The Development of an Orbital Prosthesis Workflow
Using Advanced Digital Technologies

by
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ABSTRACT

People born with congenital differences, victims of traumatic accidents, and cancer patients can benefit from custom facial prosthetics. These custom silicone devices are usually handmade by an anaplastologist using traditional techniques such as impression-making, sculpting, mold-making, and casting. In contrast with traditional techniques, this research investigates a novel workflow for creating a combined silicone orbital and acrylic ocular prosthesis that fulfills the impression, sculpting, and mold-making phases entirely by utilizing advanced digital technologies. This research investigates and documents several key technological processes including: the 3D capture of normal facial anatomy using digital photography and photogrammetry software; the laser scanning of a stone exenterated orbit; digital sculpting for mirroring and adaptation of the unaffected eye over the affected eye; creating a 3D 3-piece mold; and 3D printing a mold that can be used to produce a final, traditional silicone orbital prosthesis and acrylic ocular prosthesis. The project provided an opportunity to explore potential future workflows and to evaluate the efficacy of using advanced technologies new to the field of anaplastology. This research identified several unique challenges to the capture and replication of a 3D eye form in order to create a digital prosthesis. The documented workflow proposes several possible solutions integral to the results obtained in this project.

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# TABLE OF CONTENTS

Abstract................................................................................................................................. ii
Acknowledgements............................................................................................................... iii
Table of Contents................................................................................................................... v
Index of Tables and Figures.................................................................................................... vi

## Introduction...................................................................................................................... 1
   Background....................................................................................................................... 1
   Technological Background.............................................................................................. 5

## Materials and Methods..................................................................................................... 13
   Creation of Normalized Eye Model and Wax Pattern....................................................... 13
   Image Capture Via Photogrammetry............................................................................... 16
   Skin Texture Optimization.............................................................................................. 18
   Digital Production of an Orbital Prosthesis...................................................................... 18
   Digitally Designing a 3-Piece Mold................................................................................ 24
   Testing and Ordering 3D Printed Mold........................................................................... 29
   Traditional Casting of Orbital Prosthesis........................................................................ 30
   Ocular Prosthesis Production.......................................................................................... 36

## Results.............................................................................................................................. 43

## Discussion....................................................................................................................... 48
   Facial Capture Via Photogrammetry............................................................................... 48
   Digitally Sculpting and Adapting the Facial Data........................................................... 54
   Digitally Designing the 3D Mold.................................................................................... 54
   3D Printing the Digitally-Designed Mold....................................................................... 56
   Casting the Silicone Prosthesis...................................................................................... 62

## Conclusion....................................................................................................................... 63

## Appendix: List of Software and Hardware...................................................................... 64

References............................................................................................................................. 65
Vita........................................................................................................................................... 67
INDEX OF TABLES AND FIGURES

TABLES
Table 1 Standardized Measurements of a Human Eyeball.........................................................14
Table 2 Results of two silicone swatch cure tests on four 3D print materials.................................31

FIGURES
Fig. 1 Simulated patient with an orbital exenteration.................................................................2
Fig. 2 Digital Iris Buttons by Advanced Artificial Eyes..............................................................4
Fig. 3 Position of camera for each photograph taken.................................................................8
Fig. 4 Tie points.......................................................................................................................8
Fig. 5 Dense points comprising cloud......................................................................................8
Fig. 6 Mesh............................................................................................................................8
Fig. 7 Generated texture map...................................................................................................8
Fig. 8 Wireframe closeup..........................................................................................................9
Fig. 9 Wireframe extreme closeup............................................................................................9
Fig. 10 Polyjet Objet 260 Connex printer..................................................................................10
Fig. 11 Cross-sectional paths created in Adobe Illustrator......................................................14
Fig. 12 Cinema 4D model of eye..............................................................................................14
Fig. 13 Three locations in Cinema 4D where millimeter scale needed to be set.......................14
Fig. 14 Printrbot 3D printer printing eyeballs made in Maxon Cinema 4D.................................15
Fig. 15 3D prints of standardized eyeball shapes....................................................................15
Fig. 16 Melting Ivory wax.......................................................................................................15
Fig. 17 Wax casting of standardized eyeball shapes................................................................15
Fig. 18 Carving back side from wax eye shape with heated tools.............................................15
Fig. 19 Photogrammetry set-up..............................................................................................17
Figs. 20A and B Mascara eyelash treatment and other test materials..........................................17
Fig. 21 Photographs taken in five rows of four vertical heights (reuse of Fig. 3).......................17
Fig. 22 Image surface artifacts on 3D model created from photogrammetry...........................19
Fig. 23 Image surface artifacts closeup....................................................................................19
Fig. 24 Retopologized surface of 3D model with ZRemesher..................................................19
Fig. 25 3D model at a multi-million polygon resolution .............................................................. 19

Figs. 26A and B Unwrapped and corrected texture map image edited in Adobe Photoshop .......... 19

Figs. 27A, B and C Different views of final high resolution Facial Data ........................................ 21

Figs. 28A and B Laser scanned ocular prosthesis shape imported in ZBrush ............................... 21

Figs. 29A and B Orthostone model of exenterated orbit; Laser scanned

Exenterated Orbit Subtool appended and trimmed in ZBrush .................................................. 21

Figs. 30A and B Alignment of Extenterated Orbit and Facial Data Subtools ............................... 22

Fig. 31 Defining prosthesis margin using Slice Curve Brush ...................................................... 22

Fig. 32 Facial Data Subtool trimmed .......................................................................................... 22

Fig. 33 Orbit Subtool aligned with Facial Data Subtool ............................................................. 22

Fig. 34 Orbit Subtool trimmed ................................................................................................. 22

Fig. 35 Posterior surface of socket on Orbit Subtool smoothed .................................................. 23

Figs. 36A and B Alignment of ocular to the Facial Data Subtool .............................................. 23

Fig. 37 Intersection of Facial Data Subtool and Orbit Subtool edges ........................................ 23

Fig. 38 Potential holes in mesh if edges do not overlap before Dynamesh ................................. 23

Fig. 39 sPolish brush smoothing two unified surfaces .............................................................. 25

Fig. 40 Creation of texture brush using Adobe Photoshop ....................................................... 25

Fig. 41 Pore detail embossed on prosthesis edge ..................................................................... 25

Fig. 42 Ocular Subtool in place prior to Merge Down ............................................................... 25

Fig. 43 Finished orbital prosthesis 3D model ......................................................................... 25

Fig. 44 ZProject and Smooth Brushes used to adapt Posterior Mold Subtool to Orbit Subtool .... 26

Fig. 45 Edges of Posterior Mold Subtool raised above posterior

wall of Orbit Subtool using Alt-Move brush combination ....................................................... 26

Fig. 46 Three registration spheres appended and positioned to overlap Posterior Mold Subtool .. 26

Fig. 47 All three spheres removed with Boolean Subtract function ......................................... 26

Fig. 48 Ocular mold piece ........................................................................................................ 26

Fig. 49 Merged duplicate copies of Ocular Mold Piece, Orbital Prosthesis, and Posterior Mold Subtools ... 26

Fig. 50 Appended Cylinder Subtool scaled and positioned to overlap merged Subtool .......... 26

Fig. 51 Anterior mold piece after merged mold Subtool subtracted from Cylinder Subtool ........ 28

Fig. 52 Traditional mold with wax spacer to create overflow channel ...................................... 28

Fig. 53 Mask painted on Posterior Mold Subtool .................................................................... 28

Fig. 54 Masked area extracted to overlap Anterior and Posterior Mold Subtools .................... 28

vii
Fig. 55 Completed anterior mold piece ................................................................. 28
Fig. 56 Three platinum-based silicones used for material test .................................. 31
Fig. 57 Four 3D print material samples with silicone tests ........................................... 31
Fig. 58 Support resin residue removed from mold pieces ........................................... 32
Fig. 59 Polyester Parfilm release agent ...................................................................... 32
Fig. 60 M-511 silicone material and Human Coloration System .................................. 32
Fig. 61 Test silicone injected into mold ........................................................................ 32
Fig. 62 Mold closed ...................................................................................................... 33
Fig. 63 Mold clamped and ready for bench cure ......................................................... 33
Fig. 64 Bench cure test result ...................................................................................... 33
Fig. 65 Intrinsic silicone colors mixed ........................................................................ 33
Fig. 66 Silicone vacuum de-gassed ............................................................................. 35
Fig. 67 Intrinsic colors painted into mold ..................................................................... 35
Figs. 68A and B Fully-cured orbital prosthesis ............................................................ 35
Figs. 69A and B Extrinsic coloring supplies .................................................................. 35
Fig. 70 Sealed extrinsically painted orbital prosthesis ................................................... 37
Fig. 71 Incision made in upper eyelid (technique) ......................................................... 37
Fig. 72 Silicone adhesive injected into lid (technique) ............................................... 37
Figs. 73A and B Eyelash placed into eyelid (technique left, product right) .................. 37
Fig. 74 Ocular button trimmed to correct size ............................................................. 38
Fig. 75 Scleral acrylic materials ................................................................................. 38
Fig. 76 Wet-sand state of mixed acrylic ...................................................................... 38
Fig. 77 Scleral acrylic placed over ocular button .......................................................... 38
Fig. 78 Ocular button placed in mold ......................................................................... 38
Fig. 79 Trial packing sheet in place ............................................................................ 38
Fig. 80 Excess acrylic removed from edges of mold ................................................... 39
Fig. 81 Mold pressed .................................................................................................. 39
Fig. 82 Pressure cooker used for acrylic processing .................................................... 39
Fig. 83 Scleral acrylic with burred holes to guide grinding depth ............................... 39
Fig. 84 Scleral acrylic ground with hand piece ............................................................ 39
Fig. 85 External eye painting supplies ....................................................................... 41
Fig. 86 Painted ocular prosthesis ................................................................................. 41
Fig. 87 Clear acrylic cast over painted ocular prosthesis..................................................41
Fig. 88 Grinding and polishing burrs used (arranged from fine to course).................................41
Fig. 89 First polishing step with hand piece........................................................................41
Fig. 90 Second polishing step with lathe and pumice...............................................................42
Fig. 91 Third high-polish step on lathe, using rag wheel, and Fabulustre.................................42
Figs. 92A and B Ocular prosthesis in ZBrush.......................................................................44
Figs. 93A and B High resolution photogrammetry capture without and with texture map........44
Fig. 94 Closeup of high resolution skin detail........................................................................44
Fig. 95 3D file of laser scanned exenterated orbit..................................................................45
Fig. 96 3D orbital prosthesis made using ZBrush..................................................................45
Fig. 97 3D 3-piece Mold Subtools made using ZBrush..........................................................46
Fig. 98 3D print of 3-piece Mold using Objet 260 Connex 3D printer.....................................46
Fig. 99 Silicone orbital prosthesis made with M511 with an acrylic ocular prosthesis............47
Fig. 100 Posterior side of silicone orbital prosthesis...............................................................47
Fig. 101 Acrylic ocular prosthesis.........................................................................................47
Fig. 102 Vectra M3 System..................................................................................................49
Fig. 103 Six photographs with dense point cloud imported in ZBrush.................................49
Fig. 104 Completed model..................................................................................................49
Fig. 105 Model with texture................................................................................................49
Figs. 106A and B Comparison of mesh resolution between Vectra M3 (left) and Photoscan (right)........49
Fig. 107A Capture of fake eyelashes with paper attached.......................................................51
Fig. 108 Capture of fake eyelashes with silicone screen attached.........................................51
Fig. 109 Capture of eyelashes with no treatment (similar result with normal mascara).........51
Fig. 110 Capture of eyelashes pressed down and to the side with large amount of mascara straight from the container.................................................................51
Figs. 111A and B Mesh resulting from Artec Spider with flash option and smoothed to 0.15.......53
Figs. 112A and B Mesh and texture resulting from Artec Spider with flash option and smoothed to 0.15...53
Fig. 113 Mesh resulting from no flash option with Artec Spider............................................53
Fig. 114 Screenshot of production time for the High Quality print of the 3-piece Mold..........58
Figs. 115A and B Skin texture detail on digital file (left) compared to silicone prosthesis surface detail (right).............................................................................................................58
Fig. 116 Visible build lines on 3D printed mold.................................................................60
Fig. 117 Visible build lines on silicone prosthesis ................................................................. 60
Fig. 118 Pigment congregated in build lines ........................................................................ 60
Figs. 119A and B Level of detail in traditional orbital prosthesis vs. digitally-designed orbital prosthesis ................................................................. 61
Fig. 120 Prosthesis edge (right) placed against skin (left) for blending test ............................................. 61
INTRODUCTION

BACKGROUND

A NEED FOR ORBITAL PROSTHESES

Various aggressive cancers of the eyeball and surrounding tissues are treated with orbital exenteration surgery. The surgery is extensive and only performed when removing an eyeball (also called enucleation) is not enough to rid the patient of all cancerous cells (American Society of Ocularists 2015). While the surgery can also be performed for injuries and congenital differences, the majority is performed for cancers such as basal cell carcinoma, squamous cell carcinoma, or melanoma of the eyelid or periorcular tissue (Mahoney of Wilmer Eye Institute, e-mail message to author, September 24, 2015). There are only around five or less orbital exenterations performed per year by the Ophthalmology Department at the Johns Hopkins Wilmer Eye Institute, as compared to an estimated fifty to eighty enucleations per year (Mahoney of Wilmer Eye Institute, e-mail message to author, 2015). An exenterated orbit can result in many patients losing their self-identity, confidence, and ability to comfortably interact with their community.

Before seeing an anaplastologist to obtain a custom eye replacement, or orbital prosthesis, many patients will avoid leaving home or cover their exposed orbit with some form of eye patch. The goal of wearing an eye patch or custom orbital prosthesis is to cover and protect the site. Depending on the nature of the surgery, most often the patient is left with a closed off orbital cavity that is lined with a tissue graft (Fig. 1), although in some cases an open orbital cavity is left with a large amount of nasal mucosal tissues exposed. The goal of a well-made orbital prosthetic device is unique in that it not only addresses rehabilitation of the patient by comfortably covering, closing off and protecting the affected orbital site, but also restoring the appearance of missing anatomy, improving visual symmetry, and avoiding calling unnecessary attention to itself (The Johns Hopkins
Facial Prosthetics Clinic 2015). If the patient is a candidate for an orbital prosthetic device from a qualified provider such as an anaplastologist, quality of life can improve drastically.

Most eye prostheses that include the orbit and eyeball are created for patients using traditional impression, sculpting, and mold-making methods. The final silicone and acrylic end product needs to be made using materials that are biologically inert and produced in a manner that be safely worn in the socket over an extended period of time. These devices can either be retained using medical grade adhesives or via magnets attached to implants placed in the bony orbit. Depending on the chosen method for retention and the configuration of the affected site, the cost of an orbital prosthesis varies. According to the Centers for Medicare & Medicaid Services, the government agency that sets the costs for Medicare patients, the allowed amount for an orbital prosthesis in Maryland is $855, while that of an ocular prosthesis is $3,231 (Centers for Medicare & Medicaid Services 2015).

![Simulated patient with an orbital exenteration. In this example, resulting in the ideal of a deep, closed eye socket lined with a thin skin graft.](image)

**Fig. 1** Simulated patient with an orbital exenteration. In this example, resulting in the ideal of a deep, closed eye socket lined with a thin skin graft.
DIGITAL APPLICATION IN PROSTHETICS

Because of increases in the resolution of digital capturing devices, the ease of manipulating 3D digital datasets, and the ability to 3D print at a high resolution in a range of materials, there is an important opportunity to apply a new digital approach to creating facial prostheses. This research seeks to explore the potential for improvement upon the entirely traditional workflows currently in use.

Higher resolution prints, and the capability of printing a model comprised of various material types and colors, have expanded the range of use of 3D printing in specialized patient-centered applications. One example is the investigation by Fripp Design and Research (London, UK) and the University of Sheffield into producing facial prosthetics by infusing silicone into color 3D prints composed of a starch material (Fripp Design and Research 2014). Another example is The Cortex Exoskeleton™ produced by Evill (2015), which is a custom, immobilization cast 3D printed for patient injuries. Interest in developing digital solutions for prosthetics has also increased with the exponential growth of 3D printing technologies.

Several recent investigations involving 3D technologies have aimed at increasing patient access to prosthetics with reduced production costs and at investigating applications for modern technologies. A digital workflow similar to the one proposed in this thesis has been applied to the production of auricular and nasal prostheses. A laser scan and 3D printed wax pattern was utilized to create a stone mold that was subsequently used to cast a silicone prosthesis in two separate studies by Watson and Hatamleh (2014) for an auricular prosthesis, and Palousek, et al. (2013) for a nasal prosthesis. Additionally, a 3D printed mold based on photogrammetry has been investigated for the production of an auricular prosthesis (Reiffel, et al. 2013).
Recent digital developments surrounding the subject of ocular prostheses have included the mass production of premade ocular iris buttons based on photographs by Advanced Artificial Eyes™ (Tarzana, CA), as seen in Fig. 2, as well as 3D printing entire ocular prostheses (Strauss 2014). In either case, in order to achieve the highest quality ocular prostheses, a trained ocularist or anaplastologist is needed to ensure a correct fit in the fornix space behind existing eyelids. Within the ocularistry and anaplastology fields, professionals know that “An inappropriately sized [orbital] implant can result in superior sulcus deepening, enophthalmos, ptosis, ectropion, and lower lid laxity” (Amornvit, et al. 2014). Likewise, a properly fitted and finished ocular prosthesis is required if one is to avoid similar eyelid deformations. Therefore, it is theorized that if one were to begin the process with an eye form that is based on well established normal measurements, the end result would more closely match the shape of the original eyeball. The ocular prosthesis in this thesis was thus produced based on normalized data to have an accurate starting point, but it was also adapted to fit the simulated patient data for an unaffected eye.

Orbital prostheses have been previously developed using digital technology. A research team at the University of Miami, led by Dr. David Tse, recently developed such a workflow and its findings were presented at The American Academy of Ophthalmology annual conference in 2014 (Frelick 2014). While this report in a trade article mentions that the patient was 3D scanned and digital techniques were used to produce an injection molded rubber prosthesis, the details about this process were not released.

This thesis is by no means the first investigation into digital techniques applied to
making orbital prostheses, but it has some important contributions. These novel contributions include: removing the need for MRI or laser scanning of sensitive tissues by using photogrammetry for a facial capture; developing the orbital prosthesis shape from the photogrammetry capture using digital sculpting software; digitally designing a 3 piece mold for 3D printing; and developing a corresponding ocular prosthesis based on normalized data.

TECHNOLOGICAL BACKGROUND

TRADITIONAL METHODS

While the majority of this investigation is focused on digital innovation, there is a need to understand the traditional steps in prosthesis creation that have been replaced by digital means. A step-by-step outline of the production of an acrylic ocular prosthesis and the casting of a silicone orbital prosthesis will be addressed later on. Comprehensive descriptions of traditional facial prosthesis techniques are given by MacKinstry (1995) Fundamentals of Facial Prosthetics and Thomas (2006) The Art of Clinical Anaplastology.

A traditional approach to orbital prostheses begins by making a custom acrylic ocular prosthesis that fits within the silicone orbital prosthesis. The traditional process used to create the ocular prosthesis is the same process fully outlined in the Materials and Methods section of this study. The ocular is then incorporated into a wax pattern for an orbital prosthesis.

An orbital prosthesis typically begins by taking an alginate or silicone impression of a patient’s exenterated orbit (affected side). The impressions are then immediately filled with dental stone (orthostone) to create a stone model of the affected eye socket. Photographic images or the patient themselves are referenced to develop a wax pattern of the proposed orbital prosthesis. Typically, the anaplastologist sculpts the orbital prosthesis
while the patient is present to ensure proper alignment of the ocular prosthesis component and assess the accuracy of the sculpting and fit of the wax pattern on the affected area. The wax pattern is tested on the patient for comfort, fit, and good adaptation around potentially mobile areas of underlying skin. Finally, the impression mold is reduced to establish the adaptation and extent of very thin edges that help blend the prosthesis with the surrounding skin. Once the wax pattern is adapted onto the modified stone impression model (representing the posterior mold piece), orthostone is poured above the combined prosthesis pattern to create the anterior mold piece. Once the anterior mold piece is cured, the wax pattern is removed, and the ocular prosthesis is duplicated as the third piece of what is a 3-piece mold. The 3-piece orthostone mold can then be utilized to cast the final orbital prosthesis using the silicone of choice that is pre-tinted to match the patient’s skin color. Care is taken in selecting a biocompatible silicone, which maximizes physical properties of durometer (softness), tear strength, UV stability, inertness to perspiration, adhesive and cleaners, and other factors, as the prosthesis is used over an extended period.

The process described in this investigation seeks to implement a digital workflow for the impression, sculpting, and mold-making aspects of creating the orbital prosthesis.

PHOTOGRAMMETRY AS A MEANS OF CREATING A DIGITAL IMPRESSION

There are various ways of turning a physical object into a digital 3D file. Many different devices and equipment exist to capture 3D data, such as Computerized Tomography (CT) and Magnetic Resonance Imaging (MRI) used in the medical field; structured light scanners that project a known light pattern onto a surface and analyze the warping of the pattern to mathematically calculate the scanned surface (The MIT Center For Bits and Atoms 2010); 3D laser scanners that use a laser probe to measure a surface and generate a point cloud from which a 3D representation can be created with computer
software (Laser Design 2015); and both simultaneous and individual-shot image capture systems for use with photogrammetry.

Photogrammetry is a process by which a 3D model is generated based on a series of digital photographs taken around an object. There are various applications that can be utilized to generate the 3D models from digital photos such as: Autodesk® 123D Catch® (San Rafael, CA), Agisoft’s Photoscan™ (St. Petersburg, Russia), and proprietary applications specifically developed for capture systems such as for the Vectra M3 System™ by Canfield Scientific (Fairfield, NJ). Technically, many different types of digital cameras can be used with the various programs. This technology was ideal for the project due to the fact that taking photographs of a patient’s unaffected eye is much less invasive than radiation, bright shining light, rapid light modulations, and is also a more comfortable experience as most people are familiar with the technology.

Agisoft Photoscan and Hand-held Canon DSLR

The “digital impression” data used in this investigation were obtained using Canon DSLR cameras. After photographs are taken, .jpg files can be imported into the Agisoft Photoscan software. Photoscan works on the basis of analyzing a couple hundred pixels in each photograph. The pixels that the photographs have in common are called tie points. Overlapping tie points allow the software to identify the location of the camera relative to the photographed object (Fig. 3) as well as create a sparse point cloud, roughly representing the 3D object (Fig. 4). Next, a dense point cloud is generated using the camera positions and the pictures themselves (Fig. 5). The dense point cloud represents a series of points in x, y, and z space that describe the surface of the photographed object. The data are triangulated to create the 3D mesh or wireframe (Fig. 6). This process sets the resolution of the model. A texture map is then generated (Fig. 7) using the color information of the photographs. The texture map contains additional image data that may not be present in the 3D wireframe, as seen in Figs. 8 and 9. The result may then be
exported as a 3D .obj file (containing 2D UV color mapping information), as well as a separate texture map .jpg file.

Fig. 3 Position of camera for each photograph taken

Fig. 4 Tie points

Fig. 5 Dense points comprising cloud

Fig. 6 Mesh

Fig. 7 Generated texture map
ZBRUSH AS A MEANS OF DIGITAL SCULPTING AND MOLD-MAKING

The traditional production of facial prostheses requires an anaplastologist to finely sculpt the surface and shape of the prosthesis to match the patient. The sculpt is created in wax and includes very fine details such as pores and skin creases, as well as a very thin edge margin. Therefore, digital software that could replicate fine details such as these was needed in order to create a prosthesis digitally. Many 3D modeling programs add details to a model based on a texture map that, when rendered, reveal a high level of detail on a computer screen. However, the texture maps do not typically transform the actual surface of the model. Hence, this type of software would not result in a highly detailed surface that could be 3D printed.

Pixologic® ZBrush® (Los Angeles, CA) is a digital sculpting software that allows for a traditional sculptor’s approach to creating 3D models. Not only can a 3D shape be created, but also most of its functional capabilities are centered on manipulating the actual surface of the model. ZBrush was used in this study to establish a highly detailed skin surface from the photogrammetry capture, to produce a 3D orbital prosthesis, and to produce a 3D printable mold. The program is capable of the high level of surface detail needed for a facial prosthesis, and this project aimed to test the ease of producing a usable, highly detailed 3D mesh from photogrammetry data, and designing a 3D printable mold capable of casting a prosthesis with a thin edge margin. After the highly detailed mold pieces are created, 3D stereolithography (.stl) files can be exported from ZBrush for 3D printing.
3D PRINTING A MOLD

Not all 3D printers are alike. While many 3D print technologies can create a shape through an additive build process, the method of cure, 3D material type, resolution, cost of the printer, and speed of the print time can vary between machines. Some printers use light, whether Ultraviolet (UV), laser, or Electronic Beam Melting (EBM), in order to bind successive layers of the print material, while others rely on the combination of a two-part material that hardens (3D Printing from scratch 2015). The 3D print is made from a 3D .stl file, based on which, the printer lays down successive layers of material to create a model. The thickness of the layers depends on the resolution of the printer. In this study, a high-resolution printer was desired in order to reduce as much of the layered build line detail as possible, and reproduce a very detailed model.

This thesis focuses on Polyjet print technology developed by Stratasys® Ltd (Eden Prairie, MN). Polyjet 3D printers work on the basis of laying down material in the form of a liquid photopolymer that is cured using UV light. At the time of this reasearch, the highest resolution polyjet 3D printer available was the Objet 260™ Connex™ Printer (Fig. 10) with a resoltuion of 600x600x1600 DPI (x, y, z). In High Quality mode, the material is printed in successive 16-micron resolution layers to build a model, along with a FullCure 705 gel-like photopolymer support material that is removed after production (Anthony Francis of Stratasys, e-mail message to author, June 6, 2015).

Fig. 10 Polyjet Objet 260 Connex printer (Stratasys Ltd. 2015)
An object can either be printed directly in a positive form, or can be created by printing a multiple piece mold that can be used to cast the desired object in whatever material one wishes to use in the mold. In this study, the printing of the 3D mold allowed for the use of approved, biocompatible, platinum-based silicones for patient use. The 3D mold also allowed for multiple intrinsic colors to be present in the prosthesis, which would impart a more natural appearance than a prosthesis made from one solid silicone color. Presently, there is no technology that allows for a direct silicone print in multiple colors. Additionally, it was hypothesized that a thin prosthesis edge margin would be better obtained from a cast rather than the additive 3D printing process. Testing in this project addressed the compatibility of typically used platinum-based silicones with several Polyjet 3D print materials.
OBJECTIVES

The proposed objectives of this research were to:

1) Determine common morphometrics of the human eye, namely the radius of corneal and scleral spheres.
2) Create and print custom 3D model of an ocular shape based on measurements.
3) Determine technical considerations specific to obtaining a high resolution image capture of the eyeball and orbit using photogrammetry techniques.
4) Identify methods to digitally sculpt and adapt 3D scanned data that maintain and enhance fine skin pore level texture details of the skin surrounding the orbit, while dealing with undesirable data created by the transparent cornea and eyelashes.
5) Digitally design an orbital prosthesis with proper edge adaptation to a scan of an exenterated orbit.
6) Digitally design an ocular prosthesis that is registered to the orbital prosthesis and provides for registration of the iris button component.
7) Digitally design and 3D print a 3-piece mold from which to cast a silicone orbital prosthesis.
8) Produce a 3D-printed negative mold that is compatible with commonly used silicones for prosthetic applications.
9) Evaluate the replication of digitally captured pore texture, without introducing unwanted artifacts from the 3D printing build process.
10) Evaluate and critique the advantages and limitations of using an advanced 3D workflow.
11) Compare results to traditionally produced orbital and ocular prostheses.
MATERIALS AND METHODS

CREATION OF NORMALIZED EYE MODEL AND WAX PATTERN

A 3D model of an eyeball shape was constructed using Maxon™ Cinema 4D™ (Friedrichsdorf, Germany). To achieve this, standard measurements of the human eyeball were obtained from various sources (Table 1). An accurate cross-sectional drawing of an eye was created to scale (Fig. 11) using Adobe® Illustrator® (San Jose, CA). Half of the drawn paths were isolated and imported into Cinema 4D and made into a solid object using a Lathe Nurbs function (Fig. 12). A Mesh>Create Tools>Close Polygon Hole function was subsequently done to make sure the model was watertight.

To export in an accurate millimeter scale, it was important to set both the unit settings under preferences and the project settings to millimeters before setting the object scale (Fig. 13). By cropping the model at three varying distances posterior to the cornea (in front of the equator, at the equator, and behind the equator) three versions of the model were created. These models were subsequently 3D printed using the Simple Metal Printrbot™ 3D Printer (Lincoln, CA) (Fig. 14). Three models were thus printed (Fig. 15).

A silicone duplication mold was made of 3D print of the eye that was cropped behind the equator, using a two-part silicone putty. Ivory wax was then melted (Fig. 16) and cast in the silicone mold (Fig. 17). By carving out the backside from this, a wax positive pattern was created (Fig. 18). A post off of a corneal button was attached to the front of the wax pattern, and the medial side was widened. The wax pattern was then laser-scanned by Direct Dimensions and saved as a digital .obj file to be used later when designing the ocular prosthesis shape using ZBrush.
Table 1 Standardized Measurements of a Human Eyeball (Garcia 2015)

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<th>Anatomical Characteristic</th>
<th>Measurement in Millimeters</th>
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<td>Scleral circle radius</td>
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</tr>
<tr>
<td>Distance between scleral and corneal origins</td>
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<tr>
<td>Corneal Width (limbus diameter)</td>
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Fig. 11 Cross-sectional paths created in Adobe Illustrator

Fig. 12 Cinema 4D model of eye

Fig. 13 Three locations in Cinema 4D where millimeter scale needed to be set
Fig. 14 Printrbot 3D printer printing eyeballs made in Maxon Cinema 4D

Fig. 15 3D prints of standardized eyeball shapes

Fig. 16 Melting Ivory wax

Fig. 17 Wax casting of standardized eyeball shapes

Fig. 18 Carving back side from wax eye shape with heated tools
IMAGE CAPTURE VIA PHOTOGRAMMETRY

Photographs were used to create a 3D model of the simulated patient data. A set of photos was taken using the Canfield Vectra M3 image capture system located at Johns Hopkins Greenspring Station, Department of Otolaryngology, Facial Plastics Clinic (Lutherville, MD). While the set of photographs taken at Johns Hopkins using the Vectra M3 simultaneous image capture system yielded a lower mesh resolution than desired, it helped in determining optimization strategies to achieve better photogrammetry results around the eyelids. Five methods were tested to optimize capture around the eyelashes: fake eyelashes, natural eyelashes, fake eyelashes with a paper screen, fake eyelashes with a silicone screen, and lashes parted with mascara.

Dominic Albanese of Direct Dimensions (Owings Mills, MD) took two sets of photographs (Fig. 19). The first with a Canon D7100™ and the second with a Canon EOS Rebel T5i™ SLR camera, both sets with an aperture setting of F11 and a 1/125 shutter speed to obtain the best capture possible. Factors such as fixed bright lighting, a zoom macro lens, and distance from the face contributed to the quality of images obtained. The first set of photographs was taken without the five eyelash treatment methods described earlier. The second set was taken using these in an attempt to improve the potential data capture around the eyelids. Two adjustments were made to improve the data quality around the facial skin. L’oreal True Match™ liquid makeup was applied to the skin surface, and the eyelashes were pressed together and to the sides using a thick coating of mascara (Figs. 20A and B). Each photographic set consisted of about twenty photographs, taken in four horizontal rows of five vertical columns (Fig. 21). These photographs were then processed using Agisoft PhotoScan photogrammetry software by Dominic Albanese of Direct Dimensions. This process resulted in a final high resolution 3D mesh of the face (saved as an .obj file) with a matching color texture map (saved as a .jpg file) for subsequent digital sculpting using ZBrush.
Figs. 20A and B Mascara eyelash treatment and other test materials

Fig. 21 Photographs taken in four horizontal rows of five vertical columns (reuse of Fig. 3)
SKIN TEXTURE OPTIMIZATION

The .obj file of the 3D facial mesh was imported in ZBrush. The data required digital enhancement and cleanup, as it lacked high-level detail seen in the texture map and had many small image surface artifacts (Figs. 22 and 23). First, the Tool>Subtool>Geometry>ZRemesher function was used to even out the surface geometry (Fig. 24). Next the geometry was subdivided (Tool>Subtool>Geometry>Divide) to obtain a much higher resolution containing millions of polygons (Fig. 25). The .jpg texture map file was then imported and the UV’s were flipped. On a duplicate of the Subtool, using the lowest subdivision, the texture was converted to Polypaint. The Polypaint was then unwrapped using the Z-Plugin>UV Master>Unwrap function. Using the Z-Plugin>UV Master>Enable Control Painting function, masks were painted on the face to indicate areas of the topology to be protected (in red) and to direct the seam lines (in blue), used during texture map and UV creation thus keeping important facial features together. The texture map was then exported as a .jpg for further editing (Figs. 26A and B) using Adobe® Photoshop® (San Jose, CA).

Within Photoshop, the clone stamp tool was used to remove remaining eyelash detail on the left eye. Direct Dimensions used the edited texture map to create better UVs by reprojecting onto a very high resolution mesh within Agisoft Photoscan. Direct Dimensions also used Crazybump™ Software (www.crazybump.com) to generate a displacement map. The displacement map was then imported into ZBrush to arrive at a highly detailed surface (Figs. 27A-C).

DIGITAL PRODUCTION OF AN ORBITAL PROSTHESIS

The 3D .obj file of the previously laser scanned ocular prosthesis pattern was imported in ZBrush. The Subtool’s geometry was adjusted with the Tool>Subtool>Geometry>Dynamesh function to create a watertight object with a solid back (Figs. 28A and B) because the scan showed only the top surface. The resulting Subtool was saved as
Fig. 22 Image surface artifacts on 3D model created from photogrammetry

Fig. 23 Image surface artifacts close up

Fig. 24 Retopologized surface of 3D model with ZRemesher

Fig. 25 3D model at a multi-million polygon resolution

Figs. 26A and B Unwrapped and corrected texture map image edited in Adobe Photoshop
a ZBrush Tool .ztl file and set aside. The resulting .obj file of the 3D photogrammetry capture was then opened in ZBrush. This data was trimmed to remove unnecessary data outside of the pertinent eye region. To simulate an actual patient case and to create the posterior aspect of the orbital prosthesis, a stone model of an exenterated orbit was scanned using a FARO® ScanArm, HD® laser scanner (Lake Mary, FL) and exported as an .obj file. The file of the laser scanned exenterated orbit (Figs. 29A and B) was then appended in ZBrush. This data was also trimmed using a TrimLasso Brush>Delete Hidden function, so that only the front face of the Subtool remained. The Orbit Subtool would serve as a subtractive object from which to generate the back side of the Orbital Prosthesis.

The exenterated orbit and facial capture data were roughly aligned in ZBrush (Figs. 30A and B), and then aligned more exactly using a best fit algorithm in alternate software used by Direct Dimensions. Using the Facial Capture Subtool, the outer margin of the orbital prosthesis was defined via a Slice Curve Brush>Delete Hidden function (Figs. 31 and 32). A ZProject Brush was used to pull the portion of the base overlapping the edge of the front side forward, in order to match and preserve the contours of the facial capture. The outer edge of the posterior orbit was then trimmed using a Slice Curve Brush>Delete Hidden function to fit the margins of the trimmed facial capture (Figs. 33 and 34). The posterior portion of the orbit was decreased and back walls smoothed, using the Smooth Brush, to lessen the weight and potential for skin irritation in a patient’s exenterated orbit (Fig. 35).

The ocular .ztl file was then opened and appended to be aligned with the eye of the facial data. Some of the overlapping eye surface on the facial data was pushed posterior to the ocular mesh to improve the transition between sclera and lid (Figs. 36A and B). The facial capture .ztl file was saved.

The outer margins of the facial capture and the Orbit Subtool intersected and thus needed to be corrected (Fig. 37). The edges of the Facial Capture and Orbit Subtools also
Figs. 27A, B and C Different views of final high resolution facial data. Note pore-level detail on 3D model.

Figs. 28A and B Laser scanned Ocular Prosthesis shape imported in ZBrush

Figs. 29A) Orthostone model of exenterated orbit and B) Laser scanned Exenterated Orbit Subtool appended and trimmed in ZBrush
Figs. 30A and B Alignment of Extenterated Orbit and Facial Data Subtools

Fig. 31 Defining prosthesis margin using Slice Curve Brush

Fig. 32 Facial Data Subtool trimmed

Fig. 33 Orbit Subtool aligned with Facial Data Subtool

Fig. 34 Orbit Subtool trimmed
Fig. 35 Posterior surface of socket on Orbit Subtool smoothed

Figs. 36A and B Alignment of ocular to the Facial Data Subtool

Fig. 37 Intersection of Facial Data Subtool and Orbit Subtool edges

Fig. 38 Potential holes in mesh if edges do not overlap before Dynamesh
needed to overlap in order to avoid holes after the meshes were merged (Fig. 38). In order to combine the two, each surface was thickened using Tool>Subtool>Geometry>Modify Topology>Extract, with the Orbit Subtool set at a -.008 thickness, and the Facial Capture Subtool set a little thicker.

The newly created Orbital Prosthesis Subtool was then combined with a Tool>Subtool>Geometry>Dynamesh function set to a resolution of 2400. Subsequently, the edges of the two unified surfaces were smoothed together using the sPolish brush (Fig. 39). Pore detail along the edge surface was lost after polishing and thus needed to be added again. A portion of the texture map image with distinct pores was selected in Photoshop, and saved as a .jpg file (Fig. 40). The texture map data were then loaded as an alpha channel within the brush palette to create a custom pore texturizing brush. This brush was used to emboss pore details back onto the edges of the prosthesis (Fig. 41). The Ocular Subtool was then made visible and removed from the Orbital Subtool with a Subtool>Merge Down, Boolean subtract function to create a negative space for fitting an ocular prosthesis into the orbital prosthesis (Fig. 42).

The orbital prosthesis 3D model was thus digitally produced (Fig. 43), and could be used to digitally create a 3-piece mold.

DIGITALLY DESIGNING A 3-PIECE MOLD

Posterior Mold: Piece 1

The originally produced Exenterated Orbit Subtool was duplicated and appended to the ZBrush project file in preparation for adapting the posterior mold piece to fit the back surface and edges of the orbital prosthesis. The ZProject Brush and Smooth Brush were used to pull the area of the orbit scan around the socket up to the edges of the prosthesis data (Fig. 44). To accomplish a tight adaptation of the prosthesis edge to the exenterated orbit, traditionally, one would adapt the edge of the wax pattern to sit
**Fig. 39** sPolish brush smoothing two unified surfaces

**Fig. 40** Creation of texture brush using Adobe Photoshop

**Fig. 41** Pore detail embossed on prosthesis edge

**Fig. 42** Ocular Subtool in place prior to Merge Down

**Fig. 43** Finished orbital prosthesis 3D model
Fig. 44 Z-Project and Smooth Brushes used to adapt Posterior Mold Subtool to Orbit Subtool.

Fig. 45 Edges of Posterior Mold Subtool raised above posterior wall of Orbit Subtool using Alt-Move Brush combination.

Fig. 46 Three registration spheres appended and positioned to overlap Posterior Mold Subtool.

Fig. 47 All three spheres removed with Boolean Subtract function.

Fig. 48 Ocular Mold Piece.

Fig. 49 Merged duplicate copies of Ocular Mold Piece, Orbital Prosthesis, and Posterior Mold Subtools.
posterior to the model of the exenterated orbit. The Alt-Move Brush combination was thus used to elevate the edges of the exenterated orbit mold piece, along the normals, bordering the orbital prosthesis (Fig. 45), moving them slightly anterior to the prosthesis edge along the normals of the orbit. Surface details in the orbit were removed with a Smooth Brush along the outer edges of the orbit. This would represent the posterior mold piece.

Next, the Posterior Mold Subtool was modified with three points of registration (Fig. 46). Three small uniform spheres were appended to the project and subtracted from the posterior mold with a Merge Down, Boolean Subtract function (Fig. 47). First a Dynamesh function was used on the base at a resolution of 2400. Merge Down with the Sphere Subtool set to subtract was used three separate times, one for each sphere (Merge Down, Ctrl-click drag to Dynamesh subtract). The Posterior Mold Subtool was then saved as a separate .ztl file.

**Ocular Shape: Piece 2**

The Ocular Subtool that created the inside cavity of the orbital prosthesis was modified to create the ocular portion of the 3-piece mold. The middle post was shortened using the SliceRect, Hide Selection, and Delete Hidden functions. Two half spheres were appended and positioned onto the front surface, creating two differently sized registration points (in order to eliminate incorrect orientation placement into the mold). The two half spheres were merged together onto the Ocular Subtool using the Merge Down and Dynamesh functions (Fig. 48).

**Anterior Mold: Piece 3**

A copy was made of all three previously produced 3D Subtools (ocular, posterior mold, and orbital prosthesis) in order to create the final anterior mold piece. The three Subtools were combined with a Merge Down function and retopologized with a
Fig. 50  Appended Cylinder Subtool scaled and positioned to overlap merged Subtool

Fig. 51  Anterior Mold piece after merged mold Subtool subtracted from Cylinder Subtool

Fig. 52  Traditional mold with wax spacer to create overflow channel

Fig. 53  Mask painted on Posterior Mold Subtool

Fig. 54  Masked area extracted to overlap Anterior and Posterior Mold Subtools

Fig. 55  Completed anterior mold
Dynamesh function at a relatively high resolution of 2800 (Fig. 49). A 3D Cylinder Subtool was appended to the file, rotated, scaled, and positioned so as to overlap the combined shape (Fig. 50). The cylinder was also retopologized at a 2800 resolution using the Dynamesh function to create adequate surface geometry. The Merge Down function was used to Boolean subtract the previously combined Posterior Mold Subtool from the top cylinder, creating the anterior mold piece (Fig. 51).

**Overflow Channel**

The overflow channel is a gap between the top and bottom mold pieces where silicone is pushed out of the mold when casting. It is usually created with wax in a traditional workflow (Fig. 52) before the top mold is cast from the bottom mold.

To create this, a mask was painted onto the desired area for an overflow channel on the posterior mold piece (Fig. 53). The masked area was Extracted (Tool>Subtool> Extract) toward both top and bottom mold pieces in order to overlap the inside surface of both (Fig. 54). This ensured an accurate digital overlap and created a separate Subtool that was retopologized with the Dynamesh function and subtracted from the top mold using the Merge Down function (Fig. 55).

The final 3-piece mold was thus completed. Each piece was exported as a separate .stl file, using the Zplugin>3D Print Exporter function, selecting the millimeter scale option to ensure accurate size reproduction.

**TESTING AND ORDERING 3D PRINTED MOLD**

It was decided to 3D print using an Objet 260 Connex 3D printer by Stratasys, since this was determined to be the highest resolution Polyjet printer available at the time of this research. Stratasys provided material samples printed using this technology. These were cleaned using boiling water containing a small amount of Boil-Out Solution
by American Dental Supply, Inc. (Easton, PA). This was done to remove as much of the waxy printing support material as possible to avoid possible silicone cure inhibition. Three platinum-based silicones were tested for inhibition on four different print material options: VeroClear™, Full Cure 720™, VeroGray™, and Endur™ (white). Small swatches of each of the following silicones were painted on the 3D printed samples: 2186, M511, and RTV40 (Fig. 56). There were two sets tested, one painted above a fully dried tin foil separator coating, and one directly on the 3D printed sample (Fig. 57). These were allowed to cure for a period of 16 hours.

Since there was no significant difference found between the 3D printed samples, (Table 2). The Endur material was selected, due to its white color, to allow for visualization of silicone color against the mold during intrinsic painting. M511 by Factor II (Lakeside, AZ) was selected for the final silicone casting due to a lack of cure inhibition.

The previously produced 3-piece mold .stl files were sent to Stratasys for printing on the high quality setting of their Objet 260 Connex 3D printer using the Endur material.

TRADITIONAL CASTING OF ORBITAL PROSTHESIS

Initial Test

The 3D printed mold pieces were cleaned using boiling water containing a small amount of Boil-Out Solution to remove any residual support material (Fig. 58). The mold was dried and coated with Polyester Parfilm release agent by Price Driscoll Corp. (Waterford, CT) (Fig. 59).

The M511, 10:1 platinum cure silicone was intrinsically colorized using the Human Coloration System™ (SiliClone Studios, Valley Forge, PA) (Fig. 60). The colorized silicone was vacuum de-gassed in three passes of 2 minutes at 70mmHg negative pressure. A small amount of silicone was injected around the ocular site before
Fig. 56 Three platinum-based silicones used for material test

Fig. 57 Four 3D print material samples with silicone tests

<table>
<thead>
<tr>
<th>Non-treated surface test</th>
<th>Vero Clear</th>
<th>Full Cure 720</th>
<th>Vero Grey</th>
<th>Endur</th>
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<td>2186 Silicone</td>
<td>tacky, not fully cured</td>
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<td>tacky, not fully cured</td>
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<td>RTV40 Silicone</td>
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<td>2186 Silicone</td>
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<td>RTV40 Silicone</td>
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Table 2 Results of two silicone swatch cure tests on four 3D print materials
Fig. 58 Support resin residue removed from mold pieces

Fig. 59 Polyester Parfilm release agent

Fig. 60 M-511 silicone material and Human Coloration System™

Fig. 61 Test silicone injected into mold
Fig. 62 Mold closed

Fig. 63 Mold clamped and ready for bench cure

Fig. 64 Bench cure test result

Fig. 65 Intrinsic silicone colors mixed
snapping the ocular mold piece in place. The rest of the silicone was injection dispensed to the mold pieces so as to avoid air bubble entrapment (Fig. 61). The mold was closed (Fig. 62), clamped shut (Fig. 63), and left to bench cure overnight at room temperature.

The initial test was used to determine whether the entire silicone piece would cure properly in the 3D printed mold (Fig. 64). Because the silicone was not fully cured along the thin delicate edges, the mold was cleaned once more with boiling water and Boil-Out Solution to remove any remaining support material before the final cast.

**Intrinsic Color: Casting The Orbital Prosthesis**

The final intrinsic skin colors were mixed with the creation of five colors: a base tone, highlight, red, golden, and shadow tone (Fig. 65). Silicone pigments as well as flocking fibers were added to achieve the intrinsic colorants. The silicone was de-gassed three times, as previously described (Fig. 66).

The intrinsic colors were then painted into the anterior mold piece in three layers, allowing for a partial cure between each layer (Fig. 67). The posterior mold piece was filled with the base tone. As with the test cast, the mold was clamped shut and left to cure overnight at room temperature. The cast orbital prosthesis was removed from the mold and the extra silicone above the ocular mold piece was trimmed using a scalpel before removing the ocular mold piece (Figs. 68A and B). Finally, the extra silicone around the prosthesis edge was carefully trimmed using scissors.

**Extrinsic Color and Eyelashes: Finishing The Orbital Prosthesis**

Thin watercolor-like washes of Functional Extrinsic Color Pigments and FE100 Extrinsic Painting Solvent by Factor II (Lakeside, AZ) (Figs. 69A and B) were used to make final extrinsic color corrections. Two sealing coats were applied using Factor II’s 564 series of acetoxy SD564 Silicone Dispersion and A564 Silicone Adhesive (Fig. 70). The final matte sealing was done using a mixture of 0.25 grams of Silicone Adhesive and
Fig. 66 Silicone vacuum de-gassed

Fig. 67 Intrinsic colors painted into mold

Figs. 68A and B Fully cured orbital prosthesis

Figs. 69A and B Extrinsic coloring supplies
1.25 grams of MD564 Matting Dispersion fluid. Small amounts of A564 Silicone Adhesive were applied on areas of the orbit that are naturally shiny or wet. In between sealing coats, the prosthetic device was placed in a 125 degree Fahrenheit oven for 5-10 minutes until partially cured, except for the last two steps in which the prosthesis stayed in the oven until fully cured.

In order to insert the artificial eyelashes, an incision was made using a scalpel along the lash line on the upper and lower lids (Fig. 71). The cut portions of the eyelids were filled with A564 Silicone Adhesive (Fig. 72). Artificial eyelashes were then inserted into the adhesive using tweezers (Figs. 73A and B). The top lash was applied intact, while the bottom lashes were thinned out to provide a more natural appearance. The prosthesis was then placed back in the oven to cure the lashes in place, completing the process.

OCULAR PROSTHESIS PRODUCTION

An orthostone flashed mold was made of the 3D printed ocular mold piece and coated with Factor II F901 Separating Film. The mold would be used to cast the final acrylic ocular.

An ocular button was trimmed down until its diameter was about 0.5mm smaller than the final iris size of 12mm (Fig. 74). The post of the ocular button was trimmed, so that it was the same length as the post on the 3D printed ocular mold. The scleral acrylic was prepared by mixing J510 Factor II Scleral White Acrylic Polymer with J572 Cross-linked Monomer (Fig. 75) until its consistency was that of wet sand (Fig. 76). The acrylic mixture was then sealed in a glass jar for around 15 minutes until it reached a snappy consistency, similar to taffy. A small portion of the scleral acrylic was placed in front of the iris button post (Fig. 77), before pressing the button into the mold (Fig. 78). The remainder of the scleral acrylic was placed on top of the ocular button. A plastic sheet was placed in between the acrylic and the posterior part of the mold for trial packing.
Fig. 70 Sealed extrinsically painted orbital prosthesis

Fig. 71 Incision made in upper eyelid (technique)

Fig. 72 Silicone adhesive injected into lid (technique)

Figs. 73A and B Eyelash placed into eyelid (technique left, product right)
**Fig. 74** Ocular button trimmed to correct size

**Fig. 75** Scleral acrylic materials

**Fig. 76** Wet-sand state of mixed acrylic

**Fig. 77** Scleral acrylic placed over ocular button

**Fig. 78** Ocular button placed in mold

**Fig. 79** Trial packing sheet in place
Fig. 80 Excess acrylic removed from edges of mold

Fig. 81 Mold pressed

Fig. 82 Pressure cooker used for acrylic processing

Fig. 83 Scleral acrylic with burred holes to guide grinding depth

Fig. 84 Scleral acrylic ground with hand piece
purposes (Fig. 79). The mold was closed, compressed, opened, and the excess scleral acrylic removed from around the edges (Fig. 80). The mold was closed and compressed again, this time without the plastic layer (Fig. 81), and placed submerged in a pressure cooker (Fig. 82) for curing.

The pressure cooker was turned on for two cycles: the first on low heat for half an hour, and the second on high heat for another half an hour. Afterward, the flask compress was removed and cooled before opening the mold and removing the acrylic ocular piece. Depth impressions were made with a smaller bit (Fig. 83), and the acrylic sclera was then ground down using a hand piece (Fig. 84). This was followed by evenly grinding the scleral acrylic until the iris size was again 0.5mm smaller than the final size and enough room for a final clear layer of acrylic was achieved.

The sclera and limbus were painted using dry earth pigments, Factor II J305 Monopoly Syrup, and J570 Non-Crosslinked Monomer (Fig. 85). The vessels were created using separated fibers of red cotton thread. After the coloring was complete, several clear coats of Monopoly Syrup were applied and allowed to cure overnight. Using the same method as with the scleral acrylic, J601 Clear Acrylic Powder was used to create the final clear cap representing the cornea and conjunctiva (Fig. 86). The clear coat was cured in the same manner as the scleral acrylic. After removing the ocular from the mold (Fig. 87), the post and half spheres of the ocular mold piece were ground down and the cornea shaped using progressively finer acrylic grinding bits (Fig. 88).

Once the shape was established, the surface was roughly polished using a blue pumice substitute-polishing burr (Fig. 89). Afterward, the surface was further polished with wet, very fine pumice and a cotton rag wheel on a lathe set on low speed (Fig. 90). The third and final polishing step was done using Fabulustre Hi-Shine Polishing Compound™ by Gesswein Co., Inc. (Bridgeport, CT) and a rag wheel burr on the lathe set to high speed (Fig. 91). The polished ocular prosthesis represented the second piece of the finalized orbital prosthesis.
**Fig. 85** External eye painting supplies

**Fig. 86** Painted ocular prosthesis

**Fig. 87** Clear acrylic cast over painted ocular prosthesis

**Fig. 88** Grinding and polishing burrs used (arranged from fine to course)

**Fig. 89** First polishing step with hand piece
Fig. 90 Second polishing step with lathe and pumice

Fig. 91 Third high-polish step on lathe, using rag wheel, and Fabulustre High Shine Polishing Compound
RESULTS

The overall result of this investigation is a novel, digital approach that combines digital modeling, photogrammetry, digital sculpting, digital mold design, and 3D printing of a mold to produce a custom silicone orbital prosthesis with an acrylic ocular prosthesis. As part of this research, the following items were produced:

1) ZBrush 3D model of an ocular prosthesis based on normalized data, produced in Adobe Illustrator and Cinema 4D (Figs. 92A and B).
2) High-resolution photogrammetry facial capture of simulated patient with open eye using a Canon T5i digital SLR and Photoscan (Figs. 93A and B).
3) Digitally enhanced 3D model of patient’s orbit from texture map information using ZBrush (Fig. 94).
4) Virtual 3D model of surface laser scanned exenterated orbit using ZBrush (Fig. 95).
5) Virtual 3D orbital prosthesis produced using ZBrush (Fig. 96).
6) Virtual 3D 3-piece mold produced using ZBrush (Fig. 97).
7) 3D print of 3-piece mold using Objet 260 Connex Printer (Fig. 98).
8) Traditional orbital prosthesis cast from 3D printed mold with an acrylic ocular prosthesis (Figs. 99 and 100).
9) Acrylic ocular prosthesis produced using normalized data (Fig. 101).

Digital assets resulting from this thesis may be accessed via the Department of Art as Applied to Medicine at The Johns Hopkins University School of Medicine.
www.hopkinsmedicine.org/medart
Figs. 92A and B Ocular prosthesis in ZBrush

Figs. 93A and B High resolution photogrammetry capture without and with texture map

Fig. 94 Closeup of high resolution skin detail
Fig. 95 3D file of laser scanned exenterated orbit

Fig. 96 3D Orbital prosthesis made using ZBrush
Fig. 97 3D 3-piece Mold Subtools made using ZBrush

Fig. 98 3D print of 3-piece mold using a Objet 260 Connex 3D printer
Fig. 99 Silicone Orbital Prosthesis made with M511 with an acrylic ocular prosthesis

Fig. 100 Posterior side of silicone orbital prosthesis

Fig. 101 Acrylic ocular prosthesis
DISCUSSION

FACIAL CAPTURE VIA PHOTOGRAMMETRY

**Vectra M3 System**

During the face capture phase of this research, the Canfield Scientific Vectra M3 was tested. This is an imaging system commonly utilized in plastic surgery settings. The Vectra M3 system is capable of capturing facial data using six stationary digital SLR cameras (Fig. 102) to generate a 3D model. The Canfield software processes the six photographs to generate point clouds and then dense meshes (Fig. 103), before generating the 3D model (Fig. 104) and a corresponding texture map (Fig. 105). The overall process is quite similar to the photogrammetry process described using Agisoft Photoscan and a single, mobile DSLR camera. Data captured using the Vectra M3 resulted in a 3D model that had lower resolution as compared to the data capture method using Agisoft Photoscan described earlier (Figs. 106A and B). When further investigated, it appears that the DSLR cameras on the M3 version were made in 2011 and therefore have a lower image resolution than the DSLR cameras on the market today (White 2015). According to Mr. White, a technician for Canfield, lower resolution photographs will lead to lower resolution 3D models.

As a goal of the investigation was to obtain the highest level of detail possible, additional processing of the dataset obtained using the Vectra M3 system was not executed. It may be worth investigation to use the same workflow with a future version of the Vectra M3 system that uses cameras with similar megapixel resolution as compared to the Cannon T5i, per our conversation with Mr. White, in order to compare the level detail obtainable using this technology.
Fig. 102 Vectra M3 System
Fig. 103 Six photographs with dense point cloud imported in ZBrush
Fig. 104 Completed model
Fig. 105 Model with texture map
Figs. 106 A and B Comparison of mesh resolution between Vectra M3 (left) and Photoscan (right)
**Agisoft Photoscan**

Obtaining a high resolution mesh from photogrammetry requires highly detailed photographs, of high resolution, with diffuse even lighting without harsh shadows, a very still subject, and careful consideration of the physical properties of the subject. Agisoft Photoscan has a difficult time generating an accurate mesh from photographs of any surfaces that are wet, transparent, translucent, have undercut areas, and areas of one solid color without a distinct pattern. In order to capture more detail on the translucent skin surface, liquid foundation was applied to the face to take away the translucency.

Additionally, eyelashes tend to scatter the data of the upper eyelid creating mesh geometry lacking in definition. Several potential solutions to this issue were tested: the eyelashes were photographed: 1) pressed down with a large amount of mascara taken directly out of the container; 2) with no treatment (natural); 3) with mascara; 4) with trimmed and fake eyelashes with paper attached; and 5) trimmed and fake eyelashes with a thin layer of silicone attached. The best photographic capture resulted from pressing the eyelashes down and to the side with a large amount of mascara out of the container (Figs. 107-110). This novel solution was discovered during the investigation, and necessitated retaking the photographs to incorporate the observed improvement. To further improve the quality of the generated model, it was decided to retake photographs that had originally been taken with a Canon D7100, using a T5i for the second, improved set of photographs due to the increased megapixel resolution of this camera.
Fig. 107 Capture of fake eyelashes with paper attached

Fig. 108 Capture of fake eyelashes with silicone screen attached

Fig. 109 Capture of eyelashes with no treatment (similar result with normal mascara)

Fig. 110 Capture of eyelashes pressed down and to the side with large amount of mascara straight from the container
**Artec Spider**

The Artec Spider™ structured light scanner by Artec Group™ (Palo Alto, CA) has an accuracy of up to 50 microns and a resolution up to 100 microns. It is a hand-held scanning device that captures surface data while connected to a computer. The Artec Spider continually takes photographs with or without flash and stitches them into a real-time 3D model with their software (Artec 3D 2014). According to promotional materials, the Artec Spider, “Processes up to one million points per second” with its geometry and texture tracking technology (Artec 3D 2014). It can scan both color and surface characteristics of an object in high resolution, up to 0.1mm (Artec 3D 2014).

Due to its capacity for high resolution scanning and color capture, it is worth exploring this technology further for prosthetic applications. Structured light scanners have a difficult time capturing any geometry that is black; so one obstacle to overcome would be scanning transparent structures and dark hair. This last point could be partially addressed by first coating the hair with a skin and eye-safe makeup of a lighter value. Several test scans were done of an eye using an opaque white paste to cover the eyebrow and eyelashes (**Figs. 111A and B; and 112A and B**). Another aspect of the technology making it difficult to use for capturing faces is that it requires a continuous flash for best data capture. Otherwise, the resulting data may have too low of a resolution to be used for prosthetic applications (**Fig. 113**). The continually flashing light may be irritating for monocular patients, and can potentially pose a risk to those prone to seizures. A possible option to address this is to use an opaque contact lens to reduce the irritation or seizure risk the flash may pose for a patient. Given the high resolution of this scanning technology, further investigation may be worth pursuing to determine its best possible applications.
Figs. 111A and B Mesh resulting from Artec Spider with flash option and smoothed to 0.15

Figs. 112A and B Mesh and texture resulting from Artec Spider with flash option and smoothed to 0.15

Fig. 113 Mesh resulting from no flash option with Artec Spider
DIGITALLY SCULPTING AND ADAPTING THE FACIAL DATA

Even with the aforementioned improvements gained by creative use of mascara and foundation, the raw capture mesh and subsequently cleaned and processed 3D model had indistinct borders between the eyeball and eyelids. Because of this, the geometry of the eyeball on the Orbital Prosthesis Subtool had to be pushed posteriorly, behind the Ocular Prosthesis Subtool. The rationale was to prevent a thin and misshapen geometry when the ocular was subtracted from the Orbital Subtool.

The goal at this step in the research involved adapting the photogrammetry facial capture data to the physical model of an exenterated orbit. Thus, a laser scan of an exenterated orbit model needed to be digitally adapted to the photogrammetry capture of the facial data using ZBrush. To merge the two, the exenterated orbit model was resized and its edge margins were pulled forward to match the shape of the facial capture data around the eye. In a clinical setting, the exenterated orbit data would never be altered, as this would affect the fit of the finished prosthesis. However, it was done in this case because the datasets came from two different patients, and thus required adaptation. If a real patient’s data were used for this study, the facial capture data of the unaffected eye would be mirrored onto the affected area. The shape of the unaffected area would then be manipulated such that the edges would blend with the shape of the underlying affected anatomy, and not the other way around as done for this research.

DIGITALLY DESIGNING THE 3D MOLD

Most of the workflows published online by Pixologic, the developers of ZBrush, on the topic of digitally designing for prototyping do not typically speak to designing a multiple piece negative mold for casting (Pixologic 2015). Thus, it was helpful to receive feedback on the methods used in this research from one of the developers of the application. Digital sculpting workflow improvements were suggested during a conference call with Paul Gaboury from Pixologic (Gaboury 2015).
Should this workflow be repeated or expanded upon, the following is an amendment to technique.

In the workflow for creating the 3D mold, the laser scan file of the exenterated orbit served as the starting point for creating the posterior mold piece. As previously mentioned, this necessitated adapting the orbit to fit the shape of the facial capture containing data from a whole, unaffected face. Mr. Gaboury suggested keeping the total shape of the brow from the facial capture data in order to create the posterior mold piece directly from the patient’s face, instead of trimming the facial capture data so close to the eye. In his proposed workflow, the posterior aspect of the face would be merged to an appended Cylinder Subtool in order to create the back mold piece (Gaboury 2015). Two ways to achieve this would be moving the posterior aspect of the face (using the Alt-Move brush) to meet a Cylinder Subtool and then merging the Subtools. Or, by merging the Facial Capture Subtool to an open cylinder shape using the Zmodeler Bridge modifier tool to the weld the two pieces together (Gaboury 2015). The adaptation procedure to create the posterior mold piece would then be modified so as to subtract the affected site of the Exenterated Orbit Subtool from the newly created facial capture posterior mold piece (Gaboury 2015).

After consultation with Pixologic ZBrush over irregular results obtained after performing .stl exporting functions using the ZPlugin>3D Print Exporter function in ZBrush, a custom software patch was obtained from Pixologic to ensure accurate size exporting results (Gaboury 2015). While exporting at the correct scale is still possible without the software patch, 3DPrint Exporter settings must be carefully scrutinized before creating the final .stl file for 3D printing. This is primarily because .stl files do not code for millimeters vs. inches units, and can result in a grossly incorrectly sized model.

It is worth noting that another sculpting software could have been used to digitally create the 3-piece mold. FreeForm™ made by Solspace™ Inc. (Santa Cruz, CA) is an application that many toymakers and other industry professionals have used to design...
3D printable prototypes. There have been reports of this software being used to design auricular and nasal prostheses (Jiao, et al. 2004; Silver 2015).

ZBrush was chosen for the digital sculpting aspects of this project due to its much wider range of sculpting tools and functional capabilities. The extensive sculpting capability is appropriate for highly detailed prosthetics and closely resembles the process of sculpting a prosthesis traditionally. For those used to traditional sculpting methods, the transition to ZBrush as a means of sculpting may be more intuitive than using other digital sculpting software like Freeform or 3D modeling software packages. It is worth further exploring to determine whether the same high-quality result is achievable using FreeForm software. Recent versions of Cinema 4D also have similar digital sculpting capabilities that should be investigated as well. However, the overall digital sculpting tools and functional capabilities within ZBrush appear to be the most developed, thus making it the software package chosen for this aspect of the research.

3D PRINTING THE DIGITALLY-DESIGNED MOLD

For this investigation, a single 3D print technology (Stratasys Objet260 Connex printer) was evaluated. Using the highest resolution printer possible was essential in order to evaluate how much of the skin detail (pores, creases, etc.) could be retained in the final mold and silicone prosthesis. Part of the challenge in 3D printing facial prosthetics is that fine details can be lost due to a low print resolution resulting in a smooth surface or residual build lines. There is no current technology to 3D print in color at a high resolution using silicone and acrylic, and thus the research methodology developed was to assume a digital workflow until the final casting phase. The research produced a final silicone orbital prosthesis cast from a 3D printed mold, and an acrylic ocular piece, produced through a combination of digital and traditional techniques. Another consideration for implementing this 3D print workflow for patient treatment is the length
of time needed to print the mold pieces. In **Fig. 114**, the length of time spent printing the three mold pieces is shown.

There are two additional digital print technologies that may prove useful in the future. The first is from a company called Fripp Design and Research based in the United Kingdom. Fripp Design claims to be testing 3D printing directly in silicone (Neil Frewer of Fripp Design, e-mail message to author, June 6, 2015). Printing directly to silicone at the present time does not allow for the high resolution detail needed to show pore-level detail and skin creases, according to Frewer. Another limitation to the technology is that a Fripp silicone print appears to only be made using a single color. If so, intrinsic color variation of the 3D printed piece would not be possible, thus requiring extrinsic coloration. However, future improvements in 3D printing technology may someday lead to a viable way to print a multi-colored, multi-layered, and intrinsically colored silicone prosthesis directly.

Another 3D print technology identified in the course of this research worth exploring is the Carbon 3D™ printer by Carbon 3D™ Inc. (Redwood City, CA). This printer uses a proprietary technology called Continuous Liquid Interface Production (CLIP) (Carbon 3D 2015). An explanation of the process is provided in the Carbon3D website: “UV light triggers photopolymerization and oxygen inhibits it. By carefully balancing the interaction of light and oxygen, CLIP continuously grows objects from a pool of resin.” The build process allows for extremely high z-resolution, in the order of nanometers. The website also claims very quick printing times (25-100 times faster, depending on the type of printer it is compared to). This is due to the print being built out of a vat of liquid rather than the printer laying down successive layers of resin. According to our conversations at the time of this research, the company was in the process of releasing brand new printers to service bureaus and thus it was not possible to evaluate the effect their higher print resolution would have had compared to the results obtained using the Stratasys Objet260 Connex printer.
Fig. 114 Screenshot of production time for the High Quality print of the 3-piece mold

Figs. 115A and B  Skin texture detail on digital file (left) compared to silicone prosthesis surface detail (right)
The Objet260 Connex 3D printed mold made as part of this research was produced using a support material that was removed by the service bureau using water tckipressure. However, the mold was cleaned again to remove any residual support material remaining on the mold. This was important because the support material can cause inhibition during the silicone curing process. After cleaning the mold with boiling water containing Boil-Out Solution, a test was done to determine whether silicone cast in the mold would cure. The test cast was mostly cured, but a partial tackiness on the thin outer edges of the prosthesis was observed. Upon cleaning the mold once more, there appeared to be no observable tackiness. Therefore, it is recommended that a 3D printed mold be thoroughly cleaned to avoid possible cure inhibition.

A goal at this step was to evaluate the level of detail attainable in an orbital prosthesis cast from a 3D printed mold designed via digital means. As documented in the Results section, the combination of digital capture and sculpting techniques were able to attain pore-level detail required for a highly detailed end result. Yet, when one compares the cast silicone prosthesis to its digital data counterpart, clearly one sees that pore level detail was not replicated (Figs. 115A and B). Therefore, the limiting factor in the process appears to be the resolution available in the 3D print. Although one of the highest resolution printers available was used (Stratasys Objet260 Connex), there appeared to be visible build lines on the 3D printed mold (Fig. 116). The silicone prosthesis cast from the mold thus retained the build lines (Fig. 117). Overall, the build line detail was not as obvious after the prosthesis was extrinsically painted and sealed with silicone dispersion and matte coatings. While the seal coats made many of the build lines appear less noticeable, the extrinsic pigments did congregate along the build lines, thereby highlighting them in darker, more pigmented areas (Fig. 118). In a side-by-side comparison of the prosthesis produced in this study and one created using traditional methods (Fig. 119), it highlights the type of detail that was lost due to 3D print resolution. It is worth noting that less facial creases and signs of aging were present in
Fig. 116 Visible build lines on 3D printed mold

Fig. 117 Visible build lines on silicone prosthesis (arrow)

Fig. 118 Pigment congregated in build lines
Figs. 119A and B Level of detail in traditional orbital prosthesis vs. digitally-designed orbital prosthesis

Fig. 120 Prosthesis edge (right) placed against skin (left) for blending test
the under 30 years of age subject used for the facial capture in this study. Therefore, it may be that the lack of detail would not be as obvious on prostheses created for younger patients, or ones with very smooth skin.

Another limitation of a digitally produced prosthesis is the final thickness of the edge margins. The edges obtained by creating the mold digitally were not as thin as can be obtained with a traditional workflow. The comparative edge thicknesses can be seen in Fig. 119. This is equally contributed to by both the facial capture data and the laser scan of the exenterated orbit when merged to create the edge of the orbital prosthesis. While each component was relatively thin, merging the two halves through use of the ZBrush Dynamesh function resulted in additional edge thickness. The resulting orbital prosthesis will blend with the surrounding tissue (Fig. 120), but not as smoothly as one made traditionally.

CASTING THE SILICONE PROSTHESIS

Once the tinted silicone was intrinsically painted into the mold, it was allowed to cure at room temperature overnight. Since placing the mold in an oven to cure could potentially warp the mold and cause leaching of 3D print material chemistry that can contribute to cure inhibition (Smooth-On 2015), it was decided to not accelerate the curing with heat. In addition, heat could affect both the reproduction of surface details and the integrity of thin prosthesis margins through melting fine details and possible warping of the mold. In comparison, using a traditional workflow, a stone mold can be placed in a 165 degree Fahrenheit oven to accelerate the cure time of the silicone. The time it takes to bench cure could present a clinical challenge, as curing without heat slows the production of a prosthesis.
CONCLUSION

The creation of an orbital prosthesis via entirely digital means is not yet feasible for a high resolution and high quality end result. This research investigated the use of digital design as much as possible without compromising the quality of the end product of a traditional silicone prosthesis. Within the developed workflow, a few novel approaches to photogrammetry, digital sculpting, casting from a 3D printed mold, and ocular standardization based on normalized measurements were found. The process tested the limits of current photogrammetry, digital sculpting, and 3D print technologies, and laid the groundwork for future investigation in all three areas.

Several new technologies are currently being developed that may aid the future digital design of prostheses, especially new 3D print technologies. This investigation has highlighted several possible starting points by addressing digital impression-making methods such as photogrammetry, structured light scanning, and laser scanning, as well as a highly detailed digital sculpting approach and various printing options. The main limiting factor in the project’s success was the transition from high resolution digital data to a physical print. While the solution in this study was to cast a silicone prosthesis from a 3D printed mold, future technology may permit directly printing in high resolution silicone or other appropriate pliable materials.
# APPENDIX

## SOFTWARE UTILIZED

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<tr>
<th>Program</th>
<th>Manufacturer</th>
<th>Manufacturer Headquarters</th>
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<tbody>
<tr>
<td>Cinema 4DTM</td>
<td>Maxon®</td>
<td>Friedrichsdorf, Germany</td>
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<tr>
<td>Crazybump®</td>
<td></td>
<td><a href="http://www.crazybump.com">www.crazybump.com</a></td>
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<tr>
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<td>Adobe® Systems Inc.</td>
<td>San Jose, California</td>
</tr>
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<td>Photoscan®</td>
<td>Agisoft®</td>
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<td>Vectra M3 System®</td>
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<td>ZBrush®</td>
<td>Pixologic®</td>
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## HARDWARE UTILIZED

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<td>Artec Spider® Handheld Scanner</td>
<td>Artec Group®</td>
<td>Palo Alto, California</td>
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<td>D7100® DSLR Camera</td>
<td>Canon U.S.A® , Inc.</td>
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<td>Stratasys® Ltd.</td>
<td>Eden Prairie, Minnesota</td>
</tr>
<tr>
<td>Printrbot 3D Printer®</td>
<td>Simple Metal®</td>
<td>Lincoln, California</td>
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## ADDITIONAL SOFTWARE DISCUSSED IN THIS THESIS

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<tr>
<td>FreeForm® Digital Sculpting Software</td>
<td>Solspace® Inc.</td>
<td>Santa Cruz, California</td>
</tr>
<tr>
<td>123D Catch® Photogrammetry Software</td>
<td>Autodesk®</td>
<td>San Rafael, California</td>
</tr>
</tbody>
</table>

*Trademark, copyright and manufacturer information is provided at the first mention of the above products in the body of this thesis, and omitted in subsequent occurrences of the product name.*
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White, Daniel. Interview of Canfield representative by author and Juan Garcia. Conference Call. September 14.

VITA

Rose Perry was born in 1989, in Arlington Heights, Illinois and grew up in a supportive, artistic environment. She developed a passion for the natural sciences at a young age. She began her journey of becoming a medical illustrator when she noticed a Careers In Art poster in her high school. Intrigued, the author applied to the Biological/Pre-medical Illustration undergraduate program at Iowa State University. During her time there, the author studied Spanish abroad, learned ballroom dancing, and was introduced to the field of facial prosthetics. The author knew by her sophomore year that she wanted to pursue facial prosthetics in the future.

After graduating from Iowa State University magna cum laude in 2012, the author was awarded two degrees, a Bachelor of Arts in Biological/Pre-medical Illustration and a Bachelor of Arts degree in Spanish. She applied to Johns Hopkins University to continue her education in biomedical visualization in 2013. She was able to study topics related to facial prosthetics, both with and without digital processes, during graduate school. While at Johns Hopkins, the author was also awarded the Golden Key Graduate Scholar Award, an internationally recognized distinction.

The author’s true passion is helping others. After obtaining her Master’s degree in Medical and Biological Illustration in December of 2015, she hopes to find a place where she may work as both a clinical anaplastologist and a medical illustrator. The potential to be a stepping stone in a patient’s journey to become a more confident, active member of society is a driving force in the author’s academic and personal accomplishments.