Laser Induced Fluorescence Measurement of the Tear Film Thickness Under a Contact Lens

by

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Abstract

A device was built to measure the tear film thickness under a contact lens. Contact lenses of varying diopter were tested on both smooth and roughened model eyes. Artificial tears containing 5 mg/ml FITC-dextran 150 was placed underneath a contact lens. The sample was fluoresced with blue (495 nm) laser light. Images were taken using a Pulnix CCD camera. Tear film thickness was calibrated using flat glass slides clamped into a wedge shape, with fluorescein enhanced artificial tears between them. Graphs were made of tear film thickness versus position on the image.

The relationship of the tear film thickness to contact lens geometry, eye roughness, tear film viscosity, and contact lens material properties was examined.

It was found that the tear film thickness was affected by the surface roughness of the model eye. The device was found to provide repeatable results for the measurement of the distribution in the tear film thickness as it varied beneath the contact lens across the cornea, limbus, and scleral region of the eye. Values for the tear film thickness of between 10 and 50 microns were obtained. The values obtained were in the range of previously published values for the film depth on an eye and under a contact lens.

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Chapter 1

Introduction

The idea of placing a device directly onto the eye to improve vision is an old one. Sir John F.W. Herschel published a paper in which he realized the importance of the contact lens in 1845 [36]. Fick in 1888 foretold the use of contact lenses for optically corrective and cosmetic applications. Galezowsky in 1886 suggested that a gelatin disc, in essence a contact lens, be suffused with mercury and cocaine and applied after cataract surgery to stop pain and prevent infection. The gelatin disc idea was a precursor to the use of contact lenses for drug delivery, which does occur today. However, contact lenses were not comfortable for long-term use until the 1930s, when strides began to be made in relieving pressure on the eye by the lens at the corneoscleral limbus. The pressure under the lens was understood at that time to be a major source of contact lens discomfort. By 1948 lenses were at such a level of refinement that full day wear became possible. In 1962 hydrocolloid lenses were introduced by Wichterle and Lim, which could be worn for 8 hours at a time. Although corneal lenses exist that can provide 12 to 16 hours of wear, advances in production methods have made flexible hydrogel lenses cheaper to manufacture than rigid gas-permeable lenses. In addition, disposable hydrogel lenses, which provide advantages in lens hygiene and convenience, are now sold in significant amounts. Therefore the comfort and design of hydrogel contact lenses is of commercial and medical importance.

25 million people in the US wear contact lenses. The number of contact lens wearers is rapidly increasing, as evidenced by the fact that 1.5 million new users
appeared during the first six months of 1996 [8]. Many of these will be wearing flexible hydrogel contact lenses. Discomfort during prolonged lens wear is a major source of failure to continue wearing contact lenses; therefore discomfort must be minimized by providing the most comfortable lens with the appropriate degree of optical correction. Proper lens fit, comfort during use, and optical correction are the most important factors in determining the proper contact lens for a new patient. It is necessary to make trade-offs among these three properties when deciding on an appropriate lens.

The tear film thickness under a contact lens plays an important role in determining the comfort of a lens. The tear film is affected by various lens parameters such as basecurve radius, bevel radius, lens thickness, sagittal height, lens diameter, water content, and material properties such as elastic and modulus. These design parameters will be described in the chapters below.

The goal of this thesis is to describe an experiment to measure the tear film thickness under a contact lens. Progress toward this goal can be measured in three ways:

1. Repeatability of results
2. Correspondence to theoretical simulations of the tear film thickness
3. Agreement with previously published data.

This thesis will describe features important to the design of a contact lens, as well as provide background on the physical modeling of an eye/contact lens system. The importance of the pressure distribution under a contact lens, post lens tear film, surface roughness of the cornea, and tear film surface tension will be discussed. In addition, the important parameters of the model eye and the contact lens will be detailed.

The principals of laser induced fluorescence, which are used in the experiment, are described. In addition, alternative methods of measuring the tear film thickness using interferometry and confocal microscopy are explained. Next, an experimental
device to measure the tear film thickness under a contact lens is described. The
design constraints of the model eye and fluorescein system, laser, and optical setup
are explained. The experimental procedure is given, then results and analysis in which
trends found in tear film depth are related to lens diopter and model eye roughness.
In addition, the relationship of fluid depth to position on the model eye is examined.

1.1 Definition of Terms

Some definition of terms is needed before proceeding any further. Many of the fol-
lowing definitions were taken from Harold A. Stein et. al.: Fitting Guide for Rigid
and Soft Contact Lenses.
The cornea is the clear portion of the eye that covers the colored portion of the eye (iris) and the pupil. The cornea’s translucence and optical properties are of the utmost importance to vision. Most contact lenses cover the cornea at least partially when worn. The outer surface of the cornea is covered by microvilli which increase its surface area. This may be important to maintaining a certain tear film thickness on the eye, as a larger surface area means the tear film has more area onto which it can adhere.

The corneal cap includes the centermost area of the cornea. It has often been modeled as having a constant radius of curvature, but this is not really the case.
A more accurate model shows that the corneal cap varies in radius. [21] This is important when trying to create a model eye, as a spherical eye will not provide correct results.

The peripheral corneal region surrounds the corneal cap. It generally is much flatter in curvature than the corneal cap.

The sclera is the “white” of the eye and constitutes the majority of the eye surface. Scleral and semiscleral lenses cover this region.

A tear film covers the cornea and sclera; it acts as a protective layer for the eye and also, in a sense, acts as a cushion on which the contact lens can rest.

1.1.2 Contact Lens Terminology

Figure 1-1 on page 13 depicts the parameters important to fit of a contact lens. According to Stein et. al., “A contact lens refers to any lens that is placed on the surface of the cornea and sclera, either for optical purposes, or for therapeutic purposes.” Contact lenses can be made from rigid material such as methyImethacrylate or, as is more common today, from flexible, high water content hydrogel material. The lenses used in this study cover the cornea and a small portion of the sclera, extending past the corneo-scleral junction onto the edge of the sclera.

1.1.3 Geometry

The base curve of a contact lens includes all radii of curvature of the central portion of the lower curve of the lens. It is also called the central posterior curve or the posterior central curve.

The optic zone of a contact lens includes all radii of curvature of the central portion of the upper curve of the lens. The optic zone determines the corrective power of the lens.

The central thickness of the lens is the distance between the upper and lower surfaces of the lens, measured from the lens center.

The sagittal height is the vertical distance between the edge of the contact lens
and the center of the basecurve.

The bevel radius is the curvature at the edge of the lens; the curve is concave up rather than concave down like the rest of the basecurve. When properly fitted, the bevel zone of the lens does not directly touch the eye; instead, it rests on a layer of tear fluid.

The lens diameter is the largest distance between the edges of the lens.

1.1.4 Squeeze Pressure

The "squeeze pressure" under a lens refers to the pressure caused by the lens and tear film acting together on the cornea. As the lens deforms and relaxes due to eyelid blinking the tear film is placed under pressure which presses on the cornea. Thus the squeeze pressure is affected by the thickness, elastic modulus and steepness of fit of the contact lens [22]. It has been found that the squeeze pressure in hydrogel contact lenses is lower than in rigid lenses, due to the flexible lenses' lower elastic modulus and hence their greater pliability.

1.1.5 Types of Contact Lenses

Scleral contact lenses cover a large portion of the sclera as well as the cornea. Figure 1-3 on page 17 shows the various types of contact lenses.

Semiscleral lenses cover less of the sclera; they are the most common type of soft contact lens. These lenses cover the corneo-scleral limbus, which has been found to be an important area with respect to the comfort of the contact lens. If there is excessive pressure on the limbus, the lens will not be comfortable to wear for long periods of time. This study uses semiscleral lenses exclusively, and specifically examines the tear film thickness in the corneo-scleral region as well as toward the center of the lens. Corneal lenses do not overlap onto the sclera at all, avoiding problems with limbal pressure. Many rigid gas-permeable lenses are corneal lenses.
1.2 Optics in a Contact Lens System

Contact lenses correct vision in the same way that regular eyeglass lenses do, by focusing light onto the retina of the eye. Lenses for nearsighted (myopic) patients have a negative diopter; i.e. they are curved so that they are thinner in the center and thicker on the edges. Lenses for farsighted (hyperopic) patients are the opposite; those lenses are thicker in the center and thinner on the edges. Figure 1-4 displays the difference between a negative and a positive diopter lens.

The negative diopter lens works by focusing light further back than the myopic cornea is capable of doing. The light is adjusted so it falls on the retina (the light-sensing area at the back of the eye) to provide a clear image. Positive diopter lenses work by focusing the light further forward onto the retina to provide a focused image.

The main difference between contact lenses and spectacle lenses used to correct vision is the distance at which they are positioned in front of the eye. Eyeglass lenses are placed a few centimeters in front of the eye, while contact lenses are directly on
the cornea. Figure 1-5 on page 19 shows the differences in focal length between a contact lens and an eyeglass lens for both nearsighted and farsighted eyes. In the case of a hyperopic eye, the eyeglass lens is placed farther away from the far point of the eye, while the contact lens is closer to the far point. The opposite is true for a myopic eye; the contact lens is farther from the far point than the spectacle lens. The far point (FP) on figure 1-5 is the point on which the focal point of the lens must fall in order to provide corrected vision. A contact lens must have a shorter focal distance than an eyeglass lens to make up for the fact that it is closer to the far point of the eye. Therefore the curvature of a contact lens will vary from that of a spectacle lens of the same prescription. In the case of positive diopter lenses, the contact lens must have a higher curvature than the corresponding spectacle lens, while for negative diopter lenses the contact lens will have a lower value. The difference between the convergence needed for a contact lens and for a spectacle lens is negligible up to about 4 diopters; after that point the contact lens must be given a different curvature than the eyeglass lens to account for the difference in convergence.

High negative diopter contact lenses must be made very thin in the center to allow for a sufficiently thin edge thickness. This may lead to problems with excessive
dessiccation of the eye due to transfer and evaporation of water through the lens. The tear film under the contact lens is depleted in this situation, leading to discomfort [27].

When calculating the power of a contact lens, its thickness must be taken into account. This is due to the short radius of the contact lens compared to its thickness (i.e. the radii and thickness are of the same order of magnitude). If the thickness of the lens were not taken into account, the power of the lens would be calculated using the following formula:

\[
\text{Power of the front surface of the lens } = F_1 = \frac{n' - n}{r},
\]

where
\( n' \) = index of contact lens = approx. 1.49 for methylvethacrylate
\( n \) = index of cornea = approx 1.00 (water)
\( r \) = radius of the contact lens (varies)
\( F \) = optic power of the lens (diopters) (varies)
The power of the back surface of the lens \( F_2 \) would be calculated in a similar manner, using the correct radius for the back of the contact lens. This approximation will give an erroneous answer. The formula that needs to be used is:

\[
F = F_1 + F_2 - (t/n) \times F_1 F_2
\]

This formula will give the correct total power for a contact lens.

The tear film must also be taken into account when calculating the total dioptric power of certain types of contact lens. A flat fitting lens (i.e. a lens whose back radius is larger than the corneal radius) provides a tear film layer that is thickest at the edges of the lens and thinner in the middle. When the lens has a steep fit (i.e. its back radius is smaller than the corneal radius), the tear layer is thicker toward the center of the cornea and thinner on the edges. In the case of a neutrally fitted lens (i.e. the back lens radius is approximately the same as the corneal radius), the tear film has parallel front and back radii of curvature. The tear layer therefore adds focusing power to flat and steep fit lenses. It does not add any power to the lens when it is neutrally fit. This is true for rigid gas-permeable lenses; in the case of a flexible contact lens, the tear film is not likely to affect the optics of the lens-eye system due to the large flexibility of the lens compared to the flexibility of gas-permeable lenses.

### 1.3 Techniques for Measuring Tear Film Thickness

There are three major techniques that can be used to measure the tear film thickness under a contact lens: laser induced fluorescence (LIF), confocal microscopy, and interferometry. Laser induced fluorescence has been used to measure small parts in sensitive applications; it is a good method for measuring small and sensitive parts because it is both accurate and non-destructive. It can measure with accuracy up to a few microns, and it does not require physical contact with the part to be measured. Its disadvantage is that calibration of an LIF system is often tedious and complex. There are also problems with photobleaching and dye saturation, but these can be overcome
with care. Confocal microscopy is a variation of electron microscopy in which the excitation beam and the plane of view of the camera are focused on the same point simultaneously. Confocal microscopy is well suited for biological applications and can measure on the micron and sub-micron scale with great accuracy. Interferometric methods have provided values of the overall tear film thickness from 4 to 45 microns [30] [31]. It is unlikely that the tear film thickness has only one value; a method to measure tear film thickness distribution would provide more useful information. Laser induced fluorescence techniques may be able to provide this information.
Chapter 2

Background on Physical Modeling of an Eye/Contact Lens System

2.1 Introduction

Many parameters affect the fit of a contact lens on the eye. Among these are the post lens tear film thickness and surface tension, the pressure distribution under the contact lens, contact lens thickness, surface roughness of the eye, material properties such as elastic modulus, rigidity modulus and Poisson’s ratio, the geometry of the contact lens, and the water content of the contact lens. Variations among these parameters can lead to vast changes in how the contact lens feels on the eye, and how it is tolerated on the eye for long periods of time.

Physical modeling of an eye/contact lens system allows individual variation of the relevant parameters to determine their effect on the system and on each other. A physical model is important toward an understanding of the dynamics of the eye-contact lens system. In addition, a physical model allows theoretical and computer-simulated results to be checked against physical results. The following chapter presents previous research defining relevant parameters, and describes their importance to a physical model of an eye-contact lens system.
2.2 Pressure Distribution Under A Contact Lens

2.2.1 Theoretical Background

Pressure on the eye underneath a contact lens can affect user health and comfort. This was recognized as early as the 1930s, when an attempt was made to custom-fit contact lenses to eyes in an effort to relieve discomfort due to limbal pressure [36]. According to Martin in 1985, the fit of a contact lens to the eye can be predicted by the squeeze pressure in the post-lens tear film. Martin in 1989 stated that lens design parameters such as lens thickness and water content affect the eye primarily through changes in the squeeze pressure generated under the lens. In all likelihood these lens parameters act by changing the stress in the tear fluid due to lens deformation. In addition, fluid forces in the pre- and post-lens tear film act to change the post-lens tear film pressure. Excess pressure under the lens may lead to degradation of the corneal epithelium, although the exact mechanism through which the degradation occurs remains unknown [27]. Thus it is clear why lens geometry and the mechanical behavior of the lens and underlying tear film must be carefully studied to determine the optimum lens design for a given eye geometry.

The lens parameters that affect the post-lens tear film pressure include basecurve radius of the contact lens, lens thickness, bevel radius of the lens, sagittal height, and corneo-scleral junction radius of the eye. Figure 1-1 depicts the important parameters of the lens, figure 1-2 shows the anatomy of the eye.

It is important to know the thickness of the post-lens tear film layer because of its relationship to the post-lens pressure distribution. It has been postulated that the post-lens tear film layer is very small; it has been estimated to be on the order of 10 microns. In such a case, squeeze film lubrication would occur under the lens as it moved across the eye during blinking. The pressure distribution under the lens would persist even during lens movement if the tear film layer was small; however, several studies indicate that it may be thicker than previously believed [33] [30]; it may be up to 50 microns in depth. If so, the squeeze pressure distribution may be larger than expected for flexible hydrogel contact lenses [25], since a smaller tear layer
was found to mean a reduction in the squeeze pressure for hydrogel contact lenses. Finite-element studies of an eye/contact lens system found the opposite to be true - a reduction in tear film thickness under a contact lens increased contact pressures [7]. More studies are needed to accurately determine the pressure under the contact lens.

The pressure under a stationary contact lens can be measured using transducers placed in a model eye [11] [22]. It can also be found from a calculation of the capillary force under the lens, which is dependent on tear film height, lens radius, and surface tension. Surface tension is difficult to calculate because of the difficulty of measuring a wetting angle. If the contact lens is moving, viscous forces must be taken into consideration when calculating the pressure [40].

### 2.2.2 Previous Research

Several previous attempts have been made to examine the pressure in the fluid underneath a contact lens. Fatt and Chaston in 1976 used a spherical eye model with a spherical contact lens to measure pressure at the corneal apex. It was found that a negative pressure was induced on the eye at the center of the cornea. Fatt in 1979 measured the pressure under a silicone rubber contact lens at the corneal apex. Lenses with steeper bearing (i.e. more convex lenses) were found to induce a negative pressure at the center of the cornea.

Martin in 1985 [22] measured the pressure distribution across the eye underneath a moving contact lens after pressure was applied by a model eyelid. The Martin model eye was composed of PMMA with an aspheric cornea and spherical sclera. The pressure measurements were taken at four 0.75 mm holes drilled into the central, paracentral, limbal, and paralimbal portions of the model eye. Contact lenses of varying water content (38-71%), thickness, and bearing radius were examined. The Martin experiment found that the pressure at the cornea decreased as lens fitting became steeper. Negative pressure was least at the limbus and greatest at the corneal apex for the steepest lenses, which agreed with the results of Fatt and Chaston. However, the flat contact lenses gave a positive pressure at the corneal apex. The pressure was lower for thinner lenses, given constant water content and bearing relationship.
The pressure was also lower for less rigid (i.e. higher water content) lenses, given the same constant thickness and bearing relationship.

The model used in the Fatt and Chaston experiments was spherical, unlike a real human eye. The Martin experiment used a more realistic, non-spherical eye model. However, the holes drilled into the model were large relative to the total diameter of the model, which may have affected the pressure measurements. Each hole was 0.75 mm in diameter, compared to the total corneal diameter of 13 mm (measured from the limbus). In addition only four points were sampled, and the location of the points may have affected the calculated pressure distribution.

2.3 Post Lens Tear Film

The post lens tear film lubricates the eye and lids, allows better light refraction by creating a smooth corneal surface, allows for wound closure, and provides moisture [40]. The squeeze pressure induced in the post lens tear film is related to the fit of the contact lens [24]. Extremely thin contact lenses have been found to disrupt the corneal epithelium [27]. It has been suggested that they do so through a combination of evaporation and mechanical abrasion, which indicates that the post-lens tear film layer decreases during wear. The observed perturbation of the corneal epithelium after wear of thin high water contact lenses may therefore be due to increased pressure under the lens, caused by loss of the post lens tear film. Preliminary finite element studies [7] have demonstrated a possible link between negative pressure under a contact lens at the edge of the lens-eye interface and the tear film thickness at the interface.

Tear replenishment through the mechanism of fluid movement underneath the lens occurs at about 1% replenishment per blink [39] which is not sufficient for proper oxygenation of the cornea. This rate of replenishment does not seem to vary with changes in lens parameters, in particular the steepness or flatness of fit of the lens. However, the degree of lens movement, which does affect patient comfort, could be changed by changing the bearing relationship. It seems then that changing the bearing relationship of the lens will not increase the tear film thickness significantly once a
steady state on the eye has been reached, but other factors such as lens thickness and lens water content may affect the tear film depth.

It is difficult to model the tear film exactly due to its complex triple-layered structure. The natural tear film consists of mucus next to the cornea, topped by a layer of aqueous solution and an external lipid film. The lipid film is estimated to be less than 0.5 microns in thickness. The mucus layer has been measured to be approximately one micron in depth [31]. Estimates of the fluid film thickness vary widely, as will be discussed later. The total film has been estimated to be about 7 microns thick; however, the methods used to make these measurements have been questioned. An artificial tear solution will not be able to approximate the biological properties of the real tear film, due to a difference in its concentration of solutes, surface tension, and diffusion coefficients. Therefore previous efforts have been focused on measuring the tear film in vivo. This method has several disadvantages, the most important of which is that such a study requires living, or freshly killed subjects. In addition the measurements are sometimes affected by the invasive procedures that are required. However, new methods have been developed that can non-invasively measure the tear film on a living eye.

Tear film thickness has been measured through the use of several techniques. Fogt in 1996 determined the tear film thickness under a contact lens on human eyes by measuring the sinusoidal variations in reflectance off the center of the cornea as a function of wavelength. He obtained a measurement of 2.5 microns [12]. Prydal in 1990 measured coherent light reflected from human eyes and determined the tear film thickness from the separation of interference fringes [32]. A film thickness of 4 to 7 microns was measured using this technique. Prydal also used confocal microscopy to measure the tear film in the eyes of various animal species. A second study by Prydal using interferometry [30] found the tear film thickness in humans to be 35-45 microns, a much larger value than the previous result, in which the tear film thickness measured varied between 10.4 and 14.7 microns. Prydal and Dilly in 1995 [34] used in vivo confocal microscopy of the tear film to examine the cornea and tear film in animals. Close correlation with previous interferometric results was found.
Prydal and Dilly in 1994 measured the tear film under contact lenses on human eyes using interferometry. They found that the thickness of the tear fluid under the contact lens was between 8 and 40 microns [33]. All Prydal’s measurements were made in the center of the cornea. Fluorophotometry on live human eyes [41] has also been performed. Values for the tear film thickness obtained with this method varied between 3.69 and 2.82 microns. The previous results show that the average thickness of the tear film without a contact lens has been reported to lie in the 2-45 micron range. The tear film under a contact lens is generally thought to lie in the 10 micron range [24], however, several studies such as Prydal in 1994 indicate that it may be thicker on average than previously believed.

The variation in measurements may be due to inclusion or noninclusion of the mucus layer of the tear film. The mucus layer may compose most of the thickness of the tear film layer [30]. In some cases, the variation in the measurements of the tear film layer may be due to invasive techniques. Laser interferometry, fluorophotometry, and reflectance techniques do not share this disadvantage. In addition, these methods are able to measure the mucus layer of the tear film. Therefore, measurements made with those techniques may be more accurate than invasive procedures. Several of the techniques used fluorescein to stain the tear film so it would be visible to the measuring instruments. Use of fluorescein may change the perceived thickness of the tear film layer because of its inability to permeate the mucus layer. The lipid layer of the tear film is most likely not a significant source of error because it is less than 0.5 microns in depth [31].

2.4 Surface Tension

2.4.1 Previous Research

Surface tension forces, accompanied by viscous forces, partially determine the pressure distribution under the lens. Cerrano in 1910 [28] [6] found the surface tension of tear fluid to be 72.3 dynes/cm (0.723 N/m), by placing ground glass in calves eyes to make
them produce reflex tears. However, his experiment measured the surface tension of reflex tears only; the composition of reflex tears varies significantly from that of the tear layer normally present on the eye. Reflex tears contain very little lipid and mucus, which makes them more watery and are unlikely to have the same surface tension as the normally present tear film. The reflex tears will evaporate more quickly than normal tear film, and will not spread out on the eye in the same manner.

Surface tension measurements of the tear film layer while on the eye were conducted by Miller in 1969 [28]. A specially grooved scleral contact lens was used to pool the tear film for measurement. The surface tension was estimated to be 46.24 dynes/cm (0.4624 N/m). However, this was only an average value and no surface tension gradient across the eye was found. In addition, reflex tearing and disruption of the normal tear film layer due to the presence of the contact lens may have affected the results.

2.4.2 Pre-lens Tear Film

There is a tear film layer over the contact lens; this pre-lens layer, if it completely submerged the contact lens, would remove any surface tension forces that might otherwise appear. However most researchers agree that surface tension forces do play a role in holding the contact lens on the eye and therefore the pre-lens tear film layer does not submerge the lens. This layer is discounted in most studies of the forces holding a contact lens on the eye [17].

2.5 Surface Roughness

2.5.1 Theory

The cornea contains microvilli and other structures up to 0.75 microns in height [35]. This surface roughness may contribute to the pressure distribution between a contact lens and an eye through its contribution to the viscous forces on the moving lens. The rough surface of the lens provides more surface area over which the tear film can
adhere, possibly increasing its depth.

2.5.2 Previous research

It has been traditionally very difficult to obtain a value for the roughness of the cornea due to its inherent flexibility and ability to deform under even the slight pressure of a casting material. Fick began making casts of rabbit eyes in 1887, but did not focus on obtaining a surface impression of the eye. He was more interested in the eye’s general contours. By the 1930’s more accurate casts of the eye surface were being made, but still no surface roughness values were determined. Many casts of corneal contours have been made but little research has been done on the surface roughness of the cornea. [36]

There are several methods that could possibly be used to determine the surface roughness of the cornea. The surface roughness of contact lenses has been measured using atomic force microscopy [3]; the same might be done with excised corneas. Alternatively, microscopic measurements and fractal analysis might be used to obtain a surface roughness value for the eye. No average value for surface roughness of the cornea has been obtained as of yet.

2.6 The Model Eye

As mentioned previously in the section on the pressure underneath a contact lens, the choice of model eye is important to the results of the experiments. A spherical model eye will not simulate the fit of a contact lens on a real eye; the tear film thickness will be different and the motion of the lens on the model will not follow the pattern of the lens on a real eye. Therefore it is desirable to choose a geometry as close to a real human eye as possible. The contact lens fits over three main areas of the human eye: the cornea, the corneo-scleral sulcus (limbus), and a small portion of the sclera. The cornea has often been described as a perfect sphere but in reality this is not the case; it is more accurately described as having the radii of an ellipse of eccentricity 0.55 [21].
Figure 1-2 shows the anatomy of the eye important to contact lens fit \cite{21}. The semi-scleral contact lenses studied in this experiment rested mainly on the cornea, with only a small portion falling over the corneo-scleral junction and scleral zone. The corneal cap is the central portion of the cornea where the corneal radius varies the most. The peripheral zone surrounds the corneal cap and is flatter than the corneal cap; in addition its radius does not vary as dramatically as that of the corneal cap. The “corneal diameter” is defined as the diameter of the chord that spans the arc of the corneo-scleral junction. Human corneas vary tremendously in size, so it is important to perform any experiments on a variety of eye types. A typical corneal cap has an average radius of about 7.9 mm, ranging from 7.2 mm to 8.7 mm. It has been found that the corneo-scleral junction varies widely in diameter from person to person, so this variation must be taken into account as well.

The human cornea is flexible, but compared to the contact lens it can be considered a rigid structure. The modulus of elasticity of the human eye in tension has a value of 100 MPa \cite{4}. However, the cornea is pressurized by the intra-ocular fluid, which makes it essentially rigid compared to a contact lens. A typical contact lens modulus lies between 25 kPa \cite{25} and 1 MPa, depending on water content. So, any rigid material can be used to construct the model eye; it can be chosen for its easy machining qualities or other factors so long as it has an elastic modulus much greater than that of the contact lens to be studied. It should be roughened to approximate the surface of a true eye. This is difficult to achieve in practice because the roughness of the cornea is not fully known; a good guess at the roughness is one in which there are surface irregularities on the average of 0.75 microns in height, corresponding to the microvilli that naturally occur on the surface of the cornea.

\section{The Contact Lens}

The parameters that may affect lens fit are: lens thickness, water content, corneo-scleral junction radius, bevel radius, basecurve radius, and sagittal height. In addition, material properties such as elastic modulus, rigidity modulus, critical surface
tension, and Poisson’s ratio are important. Figure 1-1 depicts the geometric parameters of the lens.

### 2.7.1 Basecurve Radius

Basecurve radius is important to contact lens fit because it determines the “tightness” of fit over the cornea; i.e. a basecurve radius less than the corneal radius is a “tight” or “steep” fit.

### 2.7.2 Bevel radius

The bevel zone, when it is part of a properly fitted contact lens, “floats” on a layer of tear fluid. If the lens fit is too steep the bevel may penetrate the tear film and touch the surface of the eye.

### 2.7.3 Lens Thickness

A thin lens will allow more water to evaporate through it. A thicker lens will slow evaporation through the lens, thus providing a thicker tear film [18]. However, a thicker lens is not as compliant as a thinner one; hence the thicker lens will force more water out of the post-lens tear film than a thin lens. These competing factors both affect the final thickness of the tear film under the lens. Evaporative effects can be a problem with lenses for nearsighted patients, as the lens must be very thin in the center to allow for a thin enough lens edge [5]. These high-diopter negative lenses can then become uncomfortable due to a large loss of water.

### 2.7.4 Water Content

Contact lenses are made of a porous hydrogel material. Evaporation of water and diffusion of oxygen through the lens occur readily; lens oxygen permeability is on the order of 1 to $20 \times 10^{-9} \text{ (cm} \cdot \text{mlO}_{2})/(\text{s} \cdot \text{ml} \cdot \text{mmHg})$ [39]. These qualities are necessary to maintain user comfort; hypoxia is a cause of eye irritation and other problems.
Lack of water evaporation through the lens would signal that the lens was not porous enough to allow ready oxygen diffusion [39].

2.7.5 Sagittal Height

The sagittal height of a contact lens is the distance between the edge diameter of the lens and the apex of the lens (See figure 1-1). A smaller sagittal height means a flatter fitting lens [37]. Thus the sagittal height affects the tear film under the lens in that flatter or steeper fits will change the tear film thickness.

2.7.6 Material Properties

Introduction

Material properties such as tensile elastic modulus, compressive elastic modulus, critical surface tension, and Poisson’s ratio can all affect the performance of a contact lens. The tensile and compressive elastic moduli can differ due to the behavior of the water flow in the hydrogel material during deformation. Changes in the elastic modulus of a contact lens can greatly affect both user comfort and the optic power of the lens. Also, the critical surface tension, which is a property of the contact lens' behavior in tear fluid, will affect how the tear layer spreads on the lens. The Poisson’s ratio for a contact lens must be that of a nearly incompressible material. If it is not, the lens could not function properly.

Elastic Modulus

The tensile elastic modulus of a typical hydrogel contact lens varies between 25 kPa and 1 MPa, depending on the lens water content. The elastic modulus of a lens can vary over time as the lens loses and gains water through evaporation and tear pumping under the lens. It may be possible to model the lens as a bimetal where the top layer has a certain elastic modulus, and the bottom layer has a different modulus due to the water content gradient in the lens; here, the volume change in the lens and its gradient through the thickness has a large impact on the lens strain and stress...
distribution. This model may help to explain the changes in the tear film under the contact lens that occur over time.

**Critical Surface Tension**

The critical surface tension of hydrogels is about 50 dynes/cm (0.05 N/m). [38] This value is the same as that of a liquid able to wet the hydrogel material. Since tear fluid has a surface tension less than the critical surface tension of hydrogels, it is expected that the tear film will spread out over the surface of a contact lens made from hydrogel material, which helps to distribute the tear film layer evenly over the lens and the eye.

**Poisson’s Ratio**

The Poisson’s ratio of a contact lens must be close to the theoretical limit of 0.5. This is generally true for hydrogel contact lenses, because they contain mostly water, which is almost incompressible, and the remaining component is a rubberlike material that is also close to incompressible.
Chapter 3

Background on Techniques Used to Measure Liquid Film Thickness

3.1 Introduction

3.2 Laser Induced Fluorescence

3.2.1 Introduction

Laser-induced fluorescence (LIF) has been used extensively in film and part thickness measurements. It has been used to measure engine oil thickness with a high degree of accuracy [2] [19]. The method has been used most often in research applications such as the one described here. This is preferable when measuring small parts because it is non-destructive and accurate to a few microns thickness. Its non-destructive qualities and ease of use make it ideal for this experiment. The method does not require contact with the model eye, tear film, or contact lens. LIF is based on the absorption and subsequent re-release of light energy by certain molecules. Light of one wavelength is taken in by the molecule, then released at a lower energy (longer wavelength). The light released can be recorded and measurements calculated on the basis of the fluorescence intensity.
3.2.2 Theory

Laser induced fluorescence is based on the principle that photons can raise molecules to higher energy states. The molecules briefly gain energy due to absorption of the photon, then lose that energy, often in the form of visible light, as they collide with surrounding molecules. Figure 3-1 shows the S0, S1, and S2 vibrational states the molecules of dye can reach after it has been excited by incident light. In general, light is emitted from the dye molecule as it drops from the S1 to the S0 ground state. Molecules at higher energy states tend to undergo internal conversion to the S1 state, which does not cause light to be emitted. Therefore only light emission from the S1 state is important in studies that do not require a high degree of accuracy.

Beers' law describes the intensity of the light emitted from a fluorescent dye:

\[ F = \Phi I_o (1 - e^{-ebc}) = \Phi I_o ebc \]

where

- \( F \) = emitted light intensity
- \( \Phi \) = quantum efficiency
- \( I_o \) = intensity of the incident light
- \( \epsilon \) = molar absorptivity
- \( b \) = film thickness
- \( c \) = dye concentration

The quantity \( ebc \) is referred to as the optical density. When this parameter is small, the emitted light intensity, \( F \), can be interpreted as linear with respect to the film thickness.

3.2.3 LIF in Practice

The dye used to measure tear film thickness in the following experiment absorbs light at about 495 nm (blue range) and emits yellow-green light in the 520 nm range. This follows Stokes’ law, which states that the wavelength of fluorescence of a molecule is always longer than the wavelength of the exciting light. Both the absorption and emission wavelengths used are in the visible spectrum.
Figure 3-1: Excitation States of a Molecule of Fluorescent Dye (Parker) [29]
Figure 3-2: Absorption Spectrum of FITC-Dextran 150
Figure 3-2 on page 37 shows the absorption spectrum of the fluorescein used in the experiment. The emission spectrum is offset about 10 nanometers from the emission spectrum.

Disadvantages

One problem that must be overcome in such a system is the phenomenon of photobleaching. In the case of the fluorescein used in this experiment, the output light intensity of the dye will begin to decay after only a few seconds of laser beam exposure, due to heating of the dye solution by the light source. This problem is solved by allowing the solution to cool between measurements of the tear film thickness. Other methods used to prevent photobleaching include breaking up the incident light source with a chopper wheel, artificially cooling the solution, or using a shutter to prevent exposure to the incident light source. [2]

Inner filter effects may affect the results of an LIF experiment. When the optical density of a solution is small, the fluorescence emitted by the dye is equal to the intensity of the incident light times 2.3ebc.[20] The fluorescence observed depends on the geometry of the specimen with respect to the beam of exciting light, and the direction from which one views the specimen. In addition, at high enough dye concentrations, self-absorption becomes a problem - the fluorescent solute absorbs its own fluorescence. However, fluorescein in the concentration used in this study, when illuminated by light in the range of 490 nm, does not show much self-absorption.

Advantages

LIF requires less specialized equipment than the other two methods described. In addition it is fairly simple to calibrate. This method can work on a macroscopic scale, which confocal microscopy cannot do, so its range of applications is not so limited. Results are easier to obtain than with interferometry.
3.3 Confocal Microscopy

3.3.1 Introduction

There is a great deal of literature on confocal microscopy for biological applications. It is well suited for biological applications because it is sensitive to low light levels, therefore small amounts of fluorescing dye which are non-toxic to living systems can be used. Confocal microscopy is very accurate on a micron scale, and can be used to measure three-dimensional objects. In addition it removes background fluorescence from the field of view of the object to be studied, providing a clearer image than might otherwise be obtained.

3.3.2 Theory

Confocal microscopy (CFM) is a variation of scanning electron microscopy in which points on an image are illuminated sequentially as light passes over the sample. An image is built sequentially from the individual scanned images of the volume elements. The light sources most commonly used in confocal microscopes are lasers and white light passed through an aperture. White light has the advantage over laser light in that it can excite a higher range of fluorophores, but argon-ion laser light is also suitable. A diagram of the system is presented in Figure 3-3.

Light passes through a pinhole, then through a filter to block out all wavelengths except for the appropriate excitation wavelength for the dye used. The beam then is reflected onto the sample by a dichroic beam splitter, which reflects all wavelengths except for the emission wavelength of the fluorescein dye, which it transmits. The fluorescence light passes through another pinhole then enters a camera. The excitation light and the camera scan across the sample to provide a full image. There are three main types of scanning systems used with confocal microscopes:

1. The sample moves under a stationary beam

2. The apertures in front of the light source and camera move together
3. The illumination and detection beam paths are scanned.

Confocal images are often superior to conventional microscope images because the confocal microscopes remove background fluorescence from the image and provide a clear image in a narrow focal plane. Many of these narrow images can then be joined to create two- or three-dimensional pictures. The depth of field of the CFM is usually about 0.5 to 1.5 microns.

3.3.3 In practice

Advantages

Confocal imaging gets rid of background fluorescence, providing very clear pictures in a narrow focal range. It allows clearer pictures of small objects than conventional microscopy. Prydal et. al. used confocal microscopy to measure the tear film thickness on a human eye. It is suitable for this application because confocal microscopy works
well with fluorescent dyes such as fluorescein, which is commonly used in biological applications.

**Disadvantages**

Confocal microscopes tend to misalign easily; this is due to the small pinhole size required combined with the need for great accuracy in aligning the illuminating and detection beams. The detected signal is very susceptible to alignment; a misalignment of 0.1 mm can result in a signal reduction of up to 20 percent. In addition, photobleaching can be a severe problem depending on the intensity of the exciting light. Scanning confocal microscopes (SCFM) often have less than 5% efficiency; those that use lasers as their light source often have less than 0.1% efficiency in terms of the amount of emitted fluorescent light that is detected by the system. Therefore SCFM works best at low light levels using multiple scans to mitigate the photobleaching effect.

### 3.4 Interferometry

#### 3.4.1 Introduction

#### 3.4.2 Theory

The measurement of tear film thickness through interferometry can be easily described using basic principles of optics. If the tear film is modeled as a plate of varying thickness, the depth can be calculated as follows:

Figure 3-4 shows a plane-parallel plate. Interference fringes form as light from the point source, S, passes through the plate and reflects off the upper and lower film surfaces. The reflected rays then intersect at point P. The 2 rays follow slightly different paths to reach P; this path difference is given by:

\[
\Delta p = n_2(AB + BC) - n_1 AD \pm \lambda/2 = 2n_2 dc\cos \theta
\]

where:
Figure 3-4: Interference Fringe Formation in a Plane-parallel Plate

\[ \Delta p = \text{the path difference between the rays} \]
\[ n_2 = \text{The refractive index of the first medium} \]
\[ n_2 = \text{The refractive index of the second medium} \]
\[ \lambda = \text{The wavelength of the incident light} \]
\[ \theta = \text{the angle between the reflected ray and the second medium} \]
\[ d = \text{the distance between the 2 plates} \]

[16]

3.4.3 In Practice

Interferometric methods have been used to gain a rough estimate of the tear film thickness [31] [30] [33]. Prydal found an average thickness varying between 4 and 45 microns using this technique. A problem with interferometric method is that it is extremely difficult to locate and count interference fringes in an accurate manner. The fringes need to be carefully counted to give an accurate estimate of the tear film.
Chapter 4

Experimental Device and Procedure

4.1 Introduction

An experimental device to measure tear film thickness was constructed. The device used principles of laser-induced fluorescence to measure the thickness of the film under the contact lens. It was based on similar devices used to measure oil film thickness and small part thickness[2] [19].

The following section explains the design constraints and necessary properties of the tear-film thickness measuring apparatus. The major constraints were the model eye and fluorescein dye, and the laser and optical devices. The model eye had to be chosen for its similarity to a real human eye, the dye and the laser needed to match in wavelengths for excitation, and the optical devices had to provide filtering of the emitted light from the sample while allowing sufficient light to enter the camera to provide reasonable detail. The design constraints will be discussed in more detail below. The experimental procedure is also discussed.
4.2 Experimental Device

4.2.1 Design Constraints

Model eye and fluorescein

The Model Eye  The model eye used in the experiment has no eyelids, so it cannot simulate the effects of the eyelids on surface tension, tear film thickness, and squeeze pressure. These are important effects, [40] due to the no-slip condition on the eyelids, which means the eyelids help to distribute the film across the eye as they move. Martin's studies in 1985, 1986, 1987, and 1989 forward all used a model eyelid to press the lens onto the model eye when he studied the squeeze pressure distribution under a contact lens. This eyelid effect is neglected in the following experiments. In addition, gravitational and evaporative effects are neglected in the current study. The pre-lens tear film was not simulated. The surface roughness of the model eyes is not that of a real cornea; although roughened eye models were tested they do not fully simulate the surface of the cornea. Surface tension effects should not be neglected; the surface tension of tears on a true eye is estimated to be 72.3 dynes/cm (0.732 N/m). Natural variations are found in the corneo-scleral radius of real human eyes. To take these natural differences into account, model eyes of varying corneo-scleral radius should be studied. In this experiment, only one representative corneo-scleral radius was used for simplicity. Photobleaching of the dye under the lens must be considered if the dye is irradiated for more than a few seconds [2]. In this experiment the dye was allowed to cool between fluorescence measurements.

Fluorescein  The fluorescein dye was selected because it fell in the laser's emission range. In addition the dye was chosen to have a high molecular weight to prevent it from diffusing into the lens material during testing. Fluorescein dye has been used since the early days of modern optometry to examine the cornea; in more recent times it has been used to determine the fit of contact lenses. It is quite effective in showing any gaps under the lens, and so is a good choice for work with lenses and models as well as for clinical research.
Laser and Optical Setup

The following requirements had to be met by the laser and optical setup:

1. The laser had to emit light in the 495 nm range. An argon ion laser was used for this purpose. Its highest intensity lines fell in the 488 nm range, which was sufficiently close to the absorption range of the dye to be admissible.

2. The beam had to be coherent but large enough to cover the sample. This was done by placing a 10X microscope objective in the laser beam path. A beam diffuser was placed over the far end of the objective to provide an even distribution of light, about 2 cm by 2 cm in size.

3. The beam needed to reflect onto the sample. This was achieved through the use of a beam splitter, which reflected the beam onto the sample then allowed the light emitted by the sample to pass through it and into the camera.

4. Extraneous light needed to be kept from contaminating the results by increasing the perceived fluorescence. An emission filter was placed between the sample and the CCD camera to ensure that only fluorescence light was recorded. In addition, the experiments were performed in the dark to minimize the possibility of the entrance of extraneous light.

5. A CCD camera was used - its range of sensitivity made it necessary to use a high concentration of FITC - 5 mg/ml. This cause saturation of the dye to become a problem; this was overcome by the use of just enough laser intensity to fluoresce the dye to the maximum sensitivity range of the camera.
4.2.2 Physical Description of Device

Figure 4-1 on page 46 shows the configuration of the measurement device. An argon ion laser beam (a, figure 4-1) passed through a 10X microscope objective (b, figure 4-1) (Capra optical) that acted as a beam spreader. A dichroic beam splitter (f, figure 4-1) reflected the laser light onto the sample. The fluorescence light from the sample then passed through an emission filter (520 nm) (e, figure 4-1) and was recorded by a CCD camera (c, figure 4-1) (Pulnix). A TV camera lens and 5mm extension ring were used with the camera. A Mac 8600 computer was used to receive the data from the CCD camera (d, figure 4-1).

4.2.3 Operation of Device

The device was set to the parameters given in table 4.1 during the experiments. The 0.15 W laser power provided sufficient light to view the sample on the com-
Table 4.1: Device Operating Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser current</td>
<td>13 Amps</td>
</tr>
<tr>
<td>Laser power</td>
<td>0.15 Watts</td>
</tr>
<tr>
<td>TV lens f-stop</td>
<td>infinity</td>
</tr>
<tr>
<td>TV lens focal distance</td>
<td>4cm</td>
</tr>
</tbody>
</table>

puter screen while utilizing the full range of the CCD camera, and to see some intensity variations across the sample with the unaided eye. The TV lens f-stop and focal distance were chosen to focus on a horizontal section of the sample that included both the lens and the outer edge of the model eye.

Figure 4-2 shows a photograph of the experimental setup, while figure 4-3 shows a close-up of the sample stage.

4.3 Experimental Procedure

4.3.1 Calibration

A calibration sample was produced by placing 5 mg/ml FITC-Dextran 150 solution between two glass slides. One end of the slide was clamped to produce a 0 micron thickness end; the other side was clamped over a 101.6 micron shim. Although a cylindrical calibration would typically be used in measurement of a three-dimensional spherical image, in this case the lens was so closely matched to the model eye that the edge of the lens and the edge of the model were nearly parallel, making a linear calibration appropriate. A spherical or cylindrical calibration would have to be used if the edges of the contact lens were not parallel to the model eye, to take the effects of sample curvature into account. The calibration sample was fluoresced with an argon-ion laser (488nm). An image of the calibration sample was made using a Pulnix CCD camera. The image was stored in a Macintosh 3600 computer for further processing. Next, a contact lens was placed on a 4 mm corneo-scleral radius, 7.8 mm total radius model eye with 10 microliters of FITC dye solution in the film between the lens and the model. Figure 4-4 shows a diagram of the model eye/tear film/contact lens
Figure 4-2: Experimental Device
Figure 4-3: Experimental Device: Closeup of Sample Stage
system. Next the sample was fluoresced with the laser. The calibration step was repeated several times during sample acquisition.

The calibration image was processed using MatLab (See Appendix B). 20 horizontal lines of pixels taken from the center of the image were used to create a correlation between average depth and light intensity. Figure 4-5 on page 51 displays a typical calibration image used. The left hand side of the image is the 0 micron depth side, while the right hand side of the image is the 101.6 micron side. The 101.6 micron depth occurs to the left of the dark shim present on the right side of the image. A linear curve fit was calculated and the slope and intercept of the line recorded to be used when calculating depths on the corresponding image of the model eye and contact lens. Figure 4-6 on page 52 shows a typical graph of light intensity versus pixel number across the image. Figure 4-7 below shows the thickness of the tear film between the slides vs. the measured fluorescence intensity for a typical calibration image.

Figure 4-2 shows the experimental setup.
Figure 4-5: A Typical Calibration Image for LIF Measurement of Tear Film Thickness
Figure 4-6: Intensity vs. Pixel Number for A Typical Calibration Image: LIF Measurement of Tear Film Thickness
Figure 4-7: Light Intensity vs. Tear Film Depth for A Typical Calibration Image
4.3.2 Rough vs. Smooth Eye Models

10 microliters of 5 mg/ml fluorescein dye were placed on the posterior surface of a contact lens; the lens was then placed on either a factory smooth or steel wool-roughened model eye. The rough and smooth model eyes were otherwise identical. The lens was carefully placed so that no air bubbles were left between the model eye and the lens. The lens was twisted onto the eye in an attempt to spread the tear fluid evenly between the lens and model surfaces.
Chapter 5

Experimental Results for Depth of the Tear Film Thickness

5.1 Tear Film Thickness Measurements

Images were taken of smooth and rough model eyes with 4 mm corneo-scleral radius. The model eyes were imaged using the following contact lens designs:

The -1.25 diopter lens was placed on both the smooth and rough model eyes, while the -3.25 diopter lens was only placed on the smooth model eye. The -3.25 diopter lens had a higher center thickness than the -1.25 diopter lens.

Figure 5-1 shows an example of an image taken using the experimental device.

Each image was processed by taking a 45 degree wedge from the image, starting at the center of the contact lens and radiating outward to its edge. Rays were sampled from the wedge at 1 degree intervals. The intensity plots of the rays were averaged to produce an overall plot of intensity versus distance from the center of the lens.

<table>
<thead>
<tr>
<th>Diopter</th>
<th>Basecurve Radius (mm)</th>
<th>Lens Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3.25</td>
<td>8.6</td>
<td>13.8</td>
</tr>
<tr>
<td>-1.25</td>
<td>8.6</td>
<td>13.8</td>
</tr>
</tbody>
</table>

Table 5.1: Contact Lens Designs Used to Measure Tear Film Thickness

55
Figure 5-1: Image taken of -3.25 Dpt 8.6 BC 13.8 Dia Lens Using LIF Experimental Design
Figure 5-2: Relative Intensity of Emitted Light vs. Fluid Film Depth for a -3.25 Diopter Lens
Figure 5-3: Tear Film Depth vs. Position for a -3.25 Dpt Lens on a 4mm Corneoscleral Radius Model Eye
for the entire wedge. Figure 5-2 displays a typical plot for a -3.25 Dpt lens. After intensity plots were taken, the plots were calibrated using the previously calculated linear curve fits from the calibration slides. Figure 5-3 shows the depth vs. pixel number plots for a typical model eye and contact lens. The contact lens was -3.25 diopters in optical power, 8.6 mm basecurve radius, and 13.8 mm in diameter. The model eye had a 4mm corneo-scleral radius and a 7.8 mm total radius.

Images of all the lenses and eyes tested are given in appendix A.

5.2 Sources of Experimental Error

Possible sources of experimental error included:

1. Fluctuations in the power output of the laser
2. Loss of image resolution due to optical losses

The power output of the argon-ion laser varied somewhat over time, especially during the first few hours after it was turned on. The laser was equipped with a device that automatically maintained the laser at the correct power output, so this source of error should be small.

The optics used in the experiment cut down on the amount of available light to go to the camera. This problem was resolved by increasing the light intensity of the laser until the maximum resolution of the CCD camera had been reached. Therefore loss of image resolution due to optics was kept to a minimum.

5.3 Description of Results of Tear Film Thickness Measurements

A distinctive ring could be seen about the outer edge of the contact lens in the unprocessed images of the model eye/contact lens system. This ring appeared to be located over the corneo-scleral zone of the model eye. In all the samples studied,
the main ring in the corneo-scleral zone displayed a tendency to be much thicker on one side of the sample than on the other (see figure 5-1 on page 56 for an example). The area on the bottom of the figure is much brighter and therefore contains more tear fluid than the area at the top of the figure, where the fluid is more evenly distributed under the lens. Areas of brightness corresponding to higher tear film depth also appeared in irregular patches toward the center of the model eye/contact lens samples. A more uniform tear film thickness was observed under the contact lenses on the roughened model eyes than on the smooth model eyes. The tear fluid was more evenly distributed toward the center of the contact lens on the rough model eyes than it was on the smooth model eyes. Figure 5-4 shows a rough model eye image, which can be compared to figure 5-1 above. The lower tear film thickness under the smooth model eye can be attributed to the greater effect that gravity had in causing the tear fluid to flow out from under the lens. The roughened eye's greater surface area helped the tear fluid to remain under the lens.

The following graphs display the results of the previously described calculation of tear film thickness versus position. Figure 5-5 shows the tear film depth on a 4 mm corneo-scleral radius, smooth model eye. The zero point of the x-axis corresponds to the center of the contact lens, while the right side of the x-axis shows the tear fluid depth at the edge of the lens. The contact lens used was -3.25 diopter, 8.6 mm base-curve, and 13.8 outside diameter. The tear film depth ranged from 13 microns at the edge of the lens (past the corneo-scleral junction) to 44 microns at the corneo-scleral junction of the model eye. The results for the tear film thickness were repeatable, as shown in figure 5-6. The second run of the same lens-model eye system provided a range of 15 to 55 microns, about 10 microns higher at the deepest point. The profiles of both runs were similar, with only minor differences that may have been due to experimental error. Figure 5-7 shows a superposition of the two experimental runs of a -3.25 diopter contact lens on a smooth model eye. The two profiles look similar, but more experiments are necessary to determine the factors involved in making the two experimental runs different from one another.

Figure 5-8 is a depth versus position graph of a -1.25 diopter, 8.6 mm basecurve
Figure 5-4: Image of a Roughened Model Eye With A -1.25 Diopter, 8.5 Basecurve Radius, 13.8 mm Diameter Contact Lens
Figure 5-5: Tear Film Depth Under a -3.25 Diopter, 8.6 mm Basecurve, 13.8 Diameter Contact Lens on a Smooth, 4 mm Corneo-scleral Radius Model Eye
Figure 5-6: Tear Film Depth Under a -3.25 Diopter, 8.6 mm Basecurve, 13.8 Diameter Contact Lens on a Smooth, 4 mm Corneo-scleral Radius Model Eye
Figure 5-7: Tear Film Depth Under a -3.25 Diopter, 8.6 mm Basecurve, 13.8 Diameter Contact Lens on a Smooth, 4 mm Corneo-scleral Radius Model Eye: Two Sets of Experimental Results
radius, 13.8 mm diameter contact lens. The depth of the tear fluid was again highest at the corneo-scleral sulcus of the model eye, and was about 65 microns in depth at its greatest value. The profile looked the same as for the -3.25 diopter lens. A repetition of the experiment provided similar results, shown in figure 5-9. The second run contained an extra peak before the corneo-scleral depth peak; this was due to the presence of an irregular spot of dye under the lens at the point where the depth was calculated in this sample. Several spots like this one could be seen in all the samples taken; they were purposely avoided during processing to give more uniform depth profiles.

Figure 5-10 shows a -1.25 diopter, 8.6 mm basecurve, 13.8 mm diameter contact lens on a roughened model eye. The depth toward the center of the lens was more uniform than the depth in the same region of the smooth model eyes. The depth ranged from 18 to 53 microns. The corneo-scleral region still contained the highest depth of tear film, however. A second sample using the same model eye and contact lens provided lower tear film values in the range of 13 to 29 microns. The tear film in general looked slightly more uniform on the roughened eyes than on the smooth model eyes.

All the graphs showed the same general trend of a more uniform depth toward the center of the lens, with one large peak in depth in the corneo-scleral region. All data was taken in areas of the image where the corneo-scleral film thickness peak was well defined, as in the top of figure 5-1. The corneo-scleral junction peak was not so well-defined throughout the entire image, however. As stated before, the fluid under the lens tended to pool to one side or another.
Figure 5-8: Tear Film Depth Under a -1.25 Diopter, 8.6 mm Basecurve, 13.8 Diameter Contact Lens on a Smooth, 4 mm Corneo-scleral Radius Model Eye
Figure 5-9: Tear Film Depth Under a -1.25 Diopter, 8.6 mm Basecurve, 13.8 Diameter Contact Lens on a Smooth, 4 mm Corneo-scleral Radius Model Eye
Figure 5-10: Tear Film Depth Under a -1.25 Diopter, 8.6 mm Basecurve, 13.8 Diameter Contact Lens on a Roughened, 4 mm Corneo-scleral Radius Model Eye
Figure 5-11: Tear Film Depth Under a -1.25 Diopter, 8.6 mm Basecurve, 13.8 Diameter Contact Lens on a Roughened, 4mm Corneo-scleral Radius Model Eye
Chapter 6

Analysis of Results

Tear fluid viscosity, model eye roughness, lens geometry, material properties, and surface tension all affected the tear film thickness under the contact lens to some degree. The following analysis will point out which factors were more important in determining the fluid depth on the eye model.

6.1 Tear Fluid Viscosity Effects

In a real human eye, the tear fluid is spread over the cornea through the motions of blinking and through surface tension effects. Evaporation removes some water from the eye surface while the tear fluid is replenished by the tear ducts. When a contact lens is placed on the eye, the tear film under the lens is affected by these factors as well as by surface tension effects due to placement of the lens on the eye, and the geometry of the lens itself. The thickness of the tear film under the lens is therefore highly dependent on its fluid properties and on lens design. The artificial tear fluid used in this experiment is not a perfect replica of human tears. The fluid has a similar viscosity to tear fluid, but it cannot simulate the true tear film's triple-layered structure. A real tear film acts as a non-Newtonian fluid, due to its layered structure, but this cannot be easily simulated in the laboratory. The artificial tear fluid used most likely has a different effective viscosity than a real tear film. This fact may have contributed to the low tear film thickness calculated except at the corneo-scleral
junction of the model eye, where the liquid would have a chance to pool.

6.2 Model Eye Roughness Effects

The roughened model eyes showed several trends not present in the smooth eyes. The depth throughout the sample was more uniform than in the smooth eyes, which was expected since the surface of the roughened model eye would prevent the tear fluid from flowing out from underneath the eye as quickly as on a smooth model. The roughened eye shows the importance of surface roughness on maintaining a uniform tear layer. The cornea contains many microvilli which may serve the purpose of increasing the area that the tear fluid can attach itself to, which may act to increase the “roughness” of the cornea and assist adherence of tear fluid. The tear film was better distributed over the center of the model on the roughened eyes, and did not show as many irregular patches in the center of the eye, although the tear fluid still showed an irregular pooling on one side of the model near the corneo-scleral sulcus.

6.3 Lens Geometry Effects

The irregular pooling seen near the corneo-scleral sulcus on all the model eye samples showed a three-dimensional effect; that is, the lens/model eye/tear film system is not axisymmetric due to the action of the contact lens on the curved surface of the model eye. Two types of contact lens were studied which varied in diopter only. The -1.25 diopter lens results showed more variation in film thickness toward the center of the lens than the -3.25 diopter lenses, which may or may not have been due to their varying geometries. Different diopter lenses have different thicknesses, which should affect the tear film layer under the lens to some degree. However, the two lenses examined here do not vary substantially, so it is difficult to see if the differences seen are due to lens variation or to some other factors such as experimental error. It is possible that the differences in overall lens thickness had some effects on the results of the tear film thickness measurement.
6.4 Effects of Lens Material Properties

The elastic modulus of the contact lens certainly affected the tear film thickness by affecting how much the lens could deform with respect to the model eye. In this experiment both lenses had similar moduli, so differences in the tear film layer could not be due to the that material property of the lens. The effect of the elastic modulus on the tear layer should be studied in future, however, because it has an important effect on the tear layer and therefore on user comfort.

6.5 Surface Tension Effects

It could be argued that the bright ring observed near the edge of the contact lenses in the samples is due to surface tension of the tear fluid causing liquid to pool around the lens edge. In this case, the tear fluid depth peaks given in figures 5-5 through 5-11 would not be accurate representations of the tear fluid depth under the lens, but only an indication of fluid pooling at the lens edge. Figure 6-1 show a close-up image of a section at the edge of a -3.25 diopter, 8.6 mm basecurve, 13.8 mm diameter contact lens on a smooth model eye. The edge of the contact lens is faint, and the bright ring of tear fluid is within the edge of the lens. The fluid film with the highest depth occurs inside the edge of the contact lens, at the corneo-scleral zone, which could be determined from observation of the sample while it was being fluoresced with laser light. Therefore the bright ring seen in the figures is not due to surface tension effects but to pooling in the corneo-scleral zone. This is expected from previous theoretical simulations [7].

The fluid most likely pools in the corneo-scleral zone of the model eye due to its low viscosity and the curvature of the corneal surface, which would tend to let fluid flow down toward the edge of the lens under the force of gravity. This phenomenon is seen in real eyes wearing contact lenses; there is generally a region of greater fluid depth in the corneo-scleral zone.
Figure 6-1: Enlarged View of a Section of a -3.25 Diopter 8.6 mm Basecurve 13.8 mm Diameter Contact Lens on a Model Eye
Chapter 7

Conclusions and Recommendations

7.1 Conclusions

One of the goals of this experiment was to determine the feasibility of using a laser induced fluorescence system to measure the tear film thickness under a contact lens. The following attributes were examined to determine if the goal had been met:

1. Repeatability of results

2. Correspondence to theoretical predictions

3. Agreement with previously published values for the tear film thickness

The experiment was repeatable in that the same shape depth profile was obtained for different experimental runs of similar samples. The profiles obtained matched, in part, the results predicted by Day and Boyce [7]. In addition, the range of values obtained for the tear film thickness were around 10 to 50 microns, which agrees with previous experimental data. Therefore, the system did meet the goal of providing a plausible method of tear film measurement.

The following conclusions can be made about the experimental system studied and the resulting values for the tear film thickness under a contact lens:
Theoretical studies [7] have shown that important depth variations that affect the comfort of a contact lens on the eye may occur on a micron scale. The measurement system described in this paper should, with suitable modifications, be able to detect trends in the tear film on this scale. The system can already measure the tear film thickness on the order of 10 to 50 microns; with a more sensitive camera it could easily be able to work on the 1 micron scale. Sub-micron scale resolution with this method will become difficult due to limitations on light photography at a scale below the wavelength of visible light, which ranges from 0.4 to 0.7 microns.

The roughened eye model does not affect the tear film profile shape; all it does is distribute the film more evenly over the entire lens. The model eye roughness is an important factor in determining the thickness of the tear film; if a model could be made with surface roughness on the order of that of a human cornea, its effects on the tear film could be measured.

The tear film does not appear to be axisymmetric with respect to the model eye and contact lens, from the images obtained. This means that it cannot be accurately measured using an axisymmetric model. However, an axisymmetric model may be used to determine an average tear film thickness over the model eye, as long as it is noted that this average will not be correct over most of the lens.

Surface tension effects at the edge of the lens do not seem to affect the tear film layer under the model eye insofar as there is no pooling of liquid at the edge of the lens. The tear film pools a little ways inside the edge of the lens, at the corneo-scleral sulcus. Therefore the physical model of the eye and contact lens used should be a fairly accurate representation of the way the lens would behave on a real eye if the lens did not move on the eye. Moving the lens on the model eye should then provide an approximation of the tear film thickness and pressure distribution under the contact lens. This agrees with previous experimental results [23], in which it was decided that the surface tension developed around the edge of the lens was of smaller magnitude than the squeeze pressure under the lens.

The two different lenses examined in this study had nearly identically shaped depth versus position profiles. More repetitions of the experiment would be necessary
to determine whether or not the minor variations seen between the lens profiles were significantly different.

It would be wise to attempt measurements with model eyes of varying size, as well as varying basecurve radius and total diameter, to see if the non-axisymmetric behavior of the contact lenses on a model eye are functions of steepness of fit between the lens and the eye. In this case the theoretical simulations made previously might be valid for appropriate choices of the model eye and contact lens.

The contact lenses tested here were of low diopter; higher diopter lenses would have thinner centers, which should lead to a lower tear film thickness than was measured in this study.

7.2 Recommendations for Future Analysis

A series of controlled experiments in which sagittal height, diopter, basecurve radius, lens diameter, and bevel radius are varied in a controlled manner would begin to pick out which parameters are more important to the tear film thickness. In addition, all experiments should be repeated on model eyes of varying roughness and corneo-scleral radius, as well as total radius. These experiments would allow tear film thickness and distribution to be linked to changes in specific lens parameters. Next the lens could be examined as it was moving across the model eye; tear film thickness and more importantly the pressure distribution under the lens as it moved could be calculated. Computer simulations in which the eye was modeled as non-axisymmetric might also prove useful. In addition, parametric studies of changing lens and eye geometry and correlation with the tear film thickness could determine which geometric parameters are most important in controlling the tear fluid depth.

Measurements of the tear film thickness on a model eye without the contact lens would be useful to validate previously collected data.
Appendix A

Images of Model Eye/Contact Lens Systems Examined Using Laser Induced Fluorescence
Figure A-1: Image taken of -3.25 Dpt 8.6 mm BC 13.8 mm Dia Lens On Smooth Model Eye Using LIF Experimental Design
Figure A-2: Image taken of -3.25 Dpt 8.6 mm BC 13.8 mm Dia Lens On Smooth Model Eye Using LIF Experimental Design
Figure A-3: Image taken of -1.25 Dpt 8.6 mm BC 13.8 mm Dia Lens On Smooth Model Eye Using LIF Experimental Design
Figure A-4: Image taken of -1.25 Dpt 8.6 mm BC 13.8 mm Dia Lens On Smooth Model Eye Using LIF Experimental Design
Figure A-5: Image taken of -1.25 Dpt 8.6 mm BC 13.8 mm Dia Lens On Roughened Model Eye Using LIF Experimental Design
Figure A-6: Image taken of -3.25 Dpt 8.6 mm BC 13.8 mm Dia Lens On Roughened Model Eye Using LIF Experimental Design
Appendix B

Computer Programs Used to Calculate Calibration Slopes and Tear Film Thickness

B.1 Program to Calculate Calibration Slopes
clear;
filename=input('Enter calibration file name: ','s');
[a,amap]=feval('tiffread',filename);
I1=ind2gray(a,amap);
I1=imrotate(I1,90,'crop');
[row,col]=size(I1);
halfrows=row/2;
i=1:col;
j=(halfrows-9):(halfrows+10);
I5=I1(j,i);
I6=I5(1:i);
figure;
plot(i,I6);
zoom on;
pause;
near=input('Enter the near edge: ');
far=input('Enter the far edge: ');
close;
for count=2:20
    I6=I5(count,i);
toe=far-near;
    int=101.6/toe;
    k=near: far;
    I7=I6(1,k);
    x=0:int:101.6;
    [p,S]=polyfit(x,I7,1);
    r=1:2;
    P(count,r)=p(r);
end
save 'slopes' P
B.2 Program to Calculate Tear Film Thickness

clear;
filenamel=input('Enter file name: ','s');
[A, amap]=feval('tiffread', filenamel);
[rows, cols]=size(A);
colormap(amap);
image(A);
title('Image of 4s lens: April 11 1997: -3.25 Dpt 8.6 BC');
xlabel('X Pixel Number');
ylabel('Y Pixel Number');
Il=ind2gray(A, amap);
axis('image');
[x,y]=ginput(3);

%Here I enter the maple environment to calculate the circle constants

mpa('x1', x(1));
mpa x1 = evalf(x1);
mpa('x2', x(2));
mpa x2 = evalf(x2);
mpa('x3', x(3));
mpa x3 = evalf(x3);
mpa('y1', y(1));
mpa y1 = evalf(y1);
mpa('y2', y(2));
mpa y2 = evalf(y2);
mpa('y3', y(3));
mpa y3 = evalf(y3);
mpa ('eqns', '((x1-co)^2+(y1-c2)^2=c3^2, (x2-co)^2+(y2-c2)^2=c3^2, (x3-co)^2+(y3-c2)^2=c3^2));
mpa C = fsolve(eqns);
C=maple('C');
mpa('co', 'subs(C,co)');
mpa('c2', 'subs(C,c2)');
mpa('c3', 'subs(C,c3)');
C=zeros(1,3);
co=maple('co');
c2=maple('c2');
c3=maple('c3');

%Leaving Maple environment
C=[str2num(co) str2num(c2) str2num(c3)];
C=C'; %I now have a matrix of circle constants.

%Next I have to draw a 1/4 circle on the figure window, then take a line from
%the circle center to the circle edge.

k=1;
for i=rows/2:rows
  for j=cols/2:cols
    if abs(sqrt((i-C(1)).^2+(j-C(2)).^2)-C(3))<0.5
      plotx(k)=i;
      ploty(k)=j;
      k=k+1;
    end
  end
end
end
sy=size(ploty,2);  %This gets rid of duplicate numbers in my plotx and ploty
sx=size(plotx,2);  %matrix
lowx=plotx(1);
highx=plotx(sx);
sy=size(ploty,2);
yvar=ploty(sy);  %Saves the last y integer position for use in plot
plotx=lowx:1:highx;
ploty=C(2)+sqrt(C(3)^2-(plotx-C(1)).^2);  %Calc y=f(x)

%plot(plotx,ploty,'r.');

%Next I have to chose a line going from the center of the circle to the edge of
%the circle, and plot that line's pixel intensity versus pixel position.

ang=46;  %number of degrees-i the circle turns through before taking an average
sx=size(plotx,2);
p=1:sx;
I4=zeros(sx,ang);
for t=1:ang
    for q=1:sx
        I2(q,1)=I1(plotx(q),yvar);  %Places that line in a matrix.
    end
    I1=imrotate(I1,1,'crop');
    I4(:,t)=I2;  %Stores individual lines for later averaging.
end
for s=1:sx
    I5(s)=I4(s,1);  %Begins the averaging procedure by placing the first line into the
    end  %average matrix
    for s=1:sx
        for w=2:ang
            I5(s)=I4(s,w)+I5(s);  %Averaging process.
        end
    end
    I5=I5./ang;

figure;
plot(p,I5);
title('Intensity Plot for 4s lens: April 11 1997: -3.25 Dpt 8.6 BC');
ylabel('Relative Intensity (1=256=white)');
xlabel('X Pixel Number');

%Now I have to change from an intensity graph to a depth graph. using a
%previously calculated linear relationship between depth and intensity
%(see slop.m)

load('slopes');
P=sum(P);
P=P/20;
depth=(I5-P(2))/P(1);
figure;
plot(p,depth);
title('Tear Film Depth Under 4s lens: April 11 1997: -3.25 Dpt 8.6 BC');
xlabel('X Pixel Number');
ylabel('Depth, microns');
print('depth');
close;
print('rel');
close;
hold on

%This stuff is just cosmetic; I want to graph the Intensity/Depth
%plot on top of the model image. The hard part is locating the circle
%center....in a way that MatLab can understand. OH and making sure
%that the axes on the 2 graphs match up.
clf;
b = linspace(0,sx/230,sx); %Sets up linespace vector for the depth chart;
r=linspace(-1,1,460);
image(r,-r,A); %plots the model eye image with 0 at the center.
hold on

axis equal
plot(b,I5-0.2,'w.'); %plots the intensity image onto the model image
title('Image of 4s lens: April 11 1997: -3.25 Dpt 8.6 BC');
xlabel('X Pixel Number');
ylabel('Y Pixel Number');
[b,bmap]=capture(1);
tiffwrite(b,bmap,'super');
close
Bibliography


