2.3	2.4	2.0	5.1	2.1	4.4

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : p = 0.92

TEST 1 / TEST 3 : p = 0.90

TEST 2 ? TEST 3 : p = 0.98

SUBJECT 10

MATERIAL: POLYCON 1

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	59	25	64	29	62	26
2	59	27	62	29	62	27
3	64	24	59	26	60	27
4	60	29	60	27	54	24
5	59	24	64	23	62	19
6	60	23	61	24	56	22
7	63	19	61	22	54	24
8	58	19	59	18	59	22
9	52	24	59	22	60	21
10	62	19	63	21	60	24
AVERAGE	59.6	23.3	61.2	24.1	58.9	23.6
STD.DEV.	3.3	3.4	2.0	3.6	3.1	2.6

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.95$

TEST 1 / TEST 3 : $p = 0.98$

TEST 2 / TEST 3 : $p = 0.93$

SUBJECT 10

MATERIAL: SM 38

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	66	19	64	23	64	23
2	62	22	65	24	69	24
3	63	16	60	22	66	26
4	64	18	59	19	69	22
5	63	22	57	22	64	21
6	58	25	58	27	63	22
7	60	27	61	29	62	19
8	58	28	66	27	60	25
9	62	27	64	26	58	24
10	62	26	61	26	58	25
AVERAGE	61.8	23.0	61.5	24.5	63.3	23.1
STD.DEV.	2.5	4.2	3.1	3.0	3.8	2.1

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.99$

TEST 1 / TEST 3 : $p = 0.96$

TEST 2 / TEST 3 : $p = 0.95$

SUBJECT 10

MATERIAL: BOSTON IV

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	72	26	64	30	69	19
2	70	28	64	27	65	17
3	68	25	64	23	65	21
4	64	23	63	19	64	17
5	64	19	64	18	66	23
6	65	17	61	19	64	21
7	65	18	59	22	63	22
8	69	21	61	21	64	25
9	64	22	61	20	64	27
10	62	25	61	19	65	23
AVERAGE	66.3	22.4	62.2	21.8	64.9	21.5
STD.DEV.	3.2	3.7	1.8	3.9	1.7	3.2

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.89$

TEST 1 / TEST 3 : $p = 0.96$

TEST 2 / TEST 3 : $p = 0.93$

SUBJECT 10

MATERIAL: FLUOROPOLYMER

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	71	18	70	27	77	19
2	70	21	71	24	74	17
3	74	19	71	21	70	20
4	78	19	72	23	71	21
5	71	21	78	27	68	18
6	70	24	76	26	67	22
7	70	25	72	26	70	26
8	69	27	67	26	71	29
9	67	29	70	27	71	27
10	71	27	70	26	72	27
AVERAGE	71.1	23.0	71.7	25.3	71.1	22.6
STD.DEV	3.0	3.9	3.2	2.0	2.9	4.3

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.98$

TEST 1 / TEST 3 : $p = 1.0$

TEST 2 / TEST 3 : $p = 0.98$

SUBJECT 11

MATERIAL: PMMA

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	55	22	51	24	57	24
2	53	21	51	25	56	23
3	51	17	50	19	59	24
4	48	21	51	16	56	27
5	49	24	50	17	52	27
6	51	25	47	17	51	25
7	52	26	49	19	54	22
8	51	28	50	22	52	23
9	53	26	50	24	53	25
10	52	27	51	26	53	25
AVERAGE	51.5	23.7	50.0	20.9	54.3	24.5
STD.DEV.	2.0	3.4	1.25	3.7	2.5	1.7

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : p = 0.95

TEST 1 / TEST 3 : p = 0.91

TEST 2 / TEST 3 : p = 0.86

SUBJECT 11

MATERIAL: POLYCON 1

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	57	25	54	19	62	24
2	55	24	54	21	60	24
3	52	22	57	26	59	23
4	48	20	62	26	59	22
5	52	22	63	27	54	17
6	55	26	62	26	54	21
7	57	27	61	27	57	24
8	59	26	64	25	60	26
9	62	27	63	26	61	27
10	62	26	62	26	62	26
AVERAGE	55.9	24.5	60.2	24.9	58.8	23.4
STD.DEV.	4.8	2.4	3.8	2.7	2.9	2.9

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : p = 0.87

TEST 1 / TEST 3 : p = 0.91

TEST 2 / TEST 3 : p = 0.96

SUBJECT 11

MATERIAL: SM 38

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	64	29	62	24	66	23
2	68	25	64	27	65	19
3	69	24	64	29	64	20
4	67	24	67	27	61	17
5	68	26	67	26	63	19
6	64	23	65	24	62	22
7	62	21	66	26	61	24
8	61	19	65	22	62	26
9	60	20	63	17	63	27
10	60	24	60	19	63	27
AVERAGE	64.3	23.5	64.3	24.1	63.0	22.4
STD.DEV.	3.5	3.0	2.2	3.8	1.6	3.6

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 1.0$

TEST 1 / TEST 3 : $p = 0.96$

TEST 2 / TEST 3 : $p = 0.96$

SUBJECT 11

MATERIAL: BOSTON IV

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	66	19	62	22	64	15
2	68	21	63	22	61	19
3	67	24	64	24	60	19
4	66	24	66	27	60	22
5	64	25	68	29	61	27
6	64	29	69	29	64	26
7	67	28	67	22	66	27
8	66	27	65	24	66	26
9	65	25	66	23	65	26
10	64	25	66	22	64	27
AVERAGE	65.7	24.7	65.6	24.4	63.1	23.4
STD.DEV	1.4	3.0	2.1	2.9	2.4	4.4

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.99$

TEST 1 / TEST 3 : $p = 0.92$

TEST 2 / TEST 3 : $p = 0.93$

SUBJECT 11

MATERIAL: FLUOROPOLYMER

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	67	27	72	17	70	24
2	66	27	71	23	70	25
3	67	24	70	25	72	27
4	70	26	67	26	73	26
5	72	27	68	27	72	28
6	74	28	70	26	73	27
7	77	29	72	26	73	29
8	74	27	74	26	77	28
9	75	26	74	27	76	27
10	75	27	72	26	72	27
AVERAGE	71.7	26.8	71.0	24.9	72.8	26.8
STD.DEV.	4.0	1.32	2.31	3.0	2.2	1.5

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : p = 0.98

TEST 1 / TEST 3 : p = 0.97

TEST 2 / TEST 3 : p = 0.95

SUBJECT 12

MATERIAL: PMMA

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	56	21	59	24	52	19
2	59	19	59	23	55	19
3	58	17	57	25	56	23
4	57	24	60	21	58	23
5	55	24	60	19	55	19
6	53	14	55	15	52	19
7	52	19	55	24	51	23
8	53	23	57	27	51	26
9	52	24	55	26	52	27
10	53	25	53	26	53	27
AVERAGE	54.8	21.0	57.0	23.0	53.5	2.5
STD. DEV.	2.5	3.7	2.5	3.7	2.4	3.4

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.93$

TEST 1 / TEST 3 : $p = 0.96$

TEST 2 / TEST 3 : $p = 0.89$

SUBJECT 12

MATERIAL: POLYCON 1

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	61	17	59	19	58	23
2	56	14	56	21	61	21
3	54	16	61	19	61	21
4	54	19	56	21	59	23
5	56	26	56	21	58	23
6	64	24	58	25	55	26
7	64	24	62	26	61	26
8	62	26	63	29	64	27
9	64	27	65	27	66	28
10	63	26	65	25	65	26
AVERAGE	59.8	21.9	60.1	23.3	60.8	24.4
STD. DEV.	4.3	4.9	3.6	3.5	3.5	2.5

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.99$

TEST 1 / TEST 3 : $p = 0.97$

TEST 2 / TEST 3 : $p = 0.98$

SUBJECT 12

MATERIAL: SM 38

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	61	27	58	22	66	23
2	64	28	61	24	66	29
3	64	25	66	24	66	25
4	68	22	64	21	62	26
5	62	21	59	22	57	17
6	63	22	58	19	56	13
7	62	22	55	14	54	24
8	62	22	54	27	60	28
9	61	19	58	25	61	26
10	62	24	61	26	60	27
AVERAGE	62.9	23.2	59.4	22.4	60.8	23.8
STD. DEV.	2.1	2.8	3.7	3.8	4.3	5.1

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.90$

TEST 1 / TEST 3 : $p = 0.94$

TEST 2 / TEST 3 : $p = 0.96$

SUBJECT 12

MATERIAL: BOSTON IV

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	68	19	58	17	68	22
2	64	17	59	19	69	26
3	58	19	60	23	66	23
4	56	21	60	21	65	22
5	62	22	60	21	68	26
6	63	26	61	28	65	19
7	66	22	69	26	61	17
8	69	17	67	21	59	21
9	67	14	66	22	61	20
10	66	24	67	24	64	19
AVERAGE	63.9	20.1	62.7	22.2	64.6	21.5
STD. DEV.	4.3	3.6	4.1	3.2	3.4	3.0

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.96$

TEST 1 / TEST 3 : $p = 0.98$

TEST 2 / TEST 3 : $p = 0.95$

SUBJECT 12

MATERIAL: FLUOROPOLYMER

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	63	24	61	20	76	25
2	61	23	60	22	71	20
3	60	21	63	18	74	19
4	62	17	66	21	76	21
5	64	19	68	22	69	21
6	66	21	66	24	68	25
7	77	23	65	26	67	26
8	76	23	73	25	62	19
9	72	26	72	27	61	22
10	74	27	70	24	59	24
AVERAGE	67.5	22.4	66.4	22.9	68.3	22.2
STD. DEV.	6.6	3.0	4.4	2.8	6.1	2.6

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.97$

TEST 1 / TEST 3 : $p = 0.98$

TEST 2 / TEST 3 : $p = 0.95$

SUBJECT 13

MATERIAL: PMMA

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	52	26	57	25	51	22
2	52	26	58	29	51	23
3	53	25	56	26	51	24
4	54	24	54	24	53	21
5	52	22	53	23	55	23
6	50	22	53	23	55	25
7	50	19	54	24	53	25
8	51	15	56	26	52	22
9	50	19	58	29	51	18
10	53	21	58	27	50	18
AVERAGE	51.7	21.9	55.7	25.6	52.2	22.1
STD. DEV.	1.42	3.5	2.1	22.2	1.8	2.5

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.87$

TEST 1 / TEST 3 : $p = 0.98$

TEST 2 / TEST 3 : $p = 0.89$

SUBJECT 13

MATERIAL: POLYCON 1

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	62	23	65	21	56	25
2	64	23	64	19	58	25
3	63	25	61	22	61	28
4	64	24	64	19	63	25
5	61	27	59	21	60	29
6	60	25	62	27	62	21
7	58	25	61	26	60	17
8	57	18	60	22	54	19
9	56	21	61	23	58	25
10	61	24	62	23	62	27
AVERAGE	60.6	23.5	61.9	22.3	59.4	24.1
STD. DEV	2.8	2.5	1.9	2.6	2.9	3.9

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.96$

TEST 1 / TEST 3 : $p = 0.97$

TEST 2 / TEST 3 : $p = 0.93$

SUBJECT 13

MATERIAL: SM 38

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	66	25	68	24	63	27
2	65	23	71	26	65	29
3	63	21	66	26	68	26
4	61	19	63	25	63	25
5	57	24	60	24	63	22
6	61	22	56	23	60	17
7	60	25	57	24	60	18
8	63	25	61	18	62	24
9	64	24	62	19	65	26
10	66	25	64	22	69	27
AVERAGE	62.6	23.3	62.8	23.1	63.8	24.1
STD. DEV.	2.9	2.1	4.7	2.7	3.0	4.0

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.99$

TEST 1 / TEST 3 : $p = 0.97$

TEST 2 / TEST 3 : $p = 0.97$

SUBJECT 13

MATERIAL: BOSTON IV

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	68	27	66	22	65	24
2	66	26	67	24	67	27
3	64	24	65	23	69	29
4	64	21	64	21	71	27
5	61	19	63	19	67	26
6	60	18	63	17	64	24
7	58	17	60	19	63	23
8	60	26	62	22	61	21
9	62	25	66	25	61	21
10	63	24	68	27	59	17
AVERAGE	62.6	22.7	64.4	21.9	64.7	23.9
STD. DEV.	3.0	3.7	2.5	3.0	3.8	3.6

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.95$

TEST 1 / TEST 3 : $p = 0.94$

TEST 2 / TEST 3 : $p = 0.99$

SUBJECT 13

MATERIAL: FLUOROPOLYMER

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	71	27	70	26	72	27
2	67	29	70	27	71	27
3	69	27	67	26	71	29
4	70	25	72	26	70	26
5	70	24	76	26	67	22
6	71	21	78	27	68	19
7	68	19	78	23	71	21
8	64	19	71	21	70	22
9	65	21	71	24	74	17
10	67	26	73	26	65	19
AVERAGE	68.2	23.8	72.6	25.2	69.9	22.9
STD. DEV.	2.4	3.6	3.7	1.9	2.6	4.1

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : p = 0.89

TEST 1 / TEST 3 : p = 0.96

TEST 2 / TEST 3 : p = 0.93

SUBJECT 14

MATERIAL: PMMA

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	50	23	57	24	53	23
2	52	21	58	27	54	25
3	54	24	60	28	58	24
4	53	21	60	24	58	26
5	52	17	62	28	60	29
6	52	24	61	24	61	26
7	56	27	59	22	62	25
8	58	28	55	19	60	22
9	61	31	52	17	60	17
10	66	29	51	20	58	19
AVERAGE	55.4	24.5	57.5	23.3	58.4	23.6
STD. DEV.	5.0	4.3	3.6	3.8	2.9	3.5

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.94$

TEST 1 / TEST 3 : $p = 0.91$

TEST 2 / TEST 3 : $p = 0.97$

SUBJECT 14

MATERIAL: POLYCON 1

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	62	21	58	19	63	24
2	60	19	59	21	64	23
3	58	21	60	23	63	25
4	59	23	62	26	64	23
5	62	25	64	24	61	19
6	64	23	63	19	56	17
7	62	21	59	17	52	16
8	58	14	54	17	52	19
9	54	21	53	22	54	23
10	56	24	55	26	57	27
AVERAGE	59.5	21.2	58.9	21.4	58.6	21.6
STD. DEV.	3.1	3.1	3.8	3.3	5.0	3.6

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.98$

TEST 1 / TEST 3 : $p = 0.97$

TEST 2 ? TEST 3 : $p = 0.99$

SUBJECT 14

MATERIAL: SM 38

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	59	23	61	25	62	24
2	55	27	60	22	60	22
3	59	24	62	24	63	25
4	62	19	58	24	60	22
5	61	22	61	23	56	17
6	61	24	60	17	59	21
7	63	24	64	27	62	24
8	62	24	61	23	63	23
9	64	24	59	27	64	26
10	63	25	62	24	63	24
AVERAGE	60.9	23.6	60.8	23.6	61.2	22.8
STD.DEV	2.6	2.1	1.7	2.8	2.4	2.5

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.99$

TEST 1 / TEST 3 : $p = 0.99$

TEST 2 / TEST 3 : $p = 0.99$

SUBJECT 14

MATERIAL: BOSTON IV

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	64	26	68	27	64	25
2	68	27	69	25	66	27
3	69	25	65	23	67	24
4	65	22	62	19	65	21
5	60	19	59	19	64	19
6	59	18	60	22	60	22
7	56	22	62	24	61	22
8	57	24	65	27	62	25
9	60	26	64	26	64	27
10	60	25	63	27	65	27
AVERAGE	61.8	23.4	63.7	23.9	63.8	23.9
STD. DEV.	4.5	3.1	3.2	3.1	2.2	2.8

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.95$

TEST 1 / TEST 3 : $p = 0.94$

TEST 2 / TEST 3 : $p = 0.98$

SUBJECT 14

MATERIAL: FLUOROPOLYMER

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	67	26	65	26	67	26
2	66	21	66	24	68	23
3	64	19	68	22	69	21
4	62	17	66	21	66	21
5	60	21	63	18	64	19
6	61	23	60	22	61	19
7	63	24	62	25	61	23
8	64	26	63	26	62	27
9	66	29	65	27	67	26
10	70	27	68	29	72	27
AVERAGE	68.3	23.3	69.6	24.0	65.7	23.2
STD. DEV.	5.4	3.8	4.8	3.3	3.7	3.2

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.96$

TEST 1 / TEST 3 : $p = 0.93$

TEST 2 / TEST 3 : $p = 0.90$

SUBJECT 15

MATERIAL: PMMA

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	58	23	57	22	59	28
2	58	21	54	19	56	27
3	56	22	50	17	57	17
4	56	19	52	21	56	22
5	55	29	56	26	51	24
6	54	27	60	27	54	23
7	57	25	58	24	53	27
8	50	23	53	24	61	25
9	53	27	60	23	61	27
10	58	23	58	19	59	28
AVERAGE	55.5	23.9	55.8	22.2	56.7	24.8
STD. DEV.	2.6	3.1	3.4	3.2	3.4	3.52

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : p = 0.99

TEST 1 / TEST 3 : p = 0.96

TEST 2 / TEST 3 : p = 0.97

SUBJECT 15

MATERIAL: POLYCON 1

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	63	19	60	17	54	19
2	58	19	59	18	62	24
3	52	26	59	21	60	20
4	59	27	62	19	62	27
5	64	24	61	22	60	24
6	59	24	64	23	62	19
7	60	21	61	24	59	24
8	63	19	60	17	54	19
9	58	19	59	18	62	24
10	57	21	58	19	63	25
AVERAGE	59.5	21.9	60.3	19.8	59.8	22.5
STD. DEV.	3.4	3.1	1.8	2.5	3.3	3.0

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : p = 0.97

TEST 1 / TEST 3 : p = 0.99

TEST 2 / TEST 3 : p = 0.98

SUBJECT 15

MATERIAL: SM 38

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	51	23	54	24	55	23
2	51	24	53	22	61	19
3	59	25	59	29	57	22
4	60	26	66	24	59	23
5	62	28	67	24	61	21
6	66	25	62	27	61	24
7	67	24	64	24	63	27
8	65	25	62	25	64	26
9	64	23	65	27	59	25
10	63	21	65	24	60	24
AVERAGE	60.8	24.4	61.7	25.0	60.0	23.4
STD. DEV.	5.7	1.9	4.9	2.0	2.7	2.4

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.97$

TEST 1 / TEST 3 : $p = 0.98$

TEST 2 / TEST 3 : $p = 0.95$

SUBJECT 15

MATERIAL: BOSTON IV

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	66	27	62	22	61	23
2	67	26	64	24	60	24
3	63	24	63	24	62	24
4	64	22	63	21	63	22
5	64	26	63	24	60	25
6	62	23	62	22	64	23
7	62	21	64	23	66	24
8	61	19	62	26	67	24
9	59	24	62	25	65	28
10	63	23	66	24	64	27
AVERAGE	61.1	23.5	63.4	23.5	63.7	24.4
STD. DEV.	2.8	2.5	1.3	1.5	2.6	1.8

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.94$

TEST 1 / TEST 3 : $p = 0.93$

TEST 2 / TEST 3 : $p = 0.99$

SUBJECT 15

MATERIAL: FLUOROPOLYMER

READING	TEST 1		TEST 2		TEST 3	
	pO_2	BLINK	pO_2	BLINK	pO_2	BLINK
1	78	27	73	23	78	29
2	70	23	68	24	74	26
3	69	22	68	26	71	24
4	69	23	71	27	70	20
5	73	22	68	25	74	22
6	71	24	65	26	72	22
7	70	20	67	24	73	19
8	72	18	69	22	74	21
9	72	24	72	20	68	18
10	71	20	75	24	72	23
AVERAGE	71.5	22.3	69.6	24.1	72.6	22.2
STD. DEV.	2.6	2.5	3.1	2.1	2.7	3.3

t-DISTRIBUTION (two tailed):

TEST 1 / TEST 2 : $p = 0.95$

TEST 1 / TEST 3 : $p = 0.97$

TEST 2 / TEST 3 : $p = 0.99$