6-8-2016

3D Printed Imaging Apparatus for Monitoring Intraocular Pressure Using Smartphone Camera

Giovanni Castillo
Santa Clara University

Joshua Godfrey
Santa Clara University

Michael Zhao
Santa Clara University

Christopher Gaines
Santa Clara University

Follow this and additional works at: https://scholarcommons.scu.edu/bioe_senior

Recommended Citation
Castillo, Giovanni; Godfrey, Joshua; Zhao, Michael; and Gaines, Christopher, "3D Printed Imaging Apparatus for Monitoring Intraocular Pressure Using Smartphone Camera" (2016). Bioengineering Senior Theses. 37.
https://scholarcommons.scu.edu/bioe_senior/37

This Thesis is brought to you for free and open access by the Engineering Senior Theses at Scholar Commons. It has been accepted for inclusion in Bioengineering Senior Theses by an authorized administrator of Scholar Commons. For more information, please contact rscroggin@scu.edu.
I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Giovanni Castillo, Joshua Godfrey, Michael Zhao, Christopher Gaines

ENTITLED

3D Printed Imaging Apparatus for Monitoring Intraocular Pressure Using Smartphone Camera

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE IN
BIOENGINEERING

I. Emre Araci
Thesis Advisor

06/07/2016

Department Chair

06/08/2016
3D Printed Imaging Apparatus for Monitoring Intraocular Pressure Using Smartphone Camera

By

Giovanni Castillo, Joshua Godfrey, Michael Zhao, Christopher Gaines

Equal participants

SENIOR DESIGN PROJECT REPORT

Submitted to
the Department of Bioengineering

of

SANTA CLARA UNIVERSITY

in Partial Fulfillment of the Requirements
for the degree of
Bachelor of Science in Bioengineering

Santa Clara, California

Spring 2016
ABSTRACT

Glaucoma is one of the leading cause of blindness in the modern age, with more than 65,000,000 afflicted individuals world-wide. High intraocular pressure (IOP) is the main risk factor of the disease. Current methods of monitoring IOP require a visit to an ophthalmologist and expensive medical equipment which greatly reduces the frequency of measurement. We utilize 3D printing to develop an apparatus that will allow us to take accurate pictures of an implantable IOP sensor with a smartphone camera. This apparatus has a lens to magnify the image and an illumination system to provide appropriate lighting. Our results show that viable images can be taken of the sensor using the final design of the apparatus. We discovered that lighting of the eye could be achieved through the smartphone’s built-in flash directed through a fiber optics cable. However, the small window of focus on the sensor created inconsistencies in our images. Consequently, future developments of our apparatus should integrate with a proprietary app that will manage image focus and processing, and submit data directly to the patient’s doctor. Improved lighting can increase image quality by improving the seals between the phone, apparatus, and eye and reducing hotspots on the sensor.
Acknowledgements

We would like to thank our advisor Dr. Ismail Emre Araci, who provided us with the project idea and guided us through the design process. He gave us the necessary background information and a fuller understanding that we needed of the optical and microfluidic aspects of our project.

We would also like to thank the school of engineering for providing us with the funds we needed to buy the testing equipment and materials for our project. We also want to thank the Maker Lab for providing us with a place to 3D print our apparatus and laser cut our acrylic interface.

We would also like to thank Adrian Valones for purchasing the supplies for our project, Dr. Allia Griffin for advising us as we made our PowerPoint presentation and wrote our thesis, and Dr. Zhang for challenging us to pay attention to the details in our project.
Table of Contents

Abstract...........................................................................................................................................iii

Chapter 1 – Introduction..................................................................................................................1
  1.1 Background.............................................................................................................................1
  1.2 Review of Literature..............................................................................................................1
  1.3 Current Technology...............................................................................................................3
  1.4 Statement of Project Goal.....................................................................................................3
  1.5 Significance...........................................................................................................................4

Chapter 2 – System Overall Integration.......................................................................................5
  2.1 Design Description...............................................................................................................5
  2.2 Details of Key Constraints....................................................................................................5
  2.3 Team Management..............................................................................................................6
  2.4 Materials..............................................................................................................................7
  2.5 Methods...............................................................................................................................10

Chapter 3 – 3D Printed Apparatus...............................................................................................13
  3.1 Generation I.........................................................................................................................13
  3.2 Generation II.......................................................................................................................14
  3.3 Generation III.....................................................................................................................15
  3.4 Generation IV.....................................................................................................................16
  3.5 Generation V.......................................................................................................................17

Chapter 4 – Optical Tests.............................................................................................................19
  4.1 Focal Length Tests...............................................................................................................19
  4.2 Distance Test between Camera and Lens...........................................................................21

Chapter 5 – Illumination Tests.....................................................................................................24
  5.1 Preliminary Illumination Tests............................................................................................24
5.2 Illumination Test with Mirror on Sensor and Generation I Eye Model……………...25
5.3 Sensor Imaging with Generation IV Apparatus on Sensor………………………...27

Chapter 6 – Eye Model…………………………………………………………………………29
  6.1 Initial Design…………………………………………………………………………29
  6.2 Epoxy…………………………………………………………………………29
  6.3 Generation I Eye Model……………………………………………………………..30
  6.4 Generation II Eye Model…………………………………………………………..31
  6.5 Liquid-Gas Interface……………………………………………………………..33
  6.6 Future Iterations of Eye Model……………………………………………………33

Chapter 7 – Experimentation…………………………………………………………….35
  7.1 Results…………………………………………………………………………....35
  7.2 Discussion………………………………………………………………………..47

Chapter 8 – Engineering Standards and Realistic Constraints………………………51

Chapter 9 – Conclusion…………………………………………………………………53

Bibliography……………………………………………………………………………54

Appendix 1: Drawings and Solidworks Design……………………………………..55

Appendix 2: Funding Proposal…………………………………………………………58

Appendix 3: Bill of Materials…………………………………………………………..60
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>LB1014 Lens</td>
<td>7</td>
</tr>
<tr>
<td>2-2</td>
<td>LB1761 Lens</td>
<td>7</td>
</tr>
<tr>
<td>2-3</td>
<td>LMR05 Mount</td>
<td>7</td>
</tr>
<tr>
<td>2-4</td>
<td>LMR1 Mount</td>
<td>8</td>
</tr>
<tr>
<td>2-5</td>
<td>iPhone 5</td>
<td>8</td>
</tr>
<tr>
<td>2-6</td>
<td>Custom Fiber Optics Cable</td>
<td>8</td>
</tr>
<tr>
<td>2-7</td>
<td>VC1 V Clamp</td>
<td>9</td>
</tr>
<tr>
<td>2-8</td>
<td>VC3 V Clamp</td>
<td>9</td>
</tr>
<tr>
<td>2-9</td>
<td>Polydimethylsiloxane</td>
<td>9</td>
</tr>
<tr>
<td>2-10</td>
<td>Gorilla Glue</td>
<td>10</td>
</tr>
<tr>
<td>2-11</td>
<td>Optical Test Setup</td>
<td>11</td>
</tr>
<tr>
<td>2-12</td>
<td>Illumination Test Setup</td>
<td>11</td>
</tr>
<tr>
<td>3-1</td>
<td>Olloclip iPhone Lens</td>
<td>13</td>
</tr>
<tr>
<td>3-2</td>
<td>Generation I Apparatus Design</td>
<td>14</td>
</tr>
<tr>
<td>3-3</td>
<td>Generation II Apparatus Design</td>
<td>15</td>
</tr>
<tr>
<td>3-4</td>
<td>Generation III Apparatus Design</td>
<td>16</td>
</tr>
<tr>
<td>3-5</td>
<td>Generation IV Apparatus Design</td>
<td>17</td>
</tr>
<tr>
<td>3-6</td>
<td>Generation V Apparatus Design</td>
<td>18</td>
</tr>
<tr>
<td>3-7</td>
<td>Side View of Acrylic Fit</td>
<td>18</td>
</tr>
<tr>
<td>4-1</td>
<td>15 mm FL, ½” Diameter Lens</td>
<td>19</td>
</tr>
<tr>
<td>4-2</td>
<td>20 mm FL, ½” Diameter Lens</td>
<td>20</td>
</tr>
<tr>
<td>4-3</td>
<td>25 mm FL, ½” Diameter Lens</td>
<td>20</td>
</tr>
<tr>
<td>4-4</td>
<td>25.4 mm FL, 1” Diameter Lens</td>
<td>21</td>
</tr>
<tr>
<td>4-5</td>
<td>15 mm Distance Test</td>
<td>22</td>
</tr>
<tr>
<td>4-6</td>
<td>20 mm Distance Test</td>
<td>22</td>
</tr>
<tr>
<td>4-7</td>
<td>30 mm Distance Test</td>
<td>23</td>
</tr>
<tr>
<td>4-8</td>
<td>40 mm Distance Test</td>
<td>23</td>
</tr>
<tr>
<td>5-1</td>
<td>Preliminary Illumination Test Side 90 Degrees</td>
<td>24</td>
</tr>
</tbody>
</table>
Figure 5-2 Preliminary Illumination Test Side 45 Degrees ..............................................25
Figure 5-3. Illumination Test, Sensor Outside Eye Model ..............................................26
Figure 5-4. Illumination Test, Sensor Inside Eye Model ..............................................26
Figure 5-5. Sensor Imaging, Lit Room ........................................................................27
Figure 5-6. Sensor Imaging, Dark Room ..................................................................28
Figure 6-1. Generation I Eye Model, Side .................................................................30
Figure 6-2. Generation I Eye Model, Front ...............................................................31
Figure 6-3. Generation II Eye Model .......................................................................32
Figure 6-4. Completed Generation II Eye Model .......................................................32
Figure 6-5. Liquid-Gas Interface ............................................................................33
Figure 6-6. Proof of Concept of Eye Model ..............................................................34
Figure 6-7. Future Iteration of Eye Model .................................................................34
Figure 7-1. Generation IV Image, 1 .......................................................................35
Figure 7-2. Generation IV Image, 2 .......................................................................36
Figure 7-3. Bare Fiber Optic Image, Lit Room .........................................................37
Figure 7-4. Bare Fiber Optic Image, Dark Room .......................................................37
Figure 7-5. Acrylic Ring ..........................................................................................38
Figure 7-6. Acrylic Ring Dispersion, 1 ....................................................................39
Figure 7-7. Acrylic Ring Dispersion, 2 ....................................................................39
Figure 7-8. Mirrored Acrylic ..................................................................................40
Figure 7-9. Backside of Mirrored Acrylic .................................................................41
Figure 7-10. Mirrored Acrylic Dispersion, 1 ............................................................42
Figure 7-11. Mirrored Acrylic Dispersion, 2 ............................................................42
Figure 7-12. Acrylic with Rough Surface .................................................................43
Figure 7-13. Roughened Acrylic Ring Dispersion, 1 ...............................................44
Figure 7-14. Roughened Acrylic Ring Dispersion, 2 ...............................................44
Figure 7-15. Chassis with Shaders .........................................................................45
Figure 7-16. Rough Acrylic Dispersion with Altered Chassis, 1 ..............................46
Figure 7-17. Rough Acrylic Dispersion with Altered Chassis, 2 ..............................46
Figure 7-18. Mirrored Illumination Effect ................................................................48
Chapter 1 - Introduction

1.1 Background
Glaucoma is a neurodegenerative disease that causes progressive damage to the optic nerve resulting in vision loss. It affects more than 65 million people worldwide and is the second leading cause of blindness. Pressure inside the eye, or intraocular pressure (IOP), can be used to monitor the progression of glaucoma. Abnormally high IOP (~ >22mmHg) is a key risk factor for glaucoma. All treatments aimed at slowing the progression of glaucoma, be it pharmaceutical or surgical, aim to decrease IOP. Being able to constantly monitor IOP multiple times a day can help give a better understanding of the disease and give insight into personal treatment efficacy. The current methods for measuring IOP (i.e. Goldmann applanation tonometry) are fairly expensive and are only accessible through a visit to the ophthalmologist’s office. Even those with glaucoma or put into high risk groups for developing the disease are suggested to get their IOP measured once every year - a very static data point that does not accurately represent IOP. Our aim with this project is to provide a cheaper more accessible option for glaucoma patients to monitor the change in their IOP. Our hope is to allow the patient to monitor IOP from home and to send the results to their doctor in order to monitor drug and treatment efficacy. The user base for this device is primarily those who have been diagnosed with glaucoma and also require cataracts surgery. Because of this, it is safe to assume that the users of our product will be in the age range of 60 and up as the risk for development of glaucoma increases at age 60 (40 if African American)[1].

1.2 Review of Literature
The article “An Implantable Microfluidic Device for Self-monitoring of Intraocular Pressure,” authored by Dr. Ismail Araci, is published in Nature Medicine - a peer-reviewed medical journal. It was published in the twentieth volume of the biomedical journal in September 2014. Irregular intraocular pressure (IOP) may be an indicator of glaucoma, which has affected more than 65 million people worldwide. IOP is known to fluctuate throughout the day so infrequent measurements may not be sufficient. The authors propose that IOP can be measured using a pressure sensor that is implanted after cataract surgery. The sensor uses microfluidic principles in order to measure the pressure in the lens. The authors propose that a device that allows the self-
monitoring of IOP using a smartphone camera with a lens device attached may save the vision of many glaucoma patients. Dr. Araci’s novel idea of using a microfluidic device to measure the IOP is the basis of our project. [2]

J. Yan’s article, “An unpowered, wireless contact lens pressure sensor for point-of-care glaucoma diagnosis,” was published in the IEEE Engineering in Medicine and Biology Society on August 30. The author, John Yan, was a PhD student at the University of California, Davis. The author proposes that a wireless contact lens may be used for glaucoma diagnosis by measuring IOP. Yan’s device is based purely on microfluidic measurements as he tests his results using a force gauge. The lens was created using PDMS, a biocompatible synthetic polymer. [3]

Kingsley C. Okafor’s paper, “Measuring intraocular pressure,” breaks down the current state of our ability to measure Intraocular pressure. All methods have their strengths and weaknesses and are affected by other specific properties of the eye other than IOP. Applanation Tonometry uses a plastic probe to deform the cornea by a set amount and measures the force necessary to do so. Noncontact tonometry utilizes a similar deformation method, but does so with a calibrated column of air. Further developing the use of air is an Ocular Response Analyzer, which take into account the fluid damping properties of the eye and neutralizes the effects of eye rigidity to better isolate IOP. All of these methods give us insight into how IOP has traditionally been measured, and give us a framework of positives and negatives that need to be addressed to make our product more effective than anything before it, or at least more useful in certain aspects. [4]

David Myung’s paper “3D Printed Smartphone Indirect Lens Adapter for Rapid, High Quality Retinal Imaging,” outlined the design and efficacy of a device that can be attached to a smartphone and used to take pictures of the retina. They utilized phone camera mount systems to jerry rig a lens to the end of their system. The design allowed for some universality and some flexibility in lens placement versus camera placement. Our system will be fundamentally similar to theirs as we also plan to use a single lens system with a single chassis attached to a smartphone. The variations come in the illumination techniques as well as the way the device will be used. They aimed at providing a quick and cheap way to have a medical professional
image a retina (eye dilation is still required) whereas we are trying to take an image of a sensor without the help of a professional or eye dilation. We also are looking to improve precision by tailoring our focal length and camera system to achieve a specific magnification and field of view. [5]

1.3 Current Technology
In the medical field today, the current method of measuring intraocular pressure is ocular tonometry. Ocular tonometry is an in office procedure in which pressure is directly applied to the cornea using either a plastic head or compressed air. While there are many different forms of ocular tonometry, the most popular of methods is the Goldmann Tonometer. This method, a form of applanation tonometry, flattens the cornea using a plastic head and measures the force necessary to do so with a tolerance of 2mmHg. While relatively accurate, this technique is subject to errors if the patient’s cornea is thick, the tonometer is not positioned correctly or if the tip of the tonometer is not cleaned and dried properly. Furthermore, this technique requires a visit to an opthamologist and is often reported as being uncomfortable (anaesthetic eye drops are often administered). While other forms, namely non-contact tonometry, are more comfortable, they are considered less accurate. From this, we have determined that there is a need for a more immediate and user friendly form of measuring IOP.

1.4 Statement of Project Goal
Herein is the statement of our project goal, objectives and expected results. The optometric community is in need of a low-cost, accurate, and easy to use means of measuring intraocular pressure as a vehicle for more efficient prevention, diagnosis, and treatment of glaucoma. We have achieved our goals by measuring the focal length of several different lenses, constructing an apparatus using computer-aided design (CAD) software, using fiber optic fibers with a collimator, and building an eye model. The focal length determines the intensity of light convergence through the lens. It is important to choose the correct focal length due to the limited space we are allowed to work with. CAD allows for quick and optimal changes to our apparatus. Another benefit of using CAD is the ability to 3D print our device. The optic fibers and collimator are used to illuminate the inside of our device. The light that is brought through the collimator will ensure that pictures taken from our smartphone will be of maximum resolution.
The eye model will be used along with the microfluidic lens. The model will mimic a biological eye and will be used to take enhanced pictures of the lens. The expected results using all four aspects will be a device that is capable of capturing the micro-details of the microfluidic lens using a smartphone’s camera.

1.5 Significance
The immediate benefit that our project will have is that it helps better the treatment of patients suffering from glaucoma. With more information on the disease and its progression in individuals, treatment of it can be more personalized and effective. The project fits in well with the global trend towards personalized medicine. Diseases, while sharing common denominators, present themselves differently in each person. As medicine has striven to further understand why this is and how to better treat individuals, the field of personalized medicine has thrived. Our IOP device helps sustain this trend towards personalized medicine and helps to understand glaucoma as a disease on a more fundamental level. Beyond this, our device lends aid to the continual shift of bringing healthcare to the everyday consumer. The goal is to allow patients to gain even more control over their own health without having complete reliance on healthcare professionals. This too is something that is a growing trend headlined by resources such as WebMD and products ranging from anti-fungal creams to splints. Lastly, our design project integrates society’s latest technological innovations as consumer technology ultimately catches up with technology commonly used in the medical field. The simplification of healthcare by using known products is a significant factor in the development of our design.
Chapter 2 - System Overall Integration

2.1 Design Description
As a whole, our system utilizes lenses, optical fibers, and a unique light dispersion method in order to take a magnified image of a microfluidic sensor. We have designed a chassis to interface with the iPhone 5 as well as to hold all of the necessary optical equipment. Attached to the chassis on the opposite end of the phone is an eye cup which ensures consistent coupling with the human eye. Furthermore, the eyepiece helps maintain a low light environment around the eye.

Our project fulfills one aspect of a two part commercial system - the microfluidic pressure sensor in the eye and our method for reading that sensor. The product will be the pressure sensor while our project would be a necessary one time purchase or added accessory. However, our project was designed around taking pictures of sensors implanted onto the cataracts lens. The real future commercialization plan centers around a contact lens based pressure sensor. This would greatly expand the user base from those who have glaucoma and need cataracts surgery, to those who have glaucoma and need or would be open to using contacts (a much larger group). Nonetheless, the only variable that changes from our initial design constraints would be our necessity to have the image taken in a dark environment - with a contact lens pupil dilation/constriction is irrelevant. Because of this, our system will still be a good early prototype for the design of a secondary, yet necessary purchase for people looking for glaucoma monitoring options. The product would be suggested and likely prescribed by ophthalmologists, much like glasses and contacts are today.

2.2 Details of Key Constraints
When defining the key constraints of our product, accessibility and ease of use were the two greatest concerns. In order to meet both of these constraints, we opted to use a smartphone and its camera to take pictures as smartphones are the most common and accessible imaging devices around the world. This in turn meant that our device had to interface well with a smartphone and that it had to focus the smartphone camera on the sensor while magnifying the image. The pupillary response (constriction) to light was another concern and because our images were taken
of the lens lateral to the pupil, the pupil had to be dilated. In order to achieve natural pupil
dilation, operating in a dark environment was another constraint. This led to another constraint:
there needed to be a light source that flashed when the photo was taken illuminating the sensor
without causing glare. Lastly, in order to ensure consistency, the device had to fit in a well-
defined way with the human eye.

2.3 Team and Management
Our team consists of Gino Castillo, Michael Zhao, Chris Gaines, and Josh Godfrey. Castillo was
the lead contact and in charge of the optical tests. Zhao was in charge of developing the eye
model. Gaines was in charge of the 3D printing. Godfrey was put in charge of ensuring the 3D
printed model and the optical components work together.

Our budget covered the cost for the lenses, the optical testing equipment, the fiber optics cable,
the collimator, and the iPhone. The total cost came for all the equipment came out to be
$1,091.21. The most expensive item of our bill of materials was the CFC-2X-A FC/PC
Collimator at $236.00. Although most of the items in our bill of materials were not that
expensive on their own, much of the cost came from the quantity we had to buy. We had an issue
with the fiber optics cable being misdelivered which led to setbacks in the development of our
project. See Appendix 2.

Over the Fall quarter we mainly performed preliminary research. The first couple weeks of
Winter quarter we received lab training and became familiarized with the testing processes
involved in developing our device. Weeks 3-4 we found the best lens to use for our device and
made our first 3D printed model. Weeks 5-6 we did illumination testing and worked on making
the 3D printed model into an assembly rather than an individual part. See Appendix 3.
2.4 Materials

**Figure 2-1. LB1014 Lens.** An uncoated biconvex lens with ½” diameter and 25mm focal length

**Figure 2-2. LB1761 Lens.** An uncoated biconvex lens with 1” diameter and 25.4 mm focal length

**Figure 2-3. LMR05 Mount.** A lens mount with a retaining ring for ½” diameter lens, 8-32 tap
Figure 2-4. **LMR1 Mount.** A lens mount with a retaining ring for 1” diameter lens, 8-32 tap

Figure 2-5. **iPhone 5.** An iPhone 5 smartphone was used to take the pictures and design our apparatus around

Figure 2-6. **Custom Fiber Optics Cable.** A multimode fiber optics cable with SMA connectors at each end. We cut it in middle and adjusted the length to the bare end to what we needed.
Figure 2-7. VC1 V Clamp. A small V-clamp with PM3 clamping arm, 0.75" long

Figure 2-8. VC3 V Clamp. A large V-clamp with PM4 clamping arm, 2.5" long

Figure 2-9. Polydimethyilsiloxane. 3D chemical structure of polydimethyilsiloxane, a synthetic polymer used to fabricate the intraocular pressure sensor and eye model
Figure 2-10. Gorilla Glue. Epoxy used to bond the implantable sensor to the eye model

2.5 Methods

3D Printing:
The design process for our device housing was guided by a few key specifications from the onset. We utilized 3D printing in ABS plastic in order to make minute changes in design while maintaining high accuracy, and quick turnaround times for new iterations. The apparatus was to be smart-phone compatible, maintaining constant distances between the camera sensor, magnification lens, and the user’s cornea. The device’s ergonomics would focus on comfort and simplicity of use in order to better serve the older demographic typically diagnosed with glaucoma. Lastly, the housing would be light-proof in order to allow our illumination solution to work with consistency and without interruption from ambient light.

Optical Test Setup:
For our optical tests we placed a lens in between an iPhone 5 and a dummy sensor made of PDMS. The iPhone was held by a VC3 V clamp, and the sensor was placed on a piece of PDMS and taped to the PM3 sampling arm. The ½” lenses were positioned by a LMR05 lens mount and the 1” lens was positioned by a LMR1 lens mount. See Figure 1 for a picture of the optical setup.
Figure 2-11. Optical Test Setup. Initial setup to test focal length of various lenses

*Illumination Test Setup:*

To test illumination methods in the device we used the same setup as the optical tests, but added in a fiber optics cable coupled with the flashlight of another smartphone since the arms of the lens holder did not allow for it to couple with the iPhone 5. We also placed a mirror at 30° perpendicular to the sensor to angle light from the fiber optics cable to 90° to the sensor to follow the findings made in the preliminary illumination tests. Refer to Figure 2-12 for a picture of the setup.

Figure 2-12. Illumination Test Setup. Initial testing setup with generation one eye model
Eye Model Fabrication:
The first generation eye model was created using the pressure sensor bonded to a slide of PDMS which is then attached to a ping pong ball. We cut the slice of PDMS to be around 5 cm in diameter. A circular area was extracted from the center of the ping pong ball and then the PDMS was bonded to the ball using the epoxy industrially known as Gorilla Glue. We allowed the epoxy to set for about three to five minutes until the adhesive’s viscosity was high enough so that it would not flow easily and would support its own weight. In order to bond the PDMS slice to the ball, we must first ozone plasma treat the PDMS. Upon treatment, PDMS is capable of being bonded to several surfaces including the ping pong ball and other hard plastics. Since the IOP sensor is also made from PDMS, we had to plasma treat the sensor and the PDMS slice before using our epoxy to bond the two. A hole was drilled into the posterior side of the ball to allow water entrance. Upon insertion of water, we are able to see pressure buildups evident in the form of PDMS incorporating a slight curvature in its shape. More information on plasma treatment and use of epoxy can be found in chapter 6.

The latest iteration involves the use of a poly(methyl methacrylate) (PMMA) sphere. The PMMA ball consists of two hemisphere which were able to connect onto each other. Similar to the first iteration, a hole was drilled to the exterior hemisphere in order to allow for insertion of water and pressure difference simulation. The exterior was also painted using a red ink in order to simulate human blood and tissue. Plasma treatment of the IOP sensor was required in order to bond the sensor to the PMMA sphere. Gorilla Glue was used as the adhesive to bond the sensor and sphere.
Chapter 3 - 3D Printed Apparatus

3.1 Generation I

The initial concept for our design originated from a commercial iPhone lens adapter called the olloclip (Fig 3-1). We adapted the simple friction fit as a solution for mounting our device safely and strongly to a phone, and built our prototype around that idea.

Figure 3-1. Olloclip iPhone Lens. Primary inspiration for our adapter design (Source: www.olloclip.com)

Generation I consisted of a rectangular box with a 1 inch diameter hole in the eye-facing end (Fig 3-2). Cross Sectional features included a small circular lip to hold the lens in place, a 3mm thick divider with circular cutouts for the flash and camera lens to provide a light-proof seal between the apparatus and the phone, and a slot slightly thicker than the phone to account for 2 sheets of felt cushioning material. Generation I was printed in 1 piece to test the viability of those key features before delving into the final assembly of the device.
3.2 Generation II

Generation II design changes built upon the features of the previous generation (Fig 3-3). Having proved that the friction fit was viable, Gen II incorporated a new design for mounting the internal components as well as a lateral bisection of the device to allow for easy assembly. The collimator and lens mounts were made by importing their official Solidworks designs from the Thorlabs website, positioning them correctly within the device, and then creating a subtractive cut leaving cavities that conform perfectly to their real-world counterparts. The 0.2mm resolution of the Makerbot Replicator 2X printers, combined with the relative flexibility of thin ABS allowed both parts to slot into place without falling out. The snap fit to hold the two halves together did not work in this iteration, as tolerances on our proprietary locking design were not cohesive between the male and female parts of the housing. A slot running along the collimator was added to hold a fiber optic cable in yet another snap-fit solution.
Figure 3-3. Generation II Apparatus Design. Cross-sectional, isometric, and anterior view of apparatus. Visible inside is the collimator and 1 in lens

3.3 Generation III

Generation III developed mounting techniques and perfected the snap-fit (Fig 3-4). Experiments had shown that a 0.5 inch diameter lens could provide us with optimal images when packaging concerns were taken into account. Gen II had shown that the lack of flexibility in our fiber optic cables combined with the relatively large size of the collimator meant the housing would need to be redesigned with a smaller lens in mind. We later found that the collimator was not necessary to collect a useable amount of light into the fiber, so that was replaced by a smaller cylinder over the flash to hold the fiber in place. Gen III gained a slot on the eye-facing end to hold a mirror that would direct fiber optic light at a ~30 degree angle into the user’s eye. Snap fit succeeded with equidistant rectangles ~10% smaller on the male half of the apparatus than their female counterparts.
Figure 3-4. Generation III Apparatus Design. Cross-sectional, isometric, and anterior view of apparatus. Visible inside is the 0.5in lens

3.4 Generation IV

Gen IV was the first generation to produce functional images of our sensor (Fig 3-5). Minor changes included cutouts for easy insertion and removal of the fiber optic cable and mirror. The mirror was created by spraying a glass microscope slide with metallic paint and slotting it into the apparatus. A shift in focus towards device ergonomics meant testing out a basic foam eyepiece as a potential cushion and light-proof seal.
Figure 3-5. Generation IV Apparatus Design. Cross-sectional, isometric, and anterior view of apparatus. Visible inside is the fiber optic cable, 0.5in lens, and mirror

3.5 Generation V

Gen V represented a departure from the previous 3 generations, and built upon experimental and anecdotal evidence gathered previously regarding focusing distances and new lighting solutions (Fig 3-6). This iteration changes from a single box to a stacked box design in order to incorporate our microscope-grade eyecup. This was deemed necessary because we were still getting light leaks in the previous generation. The apparatus total length was shortened in order to improve the iPhone’s focusing performance as the prior distance held the eye at the very end of the iPhone's focusing limits. Snap-fit was adjusted to the new dimensions, and the interior was painted black to eliminate internal reflections and light transmitted through the ABS material. The Fiber optic cable now passed into a laser-cut acrylic ring as opposed to a mirror to evenly disperse the light around the eye and reduce the hotspotting effect we saw in earlier tests. The cable slotted into a 1/16” hole drilled through half the thickness of the acrylic.
Figure 3-6. Generation V Apparatus Design. Cross-sectional, isometric, and anterior view of apparatus. Visible inside is the black-painted interior, fiber optic cable, 0.5mm lens, and eyepiece assembly

Figure 3-7. Posterior View of Acrylic Fitment. Acrylic ring forms friction fit with eyepiece and apparatus
Chapter 4 - Optical Tests

4.1 Focal Length Tests

Through previous analysis with the magnification equation (eq. 1), we determined that a focal length of 25.4 mm would give us the best magnification within our constraints. The lens’ focal length \( f_1 \) of 25.4 mm and the iPhone camera’s focal length \( f_2 \) of 35 mm gave us a magnification of approximately 1.38.

\[
M = \frac{f_2}{f_1} \quad \text{(eq. 1)}
\]

In order to verify this, we tested four separate lenses to determine which one would best magnify the sensor but provide enough for the collimator we planned to use. We kept the lens 22 mm from the iPhone camera and placed it at the distance of the focal length of the lens for each. The focal length of the 1” D 25.4 mm FL lens was close to the ½” D 25 mm FL lens, but the two were compared to determine which had the better image of the sensor. Refer to figures 4-1 through 4-4 for images taken during the tests.

Figure 4-1. 15 mm FL, ½” Diameter Lens. Image captured during initial lens testing with ½” diameter lens at 15 mm focal length.
Figure 4-2. 20 mm FL, ½” Diameter Lens. Image captured during initial lens testing with ½” diameter lens at 20 mm focal length.

Figure 4-3. 25 mm FL, ½” Diameter Lens. Image captured during initial lens testing with ½” diameter lens at 25 mm focal length.
Figure 4-4. 25.4 mm FL, 1” Diameter Lens. Image captured during initial lens testing with 1” diameter lens at 25.4 mm focal length.

From the images we took, we determined that the 25.4 FL 1” D lens gave us the best results. It clearly displayed the tick marks of the sensor but also provided a wide enough field of view to view the sensor. The 15 mm FL lens gave the clearest image of the tick marks, but had a too small of a field of view at 22 mm to fit the fiber optics cable and a collimator. The 20 mm FL lens was barely able to capture the image of the sensor at 22 mm.

4.2 Distance test between camera and lens
After we determined that the 25.4 FL 1” D lens was the best lens to use to magnify the image of the sensor, we determined how far back we could pull back the camera from the lens and still get a good image of the sensor. We took images from 10 mm away to 40 mm away. Refer to figures 4-5 through 4-9.

We determined from the images that 30 mm between the camera and the lens was the furthest distance that still produced an image that was clear. A distance of 40 mm produced an image where we could not clearly make out the tick marks.
Figure 4-5. 15 mm Distance Test. Image taken with 1” diameter lens 25.4 focal length at 15 mm

Figure 4-6. 20 mm Distance Test. Image taken with 1” diameter lens 25.4 focal length at 20 mm
Figure 4-7. **30 mm Distance Test.** Image taken with 1” diameter lens 25.4 focal length at 30 mm

Figure 4-8. **40 mm Distance Test.** Image taken with 1” diameter lens 25.4 focal length at 40mm
Chapter 5 - Illumination Tests

5.1 Preliminary Illumination Tests
Before we started testing different illumination methods with the fiber optics cable, we learned from Dr. Araci’s previous research that light arriving at a 15° angle off of the optical axis produced negligible glare images on the retina. [6] Using a flashlight we determined that lighting the lens at a 90° angle gave the least glare and the best visual of the tick marks. At 45° there was two glare hotspots and a more blurred visual of the tick marks. Sending the flash straight through the lens from the camera gave us no usable image. Refer to figures 5-1 and 5-2.

Figure 5-1. Preliminary Illumination Test Side 90 Degrees. Image captured with light propagating at a 90 degree angle
5.2 Illumination Test with Mirror on Sensor and Generation I Eye Model:

In our illumination tests with the test setup above we took pictures of the sensor outside the eye model and inside the eye model. The pictures of the sensor outside the eye model produced good results. The sensor’s tick marks were visible and there wasn’t a strong glare. Refer to figure 5-3 for the image. The pictures of the sensor inside the eye model rather produced poor results. The tick marks were barely distinguishable to the white background. Refer to figure 5-4 for the image. The poor results at this stage were caused by a poor eye model rather than a poor illumination setup, therefore we couldn’t really evaluate whether the setup was effective. After this test we determined that our eye model was not good for testing our apparatus and that we needed to make something that was more realistic to the eye.

Figure 5-2. Preliminary Illumination Test Side 45 degrees. Image captured with light propagating at a 45 degree angle
Figure 5-3. Illumination Test, Sensor Outside Eye Model. Image captured with implantable sensor on outer layer of eye model.

Figure 5-4. Illumination Test, Sensor Inside Eye Model. Image captured with implantable sensor on inner layer of eye model.
5.3 Sensor Imaging with Generation IV Apparatus on Sensor:
After we developed our Generation IV apparatus with a working illumination system via a fiber optics cable, we took pictures of a sensor outside the eye model in a lit room and a dark room. As expected the pictures taken of the sensor in a lit room displayed a clear image of the tick marks. Refer to figure 5-5. This verified our optical setup inside the apparatus was operational. When we tried to take a picture of the apparatus in a dark room we weren’t able to take pictures with a clear image of the tick marks. In order to get an image that was barely readable we had to switch to video mode with a constant light supply from the iPhone 5’s flash. Refer to figure 5-6. This test showed us that we needed to find a better way to focus the iPhone camera on the sensor.

Figure 5-5. Sensor Imaging, Lit Room. Image captured with generation four apparatus. The sensor was placed on the outer layer of the eye model.
Figure 5-6. Sensor Imaging, Dark Room. Image captured with generation four apparatus
Chapter 6 - Eye Model

6.1 Design Idea
In vitro testing is ideal because it allows us to set certain conditions in which we can test our apparatus. The eye model was conceived so that we may validate our biodevice by mimicking the human eye with the implanted sensor.

The main material used to create the eye model is polydimethylsiloxane (PDMS) which is a synthetic polymer created using a 10:1 elastomer to curing reagent mixture. PDMS is also the polymer used to create our sensor. PDMS is ideal due to the similar traits that it shares with the human eye. It is mechanically elastic while also optically clear. The surface of PDMS is also gas permeable which can account for pressure buildup and differences. We can use the permeability to measure in vitro intraocular pressure which gives us an indicator to validate our apparatus.

6.2 Epoxy
An epoxy was used to bond the PDMS to the casing of the eye model. The epoxies that were tested include Gorilla Glue, E-30CL, and E-60HP. Initial testing of the latter two epoxies indicated a poor curing process quantified by the speed at which the epoxy sets. E-30CL and E-60HP also produced a clouded or less transparent adhesive which is not ideal in our eye model fabrication process due to the adverse aesthetic purposes that using these two epoxies would provide. Testing of Gorilla Glue suggested a better curing process as the adhesive would set in 5-8 minutes which gave us ample time to meticulously apply the epoxy. Upon completion of the curing process, Gorilla Glue also was transparent which is ideal for the model’s aesthetics. Gorilla Glue was chosen to be the main epoxy due to its efficient curing and clear properties.

Since PDMS has a natural hydrophobic surface, it is unable to be bonded to several materials such as polymethyl methacrylate and other plastics. We ozone plasma treated PDMS in order to counter the polymer’s hydrophobicity which effectively turns the surface of the PDMS to become hydrophilic. Upon treatment, the PDMS is able to be bonded to other surfaces. In order to bond PDMS to PDMS, both layers must first be plasma treated.
6.3 Generation I Eye Model

Figure 6-1 and figure 6-2 show the first generation eye model. The initial design was a thin slice of PDMS attached to a ping pong ball. The middle of the ball had a circular extraction which was where the PDMS was placed over. We bonded the IOP sensor to the PDMS before we allowed the PDMS layer to attach to the ball. In order to detect pressure differences within the model, we had to assure that the PDMS to circular extraction was water-tight. Upon verification, water was inserted through a small exterior hole by using a sharp needle and syringe. The hole was consequently filled using epoxy after filling the model with water.

The first generation eye model allowed us to establish a foundation for capturing images that partially mimicked human eye conditions. Although the model is unaesthetic, it gave us a means of testing our apparatus.

Figure 6-1. Generation I Eye Model, Side. Side view of generation one eye model made from a slice of PDMS attached to a pingpong ball
Figure 6-2. Generation I Eye Model, Front. Front view of generation one eye model. Note the implanted eye sensor

6.4 Generation II Eye Model
The second and latest iteration of the eye model can be seen in figure 6-3 and figure 6-4. We decided to abandon the ping pong ball idea and instead used another ball made of a poly(methyl methacrylate) or PMMA. The benefits of using the PMMA ball is apparent in the fabrication process and its utilities. Replicating high quality second iteration models was much easier and faster compared to the first generation. In addition, the PMMA ball had a diameter of about 30 mm which is quite similar to the human eye (~24 mm). The acrylic glass was capable of housing the PDMS sensor as well as being prone for pressure differences by being water tight. The second generation eye model was used to capture the majority of the high resolution images.
Figure 6-3. Generation II Eye Model. Front view of generation two eye model. The housing of the eye model consists of a PMMA sphere.

Figure 6-4. Completed Generation II Eye Model. Final iteration of eye model with red ink to simulate human blood and tissue
6.5 Liquid-Gas Interface
In order to measure the inner pressure of our eye model, we injected the liquid-gas interface into the microfluidic channel. As pressure increases, the interface will travel further down the channel. Pressure is quantified by the tick marks around the sensor’s channel. The liquid-gas interface that we used is mineral oil.

Figure 6-5. Liquid-Gas Interface. The interface can be seen on the left channel. As pressure increases, the interface will travel further down the channel.

6.6 Future Iterations of Eye Model
Figures 6-6 and 6-7 depict the ideal design of the eye model housing the microfluidic pressure sensor. In future iterations and in order to reach a wider user base, the internal pressure sensor is being modified to be compatible with contact lenses. In other words, instead of having the pressure sensor be implanted during surgery, it would be incorporated into a contact lens. Below are the proof of concept designs for ex-vivo eye models that would be used with the contact lens pressure sensor. The main constraint is that as pressure increases inside of the model, there has to be a surface deformation (this is the mechanism by which the pressure sensor would work). The figures below are eye models made of PDMS, a soft plastic, that deforms with increased pressure. Note: this does not affect the design of the smartphone apparatus as the effective focal length between the lens and the sensor deviates by a very small margin.
Figure 6-6. Proof of Concept of Eye Model. Design for the contact-fitted pressure intraocular pressure sensor (does not need to be medically inserted)

Figure 6-7. Future Iteration of Eye Model. The ideal eye model made strictly from PDMS
Chapter 7 - Experimentation

7.1 Results
The below results are images taken in chronological order as iterative design changes were made. Figure 7-1 and figure 7-2 are both images taken with the Generation IV apparatus. This design incorporated a mirror reflecting light coming from the flash/fiber optic cable parallel to the surface of the eye. The images taken were characterized by two bright spots on either side of the sensor. These bright spots made any gas liquid interface unreadable.

In figures 7-1 and 7-2 are images taken using the 3D printed device. In this case, the fiber optic transmitting the flash was left bare with no forms of light dispersion. The gas liquid interface could clearly be seen in figure 4-2(a), however as seen in figure 4-2(b), many of the images taken were characteristically bright. Light “hot spots” and glare made a number of these images unreadable.

Figure 7-1. Generation IV Image, 1. Image captured using Generation IV apparatus housing
In figures 7-3 and 7-4, images were taken in a low light environment using a clear piece of acrylic as a way to more evenly disperse the light and avoid glare. These images were clear, however there was still a glare (left and top of image) that inhibited the ability to see any gas-liquid interface. From these results we determined that dispersing the light more evenly was still a concern.
Figure 7-3. *Bare Fiber Optic Image, Lit Room.* This image of the sensor was taken without reflecting nor dispersing the flash in any way. This image was taken in a light environment.

Figure 7-4. *Bare Fiber Optic Image, Dark Room.* This image was taken using only the bare fiber optic and was taken in a low light environment.
Figure 7-5. Acrylic Ring. Laser cut piece of acrylic used as a means of dispersing the light source to reduce glare. The white “dot” in the image is a 1/16 inch drilled hole going through half of the thickness of the acrylic. The fiber optic cable was placed into this hole as a way of interfacing the fiber optic cable and the acrylic piece while reduce glare.
Figure 7-6. Acrylic Ring Dispersion, 1. Image taken using the last iteration of the 3D device with a bare piece of acrylic (Figure 7-5) installed.

Figure 7-7. Acrylic Ring Dispersion, 2. Image taken using a bare acrylic piece.
Figure 7-8. Mirrored Acrylic. This was an attempt to improve the dispersing piece of acrylic by reducing the hot spot observed on the images of the sensor. The piece of acrylic was coated on every side except for that facing the eye using reflective paint. A small area was coated in mirror paint directly across from the spot that the fiber optic cable was introduced in order to help limit the hot spot right across from the fiber optic cable. Every surface coated in mirror paint was then painted with a protective black layer.
Figure 7-9. Backside of Mirrored Acrylic. Backside of the mirrored acrylic dispersion system. The black hole towards the bottom is a 1/16 inch drilled hole used to feed the fiber optic cable into the acrylic cutout.
Figure 7-10. Mirrored Acrylic Dispersion, 1. Image of the sensor taken using the mirrored acrylic ring seen in figures 7-8 and 7-9.

Figure 7-11. Mirrored Acrylic Dispersion, 2. Image taken using mirrored acrylic dispersion system.
In figures 7-13 and 7-14, images were taken with the latest 3D apparatus using the roughened acrylic ring seen in figure 7-12. In order to disperse the light better and reduce the hotspot effect seen in other tests, the surface of the acrylic directly across from that of the fiber optic cable (facing the side of the eye) was filed to make a rough surface. This method yielded well let images with large hotspots on the left hand side of the image as can be seen in figures 7-13 and 7-14.

Figure 7-12. Acrylic with Rough Surface. A piece of acrylic with a roughened surface (through scraping). The rough surface was made in order to reduce hot spots of light as well as to disperse light.
Figure 7-13. Roughened Acrylic Ring Dispersion, 1. Image of the sensor taken with the latest 3D apparatus model using a clear acrylic ring with a surface feature to disperse light.

Figure 7-14. Roughened Acrylic Ring Dispersion, 2. Image taken of the sensor with a roughened piece of acrylic. Captured in a low light environment.

Due to the large glare spots seen in figures 7-13 and 7-14, modifications were made to the chassis (figure 7-15). Light was being undesirably propagated through the 3D printed channel.
that holds the fiber optic cable as opposed to through the actual fiber optic cable. In figure 7-15, electrical tape was used to prevent light from reaching the sensor from any unwanted areas. The small blue dot surrounded by electrical tape and above the central lens is the bare fiber optic cable that is introduced into a dispersing piece of acrylic. Figures 7-16 and 7-17 show better results than figure 7-13 and figure 7-14, however there is still a noticeable glare spot on the left side of the image. The microfluidic channel was clear throughout the image.

**Figure 7-15. Chassis with Shaders.** The figure shows an attempt to limit glare coming directly from the flash using electrical tape to cover up areas in which light was escaping.
Figure 7-16. Rough Acrylic Dispersion with Altered Chassis, 1. Image taken with the acrylic piece seen in figure 7-12 and with the modifications to the chassis seen in figure 7-15.

Figure 7-17. Rough Acrylic Dispersion with Altered Chassis, 2. Image taken with the same specifications as those in figure 7-16.
7.2 Discussion

The initial design of reflecting light parallel to the surface of the eye ultimately proved to be the least effective method of taking readable photographs. While illuminating from the edge of the sensor proved to be the most effective means of illumination during benchtop testing, the design did not work with our product for two reasons. Firstly, getting light to reflect and illuminate the eye at that specific angle proved to be difficult. The end of the fiber optic cable, the mirror, and the human subject positioning the device all had to be constant and correct. While the fiber optic cable and mirror were variables that we could control, the variance in how the patient held the device to their eye varied too much. While the eyepiece served as a fitting interface and yielded fairly consistent positionings, the tolerances in the positioning were too high for this illumination method. In other words, the eyepiece did not ensure a stable enough interface for this illumination method to consistently work. Slight tilts to either the right or left resulted in two bright spots marring the image. Secondly, having a point source versus having a reflection of a point source likely had an effect with our illumination method. In the benchtop testing, we had an individual light source illuminating the sensor from the side. With light sources (aside from lasers), light propagates out much like a ripple in water. When illuminating directly from the side, this waveform works out well as no light interacts with the sensor at undesired angles (causing glare). However, when this point source is reflected, light hits the mirror at different spots, due to this ripple like effect, causing light of different angles to hit the sensor. In summary, using the mirror makes light interact with the sensor at more angles than just directly from the side, which in turn causes glare. Figure 7-18 shows how this might work in practice and gives insight into why our specific setup did not work.
Figure 7-18. Mirrored Illumination Effect. Graphical representation of one of the proposed reasons of why the reflected illumination method did not work as desired

Our second design did away with the idea of illuminating the eye parallel to the surface and instead placed a light source right in front of the sensor. To do this, we left a bare fiber optic cable in the chassis and used that as the primary light source. As can be seen in the results, specifically figure 7-4, the main issue with this design was that the light was too intense and introducing that much light to a dark environment caused a bleaching effect. Furthermore, the intensity of the light caused there to be a noticeable amount of glare, further making the image difficult to read. From this, we decided that we needed to limit the amount of light being introduced by adding some form of filter. Along with this, we wanted to add some component to disperse the light more evenly in order to avoid having a “hot spot” as well as to decrease the amount of glare.
Our third design added a cylindrical clear acrylic interface in front of the fiber optic cable. It had a 33.4 mm external radius and a 16 mm interior radius, with a 1 mm lip to be in between the fiber optic cable and the eye model. It had a 1/16” drilled hole drilled through half the thickness of the interface (figure 7-5). Our hope with this interface was to create a more even dispersement of light over the eye model than the output of the bare fiber optic cable. Our results, figures 7-6 and 7-7 did display a more even dispersement of the light. However, there was a slight glare on the tick marks on the upper left portion of the sensor that made the images difficult to read. The hot spots were less pronounced and no hot spots opposite to the fiber optic cable were visible. There was slightly less contrast than the bare fiber optic but it was enough to still make out the tick marks. We did not see a clear gas-liquid interface, but this was likely because the oil ejected after it was added. It is a common setback that happens in this iteration of the sensors. From these results, we determined that while the bare acrylic piece provided acceptable results, there was still significant room for improvement.

The fourth design aimed to better the overall dispersion and limit the hot spots by coating the piece of acrylic in a reflective material. As seen in figures 7-8 and 7-9, all sides of the acrylic piece were coated in a reflective paint except for the side facing the eye. On that side, only a strip was coated in reflective paint located directly across from where the fiber optic cable was introduced to the acrylic. The theory was that any light introduced into the acrylic would reflect throughout the acrylic piece and eventually exit the ring on the side of the eye, illuminating the sensor. In other words, no light would be lost to reflection off the acrylic back into the apparatus. The mirrored portions were then coated in a black paint to protect the mirrored paint from scraping off. There were five coats of mirror paint added to each acrylic ring used in the tests and three coats of protective black paint. The unpainted side was masked using painters tape. Unfortunately, this method proved to be the least effective (in terms of illumination). Figure 7-8., the best of the samples made, has clear microfractures in the acrylic. When the mirrored paint was applied, it seeped into the microfractures causing undesired internal formations. Due to the nature of the mirror paint, when it leaked into the acrylic’s fractures, it provided points of absorption instead of reflection in the middle of the acrylic ring. These microfractures were likely caused during the laser cutting of the acrylic rings due to natural expansion when exposed to heat. Ultimately, this led to the results seen in figures 7-10 and 7-11, which are dim due to
lack of light bouncing off of the sensor. The gas liquid interface was undeterminable and thus this method of dispersion was dismissed.

The final design was also aimed at improving the dispersion of light by adding a rough surface feature, much like that of a diffraction grating, across from the fiber optic cable (figure 7-12). Additionally, slightly opaque Scotch tape was added to further dim the hotspot. In figures 7-13 and 7-14, the resulting images can be seen. Glare on the left side of the sensor was still prevalent. However, it appeared as if a fair amount of the glare actually came from leakage of light within the chassis as opposed to there being too much light in one spot coming from the fiber optic cable. In order to limit the amount of light leaking through the 3D printed apparatus, electrical tape was added to certain areas (figure 7-15). Figures 7-16 and 7-17 were taken with the added changes to the chassis, and the reduction of glare can clearly be seen. In figure 7-17, the entire microfluidic channel can entirely be seen in focus and illuminated. This was an extremely promising sign, however it is worth noting that the gas oil interface could not be seen. This is likely due to the fact that the channels had no oil in them as it had either ejected or seeped through the entire channel due to gas escape in the reservoir.
Chapter 8 - Engineering Standards and Realistic Constraints

Economic
The economic impact of our product is one of the major contributors to its value to end users. Glaucoma and blindness can be debilitating diseases that not only directly harm those afflicted, but the economies that they participate in. Blind people are unable to perform certain jobs, and can increase the financial burden in medical fees and accessibility on those around them and to a broader extent their country. With over 65 million people afflicted with glaucoma, an investment in people’s health now can lead to a significant global increase in productivity and decrease in economic burden. Our product also can be assembled for less than $50 and can be used daily, which is a strong value advantage over doctor’s visits once a month.

Manufacturability
Manufacturability was a key concern throughout the entire design process. We made a conscious effort to select commercially available lighting and magnification components to allow for ease of assembly. Rather than opt for custom built housings with wood or another material, the use of 3D printing allows us to make many identical copies for cents per print at a larger scale. Later on in development, injection molding could be implemented to further reduce cost and simplify manufacturing. The most intensive process in the production of our apparatus is assembly. Currently, there are 10 components that must be integrated before use. Further research could eliminate, integrate, or automate the inclusion of some parts, allowing the product to be manufactured at a large scale easily.

The integrity of our design is of utmost importance during the fabrication process. Although our choice of components was designed to be frugal, we kept in mind the efficiency of our apparatus. Each iteration sought to improve on the weakness of previous apparatus generations by utilizing micro-changes to the SolidWorks schematics.

Environmental
Concerns with the environmental impact of our product are relatively small. While it is made primarily of plastics and glass, the device is designed to be useable for years to come. Main
Environmental concerns would arise from the manufacturing process of our components, which could be reconciled by choosing part suppliers carefully based on their carbon footprints and commitment to sustainable business practices.

**Ethical**

Our product has the ability to improve the quality of life and happiness of a large number of people, while reducing fiscal impact of blindness and glaucoma and providing researchers with valuable insight into the disease to develop better treatments, preventative measures, and a cure.

Our design is intended to be cost efficient and available to our demographic. The total price of construction for one apparatus unit is estimated to be 48 dollars: 30 dollars for the lens, estimated 4 cm of fiber optics cable for 5 dollars, rubber grommet for 10 dollars, acrylic piece for 1 dollar per cut, and 3D printing ink for 2 per iteration. At 48 dollars per unit, we would be able to give our clients an affordable means of IOP self-measurements. Those affected negatively would be current manufacturers of medical-grade tonometers and their shareholders, as well as patients who receive no major benefit from our device before their data can be used effectively to help them. Overall our product is ethically sound and has the potential to catalyze new developments in medicine.

**Health and Safety**

Concerns with our product stem from its usage and the implant required to use it correctly. The device has no major sharp edges and has a protective eyecup for the patient’s eye that should prevent any contact with surfaces. The acrylic donut isolates the pointy fiber optic cable from the patient's eye as well. If users are allowed to take apart the final product, there is a choking hazard with the small 0.5 in lens and the fiber optic cable. There is a small risk of a biohazard if multiple people use the eyecup (i.e. pink eye, skin rash, respiratory-transferred vectors), but these can be mitigated by provided individual eyecups, using alcohol wipes, or realizing that if people are in such close proximity, they may be transferring vectors anyway. The felt lining the iPhone cavity prevents any damage from occurring to the user’s phone. As the sensor’s first iteration will require implantation, all of the risks associated with surgery will apply. This will be reduced significantly upon the completion of the contact-lens sensor.
Chapter 9 - Conclusion

The intraocular pressure sensor and smartphone apparatus are novel technologies that could become important in treatment monitoring of glaucoma. Due to the device’s ease of use, it can provide a more accessible means of monitoring intraocular pressure.

Ideal future iterations would implement greater modularity to the apparatus-smartphone connection. By designing various builds that cater to different smartphones, the end user demographic would increase. This could be done by using a clip like anchoring device, a magnetic hold, or some other fastening method.

We also hope that future iterations will capture more consistent images. This could be improved by utilizing a camera app that was designed specifically for the IOP sensor by two Santa Clara University students for their computer engineering design project. Upon uniting the app with our device, we could potentially increase the resolution and quality of our images. More consistent images could also be attained by improving on the overall design of the device. The chassis could fit together more snuggly and the snap fits could keep the chassis from separating (causing light to seep out through the cracks and adding glare to the image). Furthermore, the 3D printed design could be improved by making the channel holding the fiber optic cable fit snuggly around it in order to stop extra and unwanted light from the flash from distorting the image.

Finally, in order to improve on image quality, the overall dispersion system could be improved. While the solutions using acrylic helped mediate the hotspot problem to some degree, most images either had a bright spot, or were too dark to be read. Future designs could improve upon this by using different dispersion methods or even by using different illumination methods (i.e.: external light sources or a CCD).

We firmly believe that our designed device serves as a viable proof of concept for the ultimate usage of the microfluidic sensor technology. While some results proved to be inconsistent, there is significant reason to believe that future improvements and modifications to the design could yield very consistent results.
Bibliography


Appendix 1 - Drawings and Solidworks Design

Generation II Solidworks design. All units are in mm.
Generation IV Solidworks design. All units are in mm.
Generation V Solidworks design. All units are in mm.
Appendix 2 - Funding Proposal

TEAM CONTACT INFORMATION

<table>
<thead>
<tr>
<th>NAME</th>
<th>EMAIL</th>
<th>DISCIPLINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gino Castillo (Primary Contact)</td>
<td><a href="mailto:gacastillo@scu.edu">gacastillo@scu.edu</a></td>
<td>Bioengineering</td>
</tr>
<tr>
<td>Chris Gaines</td>
<td><a href="mailto:cgaines@scu.edu">cgaines@scu.edu</a></td>
<td>Bioengineering</td>
</tr>
<tr>
<td>Josh Godfrey</td>
<td><a href="mailto:jlgodfrey@scu.edu">jlgodfrey@scu.edu</a></td>
<td>Bioengineering</td>
</tr>
<tr>
<td>Michael Zhao</td>
<td><a href="mailto:mszhao@scu.edu">mszhao@scu.edu</a></td>
<td>Bioengineering</td>
</tr>
</tbody>
</table>

FACULTY ADVISOR

<table>
<thead>
<tr>
<th>NAME</th>
<th>EMAIL</th>
<th>DISCIPLINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. Emre Araci</td>
<td><a href="mailto:iaraci@scu.edu">iaraci@scu.edu</a></td>
<td>Bioengineering</td>
</tr>
</tbody>
</table>

PROJECT DESCRIPTION

Abnormal intraocular pressure (IOP) is often an indicator of glaucoma, a disease that affects more than 65 million people worldwide. Early detection of pressure differences in the eyes may save the vision of the patient. A microfluidic sensor that is implanted into the eye after cataract surgery allows for actual pressure measurement. IOP is known to fluctuate throughout the day and thus an infrequent visit to the optometrist will not suffice. We are developing a 3D printed imaging apparatus that will attach to the camera of a smartphone which can be used by patients with the implanted sensor for IOP self-monitoring. The design involves a product that will latch onto the user’s smartphone and thus the smartphone’s camera. The device will have a cylindrical shape in addition to a stand that will position the user’s head so that the camera will be aimed at the pupil.

Our product will utilize comprehension of the eye’s biological behaviors and physical aspects of lights and lenses. The pupillary response to light causes relaxation of the iris dilator muscle resulting in the iris constricting. The cylindrical camera add-on of our product will block light so that the pupil’s response is to dilate in order to let more light into the eye. LEDs integrated into the cylindrical apparatus will turn on once a picture is taken so that illumination is sufficient yet allows the pupil to retain its dilated state. The other important segment is the lens which allows for maximum angle of view and magnification once the picture is captured. Focal length will be integral in the design and position of the lens.
This project ties into the SCU Engineering Mission Statement as this is a product that will be applicable in the real world. It will help early detection of glaucoma as well as monitoring the disease which will ultimately be useful for patient care and the study of the glaucoma.

**BUDGET BREAKDOWN**

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Price/Unit ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDMS</td>
<td>0.5 gal</td>
<td>700</td>
</tr>
<tr>
<td>Silicon Wafers for Mold</td>
<td>10 wafers</td>
<td>30</td>
</tr>
<tr>
<td>3D Printing Service</td>
<td>5-10 iterations</td>
<td>100</td>
</tr>
<tr>
<td>Lens</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>Fiber Optic Cables</td>
<td>5 m</td>
<td>17</td>
</tr>
<tr>
<td>Light Couplers</td>
<td>2</td>
<td>110</td>
</tr>
<tr>
<td>iPhone 5</td>
<td>1</td>
<td>300</td>
</tr>
</tbody>
</table>

**Total:** 2305
## Appendix 3 - Bill of Materials

<table>
<thead>
<tr>
<th>Item</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>LB1092</td>
<td>$23.70</td>
</tr>
<tr>
<td>LB1450</td>
<td>$23.40</td>
</tr>
<tr>
<td>LB1014</td>
<td>$21.70</td>
</tr>
<tr>
<td>LB1761</td>
<td>$25.90</td>
</tr>
<tr>
<td>LMR05</td>
<td>$15.02</td>
</tr>
<tr>
<td>LMR1</td>
<td>$15.23</td>
</tr>
<tr>
<td>iPhone 5</td>
<td>$160.00</td>
</tr>
<tr>
<td>Custom Fiber Optics Cable</td>
<td>$104.45</td>
</tr>
<tr>
<td>CFC-2X-A FC/PC Connector</td>
<td>$236.00</td>
</tr>
<tr>
<td>VC1</td>
<td>$38.90</td>
</tr>
<tr>
<td>VC3</td>
<td>$37.10</td>
</tr>
<tr>
<td>HW-KIT1 9-32 Screw and Hardware Kit</td>
<td>$55.20</td>
</tr>
<tr>
<td>UPH2 Post Holder</td>
<td>$119.20</td>
</tr>
<tr>
<td>TR2-P5</td>
<td>$23.36</td>
</tr>
<tr>
<td>TR3-P5</td>
<td>$24.39</td>
</tr>
<tr>
<td>TR3T</td>
<td>$16.00</td>
</tr>
<tr>
<td>TR3C</td>
<td>$16.00</td>
</tr>
<tr>
<td>RA90</td>
<td>$9.76</td>
</tr>
<tr>
<td>RA45</td>
<td>$11.60</td>
</tr>
<tr>
<td>SWC</td>
<td>$22.60</td>
</tr>
<tr>
<td>RP01</td>
<td>$91.70</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td><strong>$1091.21</strong></td>
</tr>
</tbody>
</table>