FILE>PRINT>OPTICAL LENSES

by Katie Boeskool and Luigi Greco

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May, 2014

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Doctor of Optometry Senior Paper

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Doctoral Candidate(s)

March 13 2015

Date

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by

Katie Boeskool and Luigi Greco

This paper is submitted in partial fulfillment of the

requirements for the degree of

Doctor of Optometry

Ferris State University
Michigan College of Optometry
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Abstract

Background: *Three dimensional, or 3D, printing continues to grow as an innovative plastics manufacturing process, with customizability and convenience as strong points. 3D printed ophthalmic frames have been created recently, but development of printed optical lenses has seen less progress. The purpose of this research is to explore the process of designing and printing an optical lens, and analysing its optical parameters and quality.* **Methods:** *The goal of this project is to design a lens in a 3D modeling program, and have that lens printed in a suitable material for ophthalmic use. Printed lenses will be quantitatively and qualitatively compared to CR-39 lenses of the same power. Lens powers compared will include: plano, +2.00, +5.00, +10.00, -2.00, -5.00 and -10.00.* **Results:** *Test parameters for each lens will include: a qualitative investigation of overall quality (with potential aid from an arc lamp as well as an MTF grid), analysis of quality using the Rotlex© Class Plus lens analyser, lensometer power verification as well as mire quality determination.* **Conclusions***: Admittedly, the quality of lenses produced from 3D printing will not be superior to traditional lens techniques. Therefore, current applications may include use as temporary lenses for patients to trial prism or a unique spectacle Rx. However, the clinical impacts of this research may be more applicable in the near future as printing resolution and quality increases, and use as everyday ophthalmic lenses may become a reality.*

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CHAPTER 1

A BRIEF HISTORY OF OPTICAL LENSES

The origin of the word “lens”, is a testament to the original lentil shaped objects constructed by ancient cultures for various purposes. Some of the oldest lenses date back 2700 years ago, and experts propose the lenses were used as magnifying lenses for starting fires or even cauterizing wounds.[1] Written records of lenses in Ancient Greece support this theory by mentioning “burning-glass” - a biconvex lens used to focus the sun's rays to produce fire.[1] Archeological evidence indicates that there was widespread use of lenses in antiquity, spanning several millennia.

Excavations in Sweden in 1999 discovered Viking lenses made from rock crystal, produced by turning on pole lathes in the 11th to 12th century.[1] The earliest use of lenses for aided human vision date between the 11th and 13th century, when monks used plano-convex lenses for reading. These lenses were made by cutting a glass sphere in half.[2]

Lenses came into widespread use in Europe with the invention of spectacles, presumably in Italy in the 1280s. This was the start of the optical industry of grinding and polishing lenses for spectacles. During this time, and for many years to follow, lenses were primarily made of glass or glass mixed with various elements to control physical and optical lens quality. As plastics technology increased, lens manufactures began experimenting with plastic as a source for optical lenses. Today plastics and various polymers are the most common lens materials in use including CR-39®, polycarbonate and Trivex®.

The one thing that all lenses have in common, from today all the way back 2700 years ago, is the way they are manufactured. Essentially, all lens manufacturing is a 'subtractive' method. In other words, lenses are made by removing material from a larger object, and what is left behind is the final product, or the lens. Ancient humans found pieces of quartz, or gems that could be slowly polished into rough lens shapes. Later pieces of glass were formed into blanks, which could be ground or polished into lenses. Currently plastic lenses are made from cylinders of clear plastic, called blanks, which require lathing to be used for ophthalmic purposes. Although the overall process is a subtractive one, the formation of plastic blanks involves an initial injection molding step.

With the advent of 3D printing, there is now an opportunity to create lenses through an additive method. Rather than removing material, 3D printers can extrude, deposit or photo-cure a substance onto a print bed and form an object from nothing. This paper will not go into great detail on the process of 3D printing, but a simple analogy can be drawn between 3D printing and traditional "2D" printing. When a document, such as this report, is printed to paper, the printer is directed by software to lay down a thin layer of ink (or toner) in the precise locations on the paper to form words or images. In 3D printing melted plastic, rather than ink, is laid down on a printing platform (rather than paper). As the first layer dries, the printer proceeds to lay down another layer of plastic onto the previous layer. Eventually the hundreds or thousands of thin layers add up to make a physical, three dimensional object. Theoretically, 3D printing can take raw materials directly to the finished product with no processing or refining steps in between.

In this study we design and manufacture (print) clear optical lenses, and compare the quality of additive method lenses to traditional subtractive method lenses. Lenses will be created using software and hardware that is readily available for any optometrist/optician, and would have a minimal physical and monetary footprint in a practice. Furthermore, the feasibility and advantages to creating lenses using 3D printing will be evaluated in this project.

CHAPTER 2

METHODS

Lens Design and Manufacturing

The primary goal of lens creation was to follow parameters typically used in standard CR-39 lens blank creation. The secondary goal with lens creation was to use software and hardware that are easily available and practical for most optometrists.

Lenses were designed with powers of -2.00, -5.00 and -10.00 diopter sphere and +2.00, +5.00, and +10.00 diopter sphere. Lens designs will follow base curve standards used with CR-39 lenses, and overall try to mimic the final shape of CR-39 lenses.[3] Final base curves, and other lens dimensions are available in table 1 (thicknesses in table define post polishing dimensions.)

Lens Power	Front Base Curve	Back Base Curve	Center Thickness (mm)	Edge Thickness (mm)	Diameter (mm)
+2.00	+6.00	-4.00	3.11	1.00	65
+5.00	+8.00	-3.00	6.28	1.00	65
+10.00	+8.00	+2.00	11.56	1.00	65
-2.00	+6.00	-8.00	2.00	4.11	65
-5.00	+2.50	-7.5	2.00	7.28	65
-10.00	+0.50	-10.5	2.00	12.56	65

Table 1: Planned lens parameters

3D modelling of the lenses was done using DesignSpark Mechanical powered by Spaceclaim Corporation, a free computer modelling program, and exported at the highest quality setting as .stl files (stereolithography file format, created by 3D Systems™) for printing.[4] Commands are sent to the printer using a separate software, PreForm by FormLabs™.

Printing in transparent or translucent materials is less popular in 3D printing than opaque materials. The print material chosen for the lenses was a clear liquid resin which becomes solid via stereo lithography using laser curing. The resin is comprised of methacrylated oligomers, methacrylated monomers, and photoinitiators. Detailed information about the resins physical properties list an index of refraction of 1.513 to 1.515 in its liquid state.[5] No information could be obtained about the materials index in its solid state. The final index is assumed to be near the initial index, and furthermore the small change in index will have a minimal effect on the final lens power. The printer used to achieve this was the Form1+ printer made by Formlabs.[6] The physical dimension of the printer itself is 30 × 28 × 45 cm, or about the size of a desktop laser printer. This small footprint makes it a suitable choice for a printer that could potentially be in an optometrist's office. An additional step that uses traditional optical lab techniques will be lens polishing using a Satisloh Toro-X-2S lens polisher, with base curve polishing heads matching those of the printed lenses.

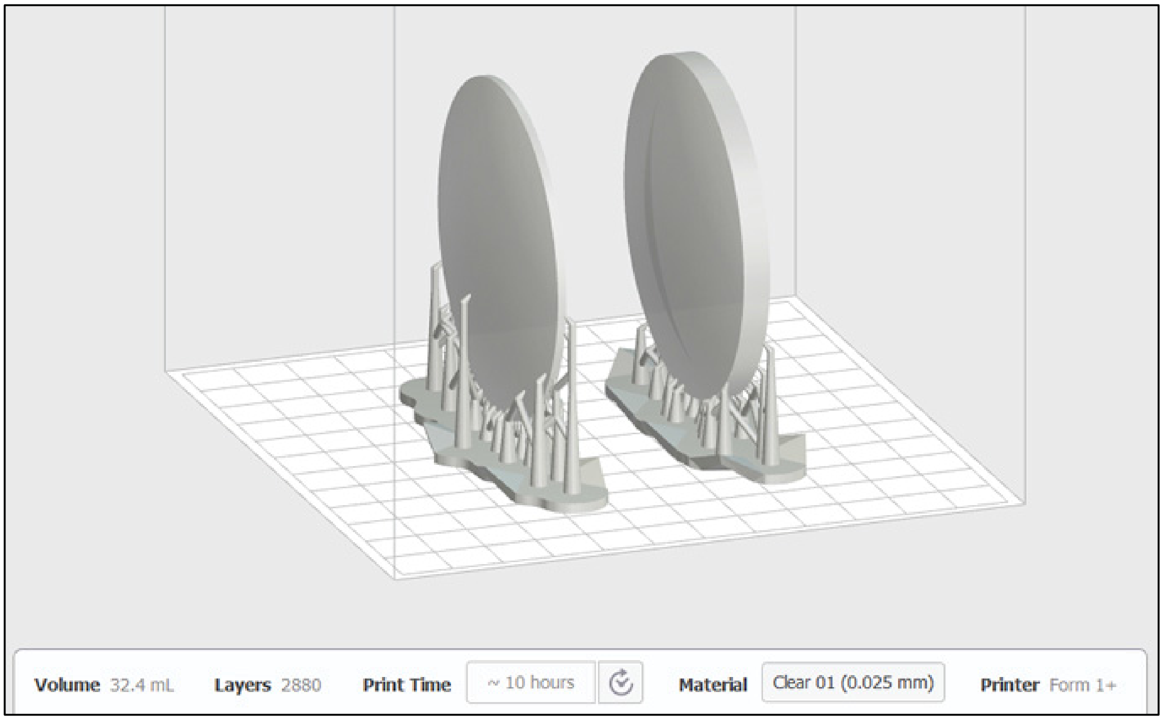

Figure 1: PreForm software showing +2.00D and -2.00D lenses with generated supports for printing.

Qualitative analyses

Printed lenses were tested for optical quality in both their raw and polished form. Using a specially designed printed pattern as a backdrop, digital photos of each lens were acquired. Similarly, this technique was carried out with the CR-39 lenses. These images allow for evaluation and comparison of aberrations, distortion, magnification, and minification. Also, lens optical quality comparison will be achieved using the Rotlex© Class Plus lens analyzer on the printed lenses, CR-39 lenses. Furthermore, mire quality during lensometry will also be photo documented for evaluation of the polished lenses.

Quantitative analyses

Lens power accuracy will be assessed for each lens type. This is the only chosen lens parameter that can be assessed quantitatively, and dioptric powers will be acquired via lensometry and the Rotlex© Class Plus analysis.

CHAPTER 3

RESULTS

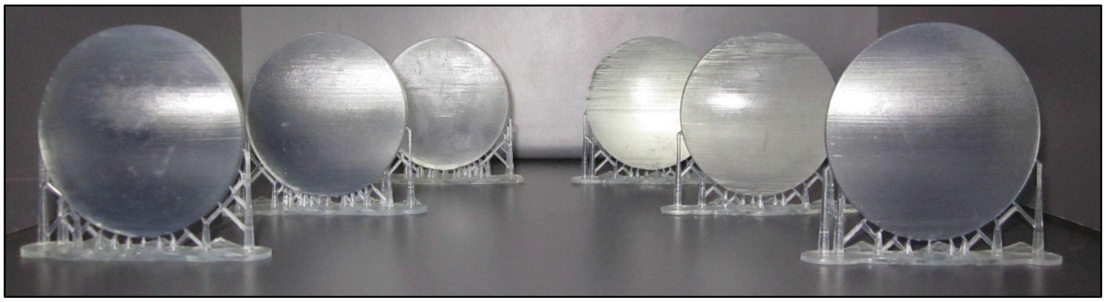

Figure 2: Unpolished printed lenses front face. Left to right: -2.00D, -5.00, -10.00, +2.00, +5.00, +10.00.

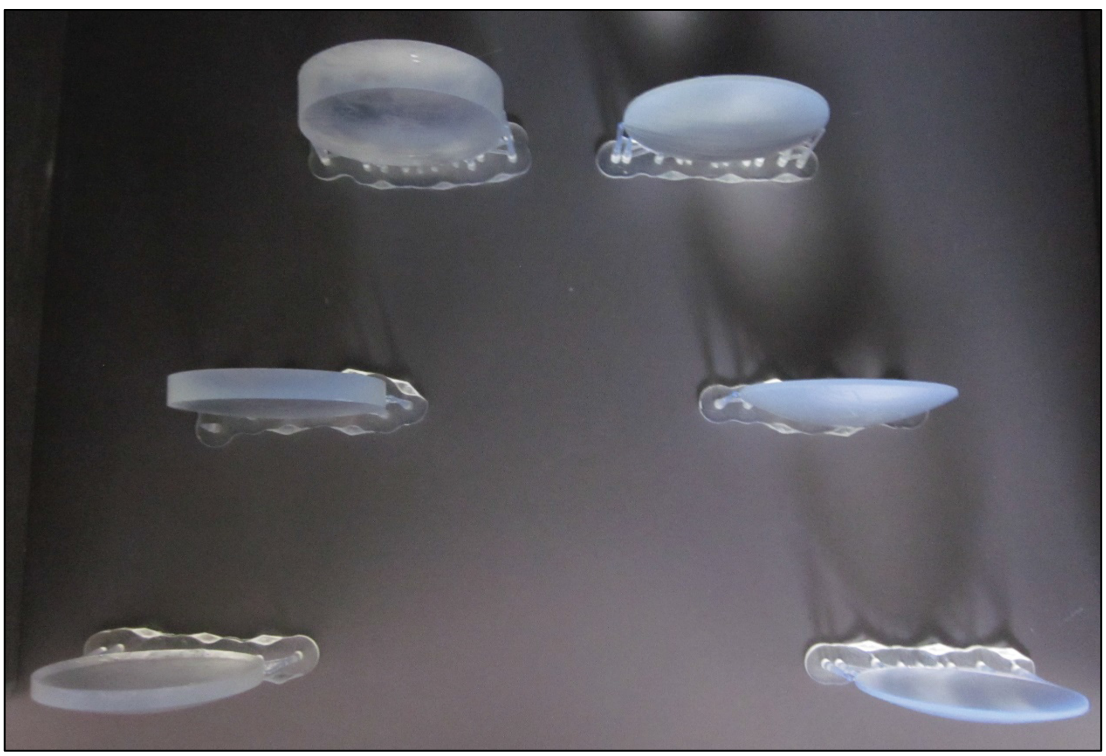

Figure 3: Unpolished printed lenses top view. Left to right: -2.00D, -5.00D, -10.00D, +2.00D, +5.00D, +10.00D.

Lens Polishing Foreword

Using Satisloh Toro-X-2S lens polisher for the 3D printed lenses was not successful for most lenses. The Toro-X-2S at our disposal was normally used to polish only the back (concave) side of lenses, since the front side came pre-polished from the factory. Attempts were made to polish the front (convex) side of the lenses but two major limitations were discovered: the wax blocking system used to hold the lenses doesn't work well with steep concave surfaces, and the polisher struggled to keep convex surfaces centered on the polishing head. In order to minimize the chance of permanent damage to the facilities Toro-X-2S, only the +2.00 printed lens was polished with the machine (along with initial hand polishing.) Therefore this hinders some potential analysis and calculations so there will be a focus on the +2.00 lens. Furthermore, for safety purposes only the central portion of the +2.00 lens was able to be polished, which will be evident in the preceding photos.

Qualitative Analyses

Printed lens quality in the raw state is substantially worse than the comparable CR-39 lens. Trace minification and magnification can be seen in the lenses, especially the higher diopter lenses. Striations in the lenses created by the lasers linear path during the printing process are evident in Figure 4, which depicts the unpolished -10.00 and +10.00

lenses. This appearance was consistent across all unpolished lenses and the greater dioptric magnitude lenses exemplify the gross minification and magnification the best.

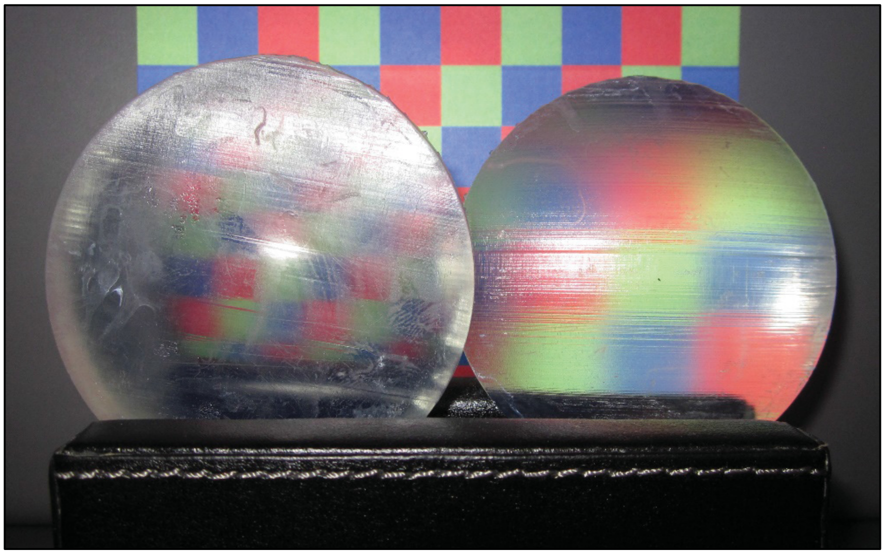

Figure 4: Unpolished printed lenses front view with RGB grid behind. Left to right -10.00D and +10.00.

Initially there was uncertainty about whether or not the striations seen in the lenses were only surface imperfections or in fact full thickness defects. However, polishing the surfaces revealed that the striations were in fact superficial, and in turn lens clarity was substantially improved as evident in Figures 5 and 6(a). Figure 7 is a great example of the dichotomy between surfaces on a semi-polished lens – note the reflectivity of the polished surface. Final lens parameters for the polished +2.00 lens were as follows: front base curve average of +6.50D, back base average curve of +4.37, and a center thickness of 2.7mm.

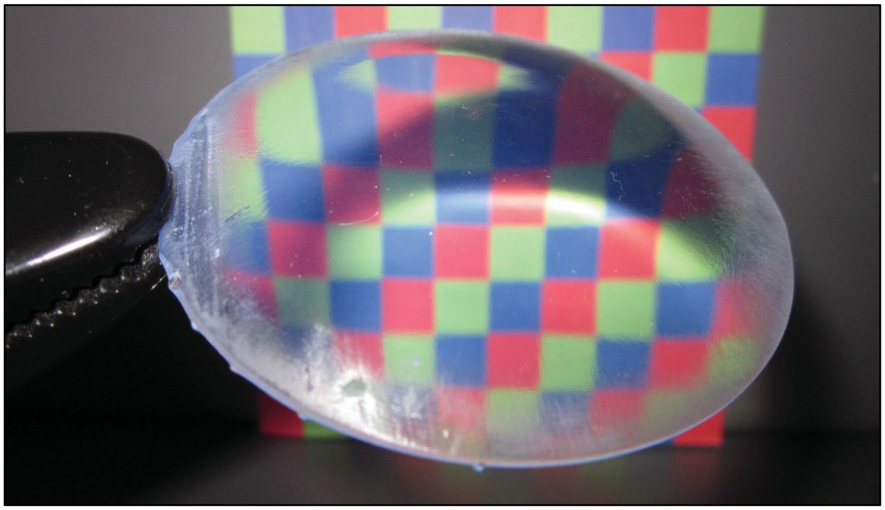

Figure 5: Polished printed +2.00 lens. Note the appearance the unpolished periphery and orange peel post polishing.

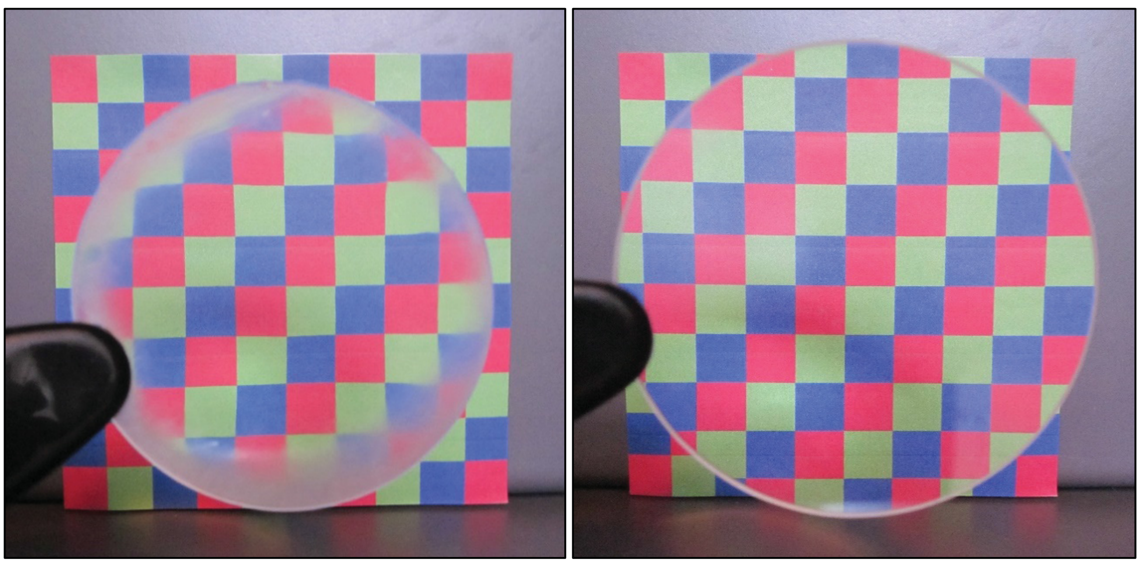

Figure 6: (a) Polished printed +2.00D on the left, (b) CR-39 +2.00D lens on the right, both with RGB grid behind.

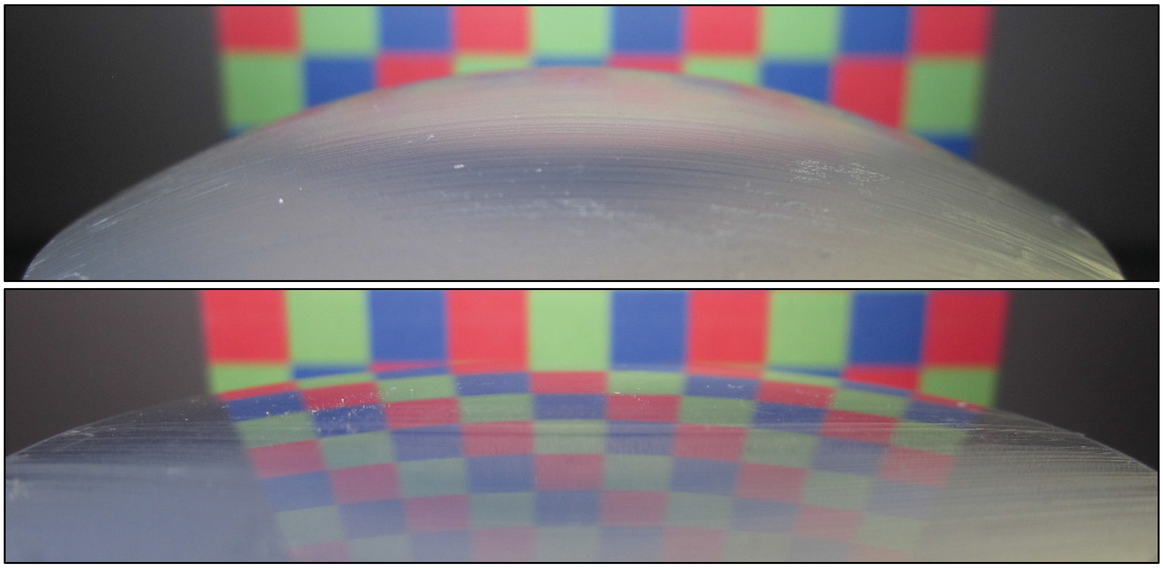

Figure 7: (Top) Unpolished front surface of the printed +10.00D lens. (Bottom) Polished surface of the same lens.

Rotlex Class Plus

The Rotlex Class Plus analyzer is able to topographically map the power and distortion of lenses in high resolution, allowing for comparison between the 3D printed and CR-39 lenses. The raw lenses have a varied and sporadic lens pattern and the Rotlex was unable to accurately determine the power of raw lenses. Because of this Rotlex images of unpolished lenses have been omitted, except for the +2.00D lens. The analysis of the unpolished +2.00D lens seen in Figure 8 is similar to all other printed lenses. Interestingly, the polished +2.00D analysis, Figure 9, shows a similar power and distortion map as the unpolished analysis, but the dioptric power calculation is much more accurate. A faint mid-peripheral ring is present. In the polished lens which presumably correlates with the transition zone from polished center to unpolished periphery.

The CR-39 lens (Figure 10) shows a fairly uniform sphere pattern, along with a distortion map that was very stable. The majority of distortion in the CR-39 lens is only evident in the periphery of the lens.

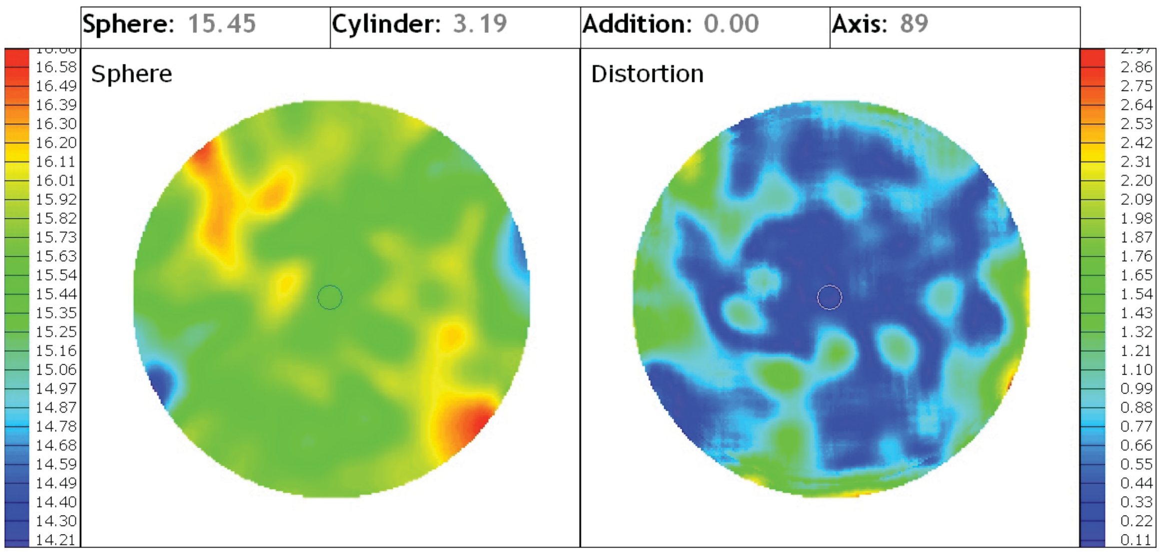

Figure 8: Rotlex analysis of the unpolished printed +2.00D lens.

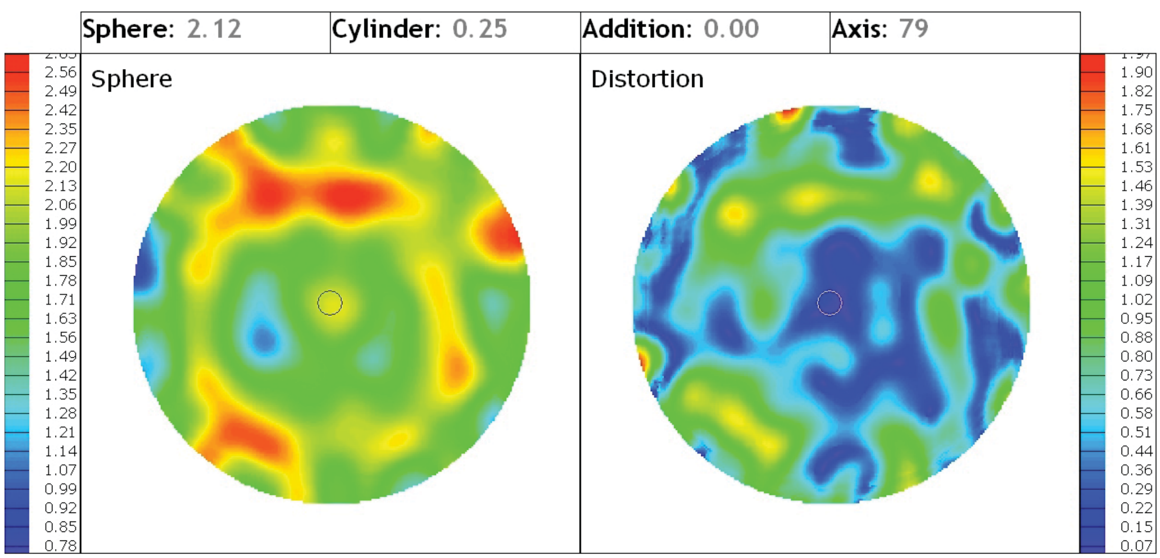

Figure 9: Rotlex analysis of the polished printed +2.00D lens. A faint mid-peripheral ring is present.

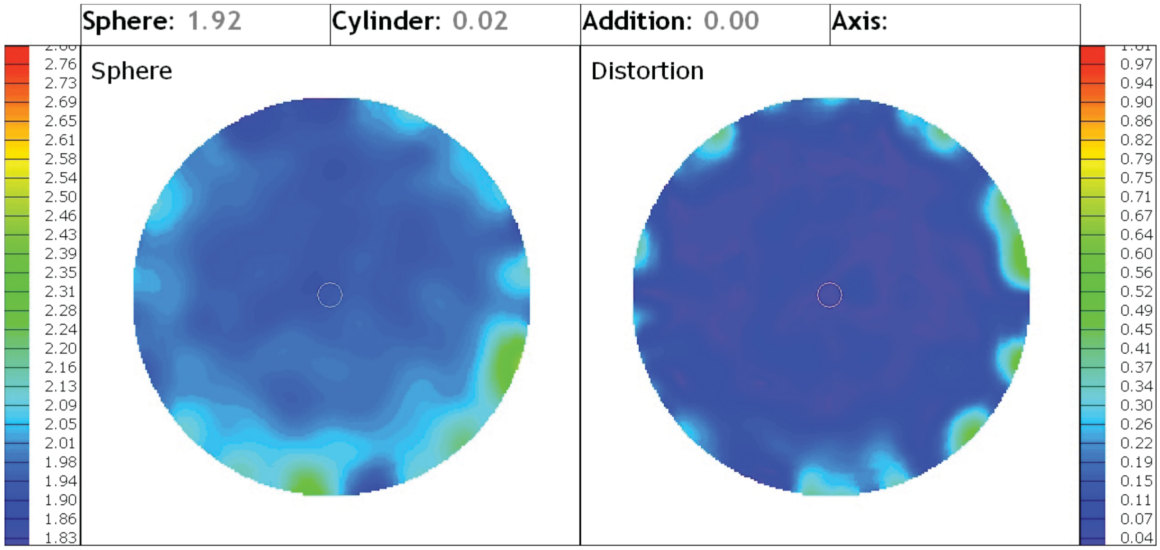

Figure 10: Rotlex analysis of the CR-39 +2.00D lens.

Quantative Analysis

Lensometer

Once again the raw lenses were of a quality too low to be analyzed by the lensometer - mires could not be focused enough to even estimate the power of the lenses. Power verification was drastically improved with the polished lens. The intended +2.00D 3D printed lens had a final power via lensometry of +2.125 diopters, with signs of mild mire defocus. This mild mire defocus is difficult to view in Figure 11 via lensometer photography, and is more appreciable during live lensometer reading. The comparable +2.00D CR-39 lens via lensometry revealed a dioptric value of +2.00, with flawless mire quality.

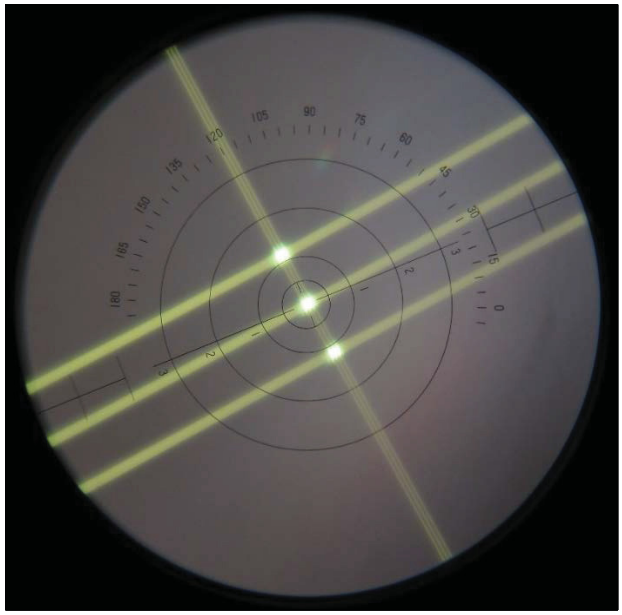

Figure 11: Mire quality of the polished +2.00 lens.

Rotlex Class Plus

The Rotlex was unable to accurately determine the power of raw lenses, but succeeded with the polished +2.00D lens and CR-39 lenses. The polished lens desired power was +2.00 sphere and the resulting power was +2.12 with -0.25 cylinder, axis 79. Considering spherical equivalent, the power would be +2.005, a difference of -0.005D from the goal. By contrast the unpolished lens was determined to have a spherical equivalent power of +13.855, a difference of +11.855D from expected.

Expected Power	Sphere Power	Cylinder Power	Axis	Spherical Equivalent	Difference from expected
2.00	15.45	3.19	89	13.855	11.855
5.00	13.51	1.28	88	12.87	7.87
10.00	19.35	3.1	75	17.8	7.8
-2.00	11.92	4.32	104	9.76	11.76
-5.00	10.88	3.09	90	9.335	14.335
-10.00	7.47	0.86	94	7.04	17.04

Table 2: Raw lens Rotlex Class Plus power analysis.

CHAPTER 4

DISCUSSION

Although 3D printing, or additive manufacturing, has been around for close to 30 years its popularity and introduction into home or office use is still very much in its infancy. From the onset of this project it was almost certain that optical quality would not be up to par with current lens manufacturing techniques, and so the main goal was to investigate how close the quality could get. The best case scenario would be an optically clear final lens that would not require polishing, but this goal was overly ambitious.

An analogy can be made between 3D printing quality and television technology (and surely other devices). When a technology is new, a proof of concept may be a sufficient start. As interest in the technology increases, research and development into that area also increases. In the television analogy, advancements in image resolution has been one of the key goals in development year over year. This same logic can be applied to 3D printing, where print resolution could be a factor to improve on, and theoretically in the future print quality could be high enough that optical lenses would need very little to no polishing. However it may remain that lens polishing is an unavoidable necessity in lens manufacturing. That said, advancements or alterations in polishing equipment may be necessary to cater specifically to needs set by 3D printed lenses.

Polishing aside, there is a more important question for 3D printing lenses. What is the advantage to providers, and consumers, over traditional lens manufacturing? Is 3D printing simply a novelty? Beginning with consumers of ophthalmic products, the list of advantages would be more focused and less apparent than regard to providers. Lower costs, quicker turnaround time, and acceptable lens quality would be the main focus for consumers. The printer used in this study can print a pair of lenses in around ten hours, and currently some labs offer 1-hour service, although the 1 hour time is for the final stages of lens processing, and does not include the manufacturing time the lenses went through in entirety.

The list of advantages for providers is much longer, likely uncountable at this time, and the examples that follow are not exhaustive. Overhead costs (both monetary and physical space) could be lowered using 3D printing of lenses. Rather than stocking hundreds of lenses blanks or molds in varying powers and sizes, an optometrist would only need to stock containers of liquid resin. The resin is universal to any combination of lens power, style, and size. Furthermore, the footprint of lab machines could be greatly reduced. A desktop 3D printer would print the lens in its near final product (barring polishing), it could even print the lens in the final shape need for the frame, eliminating the frame tracer. This would cut down on the number of processing machines needed and size of machines. The most important thing to address is the cost of individual lenses. At the current price of resin, the average price of the lenses printed in this project was $3.00 USD (estimated at the current price of $150.00 USD per 1L of resin[6].) However, as stated previously, a lens could be printed to the exact shape needed to fit the frame. This cuts down on wasted material in the shaping process, saving money for the provider. Also, as the popularity of resin based printing increases, we could see the price of resin drop well below the $100.00 per 1L range.

Possibly the greatest advantage to owning a 3D printer as an eye care provider, somewhat removed from the focus of this project, is the ability to use the printer for creating objects other than traditional lenses. The opportunity exists to print new frame temples or fronts for patients whose spectacles have broken. Creating prism lenses for patient trial at a lower cost and higher quality than Fresnel stick-on lenses may be a real possibility. The ability to custom print almost any object could impact the full scope of eye care. Pediatrics, low vision, contact lenses and even ocular disease could benefit from the dynamics of 3D printing. One could imagine a community, or repository of 3D object files designed by optometrists and shared within the profession to better serve patients. The concept of downloading a pre-designed +/- lens flipper to accommodate a pediatric patients need, or clicking print on a contact fundus lens for evaluation of an elderly patients retina, is a very tantalizing one. Overall 3D printing in eye care, and specifically lenses for ophthalmic use, is very much in its infancy and the clinical impacts of this research may be more applicable in the near future as printing resolution and quality increases.

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