Accurate Replication Of An Ear Pinnae Geometry For Use In Acoustic Testing Of Spatial Cues And Sound Localization

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ACCURATE REPLICATION OF AN EAR PINNAE GEOMETRY FOR USE IN ACOUSTIC TESTING OF SPATIAL CUES AND SOUND LOCALIZATION

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Dedication

This thesis is dedicated to my parents, who have guided me my entire life and provided me with the resources and motivation to pursue a higher education.
ACCURATE REPLICATION OF AN EAR PINNAE GEOMETRY FOR USE IN ACOUSTIC TESTING OF SPATIAL CUES AND SOUND LOCALIZATION

by

ALEJANDRA BELMONT, B.S. Engineering Leadership

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Abstract

Additive manufacturing (AM) enables freedom of design as well as fabrication of complex objects such as the human ear. In medical modeling there is a need for patient-specific customizable parts. The outer human ear consists of these main parts: the pinna, which naturally filters sound, and the ear canal, which is the point at which sound enters before being moved up to the tympanic membrane, otherwise known as the eardrum. In an attempt to accurately replicate ear models, the use of scanning and reverse engineering methods was used. A comparison of 3D laser scanning systems was performed to determine their use in medical model scanning applications. A computer-aided design (CAD) model and a standard tessellation language (STL) file of a standard pinna were generated using CT and 3D laser scanning. Multiple 3D printing technologies (desktop and industrial) were used to fabricate test samples of the generated models. These models were then compared in terms of material selection, printer capability, and acoustic performance. Applications in hearing protection devices were also explored. A CAD model of a hearing protection device integrated with the standard pinna to filter the incoming sound was designed, 3D printed, and subjected to acoustic testing. After evaluating scanning methods, CT scanning remained the most accurate, and some 3D laser scanning systems are more favorable than others. Printing and testing of 3D ear models was successful and showed similarities in acoustic testing compared to original ear models. Some printing technologies performed better than others. All were successful in replicating ear models. Results from this work will hopefully lead to improved hearing aids and hearing protection devices with applications on the battlefield, in emergency response situations, and providing improved experiences for children with sensitive hearing.
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Chapter 1: Introduction

1.1 Research motivation

According to the World Health Organization (WHO), over 600 million people suffer from hearing loss and other hearing disabilities worldwide. Gradual hearing loss occurs in many as a natural consequence of aging. Among those living with hearing disabilities, about 10 million of them have hearing loss as a result of noise exposure (Le et al., 2017). Only 14% of people with hearing loss were not significantly exposed to high impact noises. However, those exposed to high impact noise in a working environment had a higher prevalence at 44%. This noise exposure can be attributed to loud noises caused by environmental factors such as firing of arms, bombs, and airplane travel, among others. In an attempt to minimize the number of people who suffer from hearing loss, various work environments and settings with potential exposure, require the use of personal protective equipment (PPE). For example, military soldiers in a battlefield would require protective gear, not only for shielding, but to minimize harm to their ears, eyes, head, etc. In a battlefield, soldiers may be exposed to high impact noise or the noise response caused by firearms. A human ear will become vulnerable to damage, usually around 140 dB (Mlynski and Kozlowski, 2019). However, firearms tend to produce noise levels of about 150 – 180 dB, which is at least 10 dB greater than that which the human ear can safely withstand (Meinke et al., 2017). Due to this high level of risk, regulations for hearing protection are recommended in addition to those for handling firearms. Organizations such as the WHO, National Institute for Occupational Safety and Health USA, among others, give recommended peak limits of under 140 dB for exposed ears. Past that point, it is recommended to wear hearing protection, although not enforced.

While the military significantly benefits from the development and implementation of hearing protection devices and regulations, another industry that does so too is the aviation
industry. They too have implemented regulations involving hearing protection. Aircraft takeoff requires a crew aboard the plane as well as a crew on the ground directing traffic and performing maintenance. A noise study was performed on an Airbus A321 aircraft to record noise levels inside and outside of the aircraft during takeoff and as elevation occurred. Outside the aircraft, the engines recorded around 140 dB during takeoff for a 1,000 km flight. This same study also recorded noise levels of 60 – 65 dB inside the aircraft before takeoff where total noise exposure time was 30-35 minutes, 80 - 85 dB during the flight, and 75 – 80 dB during landing (Ozcan and Nemlioglu, 2006). While these recordings were specific to the Airbus A321, it is important to note that each model of aircraft is constructed differently, and insulation of these may vary throughout. While these noise levels (inside the plane) are not harmful to the human ear, long hours of exposure can cause damage. Therefore, regulations include time periods of around 8 hours to noise levels of, below or equal to, 85 dB for both flight crew and passengers (Ozcan and Nemlioglu, 2006). In an effort to reduce the number of people being affected in this manner, research efforts in hearing aids and other hearing protection devices have evolved throughout the years.

1.2 Project objectives

The goal of this project was to accurately replicate a 3D model of a Knowles Electronics Manikin for Acoustic Research (KEMAR) ear sample for use in future research efforts to develop an individualized headset for hearing protection and externalization preservation. A reverse engineering approach was adopted in order to replicate the silicone ear through scanning methods, post-processing, standard tessellation language (STL) creation, as well as computer-aided design (CAD) generation.
The four main objectives of this research were:

(1) to accurately replicate small left and right KEMAR ears through a scan-to-CAD approach all while preserving the geometries of the pinna, the outermost portion of a human ear.
(2) Develop a design for the 3D printed samples that mimics the insertion methods of the silicone ears into the KEMAR manikin head.
(3) Subject printed samples from various additive manufacturing technologies to acoustic response testing at GN ReSound headquarters in order to explore the validity of the printed ear samples as well as the technologies compared to the original silicone KEMAR ears.
(4) Design and test a preliminary headset design for acoustic response to be used in future research and development of hearing protection devices using additive manufacturing techniques.

1.3 Thesis outline

The following chapters are divided as follows. Chapter 2 provides a literature review on the anatomy of the ear and the basic principles of spectral cues, as well as the role of the pinna in acoustics. It also provides background on additive manufacturing techniques and technologies used in this project. Lastly, it provides background information on scanning methods as well as a comparison between the techniques used in the project. Chapter 3 covers the scanning techniques, laser and computed tomography (CT), used to reverse engineer the silicone KEMAR ear, as well as the generation of STL and CAD files. Chapter 4 can be divided into three sections: (1) design to interface the printed samples onto a manikin head, (2) the development of a matrix considering 3D printing technologies as well as materials and (3) testing setup for the printed samples as well as results comparing three different factors. Chapter 5 consists of: (1) a preliminary design of a
headset for acoustic testing, (2) a preliminary design of a device to mimic a human ear canal to be implemented into the testing of the headset, and (3) testing and preliminary data for the first headset design.
Chapter 2: Literature Review

2.1 Ear anatomy, spectral cues, and sound localization

2.1.1 Anatomy of an ear

The human ear is a very complex geometry, whose shape has effects on the way sound is perceived by an individual. The ear comprises several components, two of which are important in hearing and acoustic response. One part is the tympanic membrane (TM), also known as the middle ear, which serves as a sound pressure wave receiver that uses factors such as pressure and amplitude in order to retain and process sound into the brain (Luers and Hüttenbrink, 2016). The tympanic membrane has a wall thickness of 0.1 mm and an average diameter of about 10 mm, exposing one end at the eardrum, and the other at the entrance of the ear canal. The external ear, composed of the pinna, concha, and auditory meatus, take sound energy and drive it towards the TM. The other component important in hearing and acoustic response is the pinna, composed of various concavities including the helix, which is distal to the antihelix, where a convex curvature begins. Then follows the scaphoid fossa, a shallow concavity until it reaches the external acoustic meatus (EAM). The EAM begins at the concha until it reaches the entrance of the ear canal (Szymanski and Geiger, 2020) Figure 2.1.1.
The cavities presented and previously discussed are important as they influence sound as it reaches the pinna. The curves and cavities create reflection paths through which sound travels until the entrance of the ear canal is reached (Brungart and Rabinowitz, 1999). Another function of the pinna is to selectively filter sound at different frequencies in order for the brain to process it. The frequencies recorded come from various points in space; therefore, in order to identify the location of sound sources in laboratory settings, elevation and azimuth angles are used as measurements. Sound can be measured in azimuth, angles along a horizontal plane, and elevation, angles along a vertical plane (Butler, Humsinski and Musicant, 1990). Additionally, these products must undergo acoustic testing protocols that analyze factors such as sound localization and preservation. Sound localization is the ability to localize where in space sound is reaching the ear from (Middlebrooks, 1991).

Acoustic testing has evolved over the years with the introduction of acoustical test fixtures (ATFs). ATFs, such as the use of manikins for sound simulating tests have been used in this application with the oldest method using a Knowles Electronics Manikin for Acoustic Research.
(KEMAR) system developed by (Burkhard and Sachs, 1975). These ATF systems are used for free-field testing. Free-field testing is considered a protocol that performed testing in a controlled environment with no sound reflections. Testing is typically composed of a listener or ATF, and a speaker, providing direct sound to the subject. Acoustic testing setups require various considerations in order to perform near-accurate test data. ATFs should match human body dimensions, both in the ear anatomy and components, as well as surrounding body parts. Through the progression of testing methods, it has been discovered that the utilization of skin-like materials to use in testing improved the measurements, hence, the creation of G.R.A.S. KEMAR silicone ears. Artificial ears can be used for closed-coupler testing, used in research for hearing aid and earphone development (Sound, 1995).

2.1.2 Spectral cues and sound localization

The human auditory system is responsible for localization of sound through a human ear. The human auditory system will gather information from various cues, interaural level and interaural time differences (ILDs and ITDs, respectively), which are collected between signals at the ears, and any pinna filtering at frequencies in which they have an effect (Young, Tew and Kearney, 2016). These spatial cues are contained in head-related transfer functions (HRTFs) which are unique for each individual ear. HRTFs are unique due to the pinnae shape’s effect on filtering as well as head size and ear size. A current way to capture HRTFs is through physical acoustical measurement. Various head and torso simulators (HATS) exist to be used as aids in acoustic testing. For example, KEMAR possesses acoustical properties derived from the average human body. This ATF is used in testing of hearing aids, earphones, and other types of hearing protection devices.
Since every individual has different anatomical features which make each ear unique, an important application to explore would be that of improving customized hearing protection and hearing assistive devices. While acoustic testing and advancement of hearing protection technology, further development in testing capabilities can be explored. AM offers the capability for designing and fabricating customized parts, such as the human ear. In order to develop additively manufactured products for use in hearing protection or as hearing assistive devices, understanding the complex anatomical features and capabilities of the pinna can help understand possibilities in preserving spatial cues and sound localization.

2.2 Additive manufacturing

Additive manufacturing (AM), more commonly known as 3D printing, is defined by ISO/ASTM 52900 as a “process of joining materials to make 3D parts” described as a “layer upon layer process, as opposed to subtractive manufacturing.” AM offers the capability of taking complex design models to fabrication as opposed to subtractive manufacturing methods, which implies the removal of material. In addition to complex design, AM can also be combined with conventional methods to improve part fabrication, reduce material waste, and part customization (Guo and Leu, 2013). Additive manufacturing has been around since the late 1980’s, when the first technology was developed: stereolithography, known today as vat photopolymerization (Wohlers Associates Inc., 2015). Soon, commercialization of these technologies was introduced by companies such as 3D Systems, Stratasys, Z Corp, Optomec, ARCAM, and EOS (Guo and Leu, 2013). As more technologies flourished in the AM world, the need to define and categorize these innovations soon followed. ISO/ASTM 52900-2015 divides additive manufacturing into seven process categories: material extrusion, vat photopolymerization, material jetting, binder jetting, powder bed fusion, directed energy deposition, and sheet
lamination. Some of the processes, such as vat photopolymerization, defined by ISO/ASTM have been around for longer periods and are well established, while others are fairly new and continue evolving as the additive manufacturing industry continues to grow. Other methods, such as hybrid manufacturing, combine multiple AM processes or AM and conventional methods, such as electronics embedding during a 3D printing procedure (Espalin et al., 2014). This shows the potential for combining systems to create faster and more accessible procedures for printing. Since its inception, AM has evolved significantly and is increasingly adopted by industries such as aerospace, automotive, biomedical, and military. Through research efforts and the adoption of AM in such industries, the development of software, tooling, equipment, and materials have also expanded.

2.2.1 Material extrusion

Material extrusion is one of the seven process categories defined by ISO/ASTM 52900-2015 as a process in which material is selectively dispensed through a nozzle or an orifice. With the commercialization and high demand of desktop printers, generally using a material extrusion process, these can be evaluated according to cost, build time, material, and geometric accuracy (Espalin et al., 2014). The material extrusion process is composed of the following: a mechanism for feeding material, a heat source, a gantry, and a build platform (Turner et al., 2014) Figure 2.1. 2. The material feedstock travels through a dispensing mechanism driven by a stepper motor. A heat source is used to convert the material into a semi-molten form so it can feed through the nozzle and be extruded onto the build platform. The build platform must be auto leveled prior to printing; however, some technologies require a manual leveling process. If the
platform is not level, it can lead to failed prints due to delamination, warping, and shrinking, among others.

Figure 2.1. 2 Material extrusion closed envelope schematic.

The material is deposited following a path generated by the slicing software. This slicing software generates a Standard Tessellation Language (STL) file that can be read by the printer. This STL file consists of triangles, each of which contains information for a single cross-section of the part (Melchels, Feijen and Grijpma, 2010). STL files can also be generated from CAD software, however, the slicer will prepare the file to be read by the printer. The rollers move the nozzle as material is being extruded throughout the build platform to form each layer until the final part is created. When required, the nozzle may also deposit support material in addition to the model material being used to print the component. Support material is used to hold shapes that exceed a certain angle (commonly, a 45-degree angle) from the vertical in a material extrusion
process (Leary et al., 2014). Support material has other uses, including preventing warping, surface delamination, and printing failure.

A material extrusion process, like most 3D printing processes, may require post-processing to achieve the desired shape and/or surface finish. Material extrusion technologies provide resolution capability of 50 – 200 µm, low cost production, and multi-material capability (Wang et al., 2017). Material extrusion materials are generally tough and durable thermoplastics. Some of the most common materials used for material extrusion are acrylonitrile butadiene styrene (ABS), which has a low glass transition temperature of 110°C and great dimensional stability; and polycarbonate (PC) which possesses stronger mechanical properties than ABS and a lower glass transition temperature of 60°C. While these two materials are easier to use in printing, their mechanical strength suffers in turn. However, there are other materials that offer higher tensile strength such as ULTEM 9085, commonly used for high temperature applications due to its high glass transition temperature of 185 - 216°C (Torrado Perez, Roberson and Wicker, 2014). Material extrusion systems vary in capabilities providing low-cost desktop systems with little to no environmental controls, as well as high-end systems used for production.

Although material extrusion processes have evolved over the years, there are still limitations to using the technology. For example, material extrusion uses the layer by layer bonding method, resulting in anisotropic properties in a part (Urbanic and Saqib, 2019). Anisotropy is introduced in AM processes, due to the build approach. The layer by layer from the build plate towards the +Z direction introduces room for air gaps, raster angle error, delamination, and layer bonding issues (Figure 2.1. 3). Due to this, properties in the Z direction will never be as accurate as those in the XY directions. While a vast range of literature exists defining anisotropy in 3D printed material extrusion components, more research is needed in order to fully understand
the role of anisotropy in part properties. Even though anisotropy is present in fabricated parts, the addition of a heated closed environment is beneficial to the improvement of the part’s mechanical properties.

![Figure 2.1. 3 Print build job breakdown of layers and anisotropy in the direction of the build (Z).](image)

Commercial production material extrusion systems have adopted heated closed environments for fabrication (Loh et al., 2020). However, there are various commercial desktop systems that do not provide a heated envelope due to patented technology for industrial printers. Lacking a heated environment, material extrusion desktop systems also present limitations. An absent heated controlled environment introduces potential effects on part quality, such as delamination, print failure, air gaps, as well as warping. Using desktop systems are also limiting in material misuse and life cycle, as improper storing of material can lead to water absorption, and grinding may occur from feeding material through the roller system incorrectly ((Loh et al., 2020)),
2.2.2 Vat photopolymerization

Vat photopolymerization was the first of the seven additive manufacturing processes to come around in the late 1980’s. Vat photopolymerization can best be described as a process which selectively cures photosensitive resin in a vat by light-activated photopolymerization (ISO/ASTM 52900-2015) (Figure 2.1. 4).

As with material extrusion, vat photopolymerization systems require the creation of STL files, which are converted to G-code for the system to read. While seven AM process categories exist, for years vat photopolymerization provided high resolution and small feature sizes of 50 - 200 µm in comparison to others (Melchels, Feijen and Grijpma, 2010). In this process, single cross sections across a layer are scanned by a UV light source in accordance to the CAD model (Wong...
and Hernandez, 2012). With this process being the most mature, it also provides capabilities for scalable methods, allowing for fabrication of components in normal size as well as micro size manufacturing (Vaezi, Seitz and Yang, 2013). As shown in Figure 2.1, VP processes can achieve 1 µm features in micro printing capabilities. Depending on the technology being used, the process of generating a 3D component varies, where some software requires manual pre-printing setup and others provide auto processing tools for printing.

![Figure 2.1. 5 Micro fabrication using a vat photopolymerization process: Bull model fabricated by 2p-VP. The size scale bar is 1 µm. Used with permission from Springer Nature (Gibson, Rosen and Stucker, 2015)](image)

Vat photopolymerization is one of the process categories that requires post-processing of printed components. The post-processing involves submerging the printed part into a 20 – 40-minute alcohol bath in order to rid it of any excess or trapped resin. Once washed, the model is transferred from the wash station into a UV oven. Depending on the resin material being used, curing temperatures will vary due to material properties. Once the curing is complete, any support material is removed, usually by hand, which may leave some surface roughness in regions of the printed part to which the supports were attached. To remove any unwanted surface roughness, sanding or polishing of the area may be performed to achieve a smooth finish. Like with most AM processes, material selection for vat photopolymerization should be determined based on the
intended application. In order to achieve high accuracy but retain strength through mechanical properties, resin materials such as Somos NeXt can be used comparable to ABS, a material extrusion thermoplastic (Pandey, 2014).

Even as a mature technology, vat photopolymerization processes also pose limitations. A major factor is the handling and use of photopolymer resins. While resin material has been effectively used for 3D printing applications, their unique composition makes them susceptible to shrinkage during printing ((Bagheri and Jin, 2019)). Another limitation is oxygen inhibition, which is needed in order for polymer radicalization to occur and material to begin taking form (Yagci, Jockusch and Turro, 2010). This is an important factor as VP systems are limited in material selection, as only photopolymer resins can be used. Within the printing technology, there is also the limitation of build times, although printing speed using VP systems is high (1-3 cm per hour) (Gao et al., 2015). It has been proven that longer build times result in higher quality prints, and vice-versa; therefore, time is often sacrificed in order to produce higher quality components.

Figure 2.1. 5 Accuracy errors due to overcuring and surface roughness on finished VP prints.
Finished prints also oftentimes show signs of error, requiring post-processing of components to improve part quality. Some errors may occur during the building time, and others may occur during post-processing. A few errors that VP technology printed parts may encounter include overcuring, which affects accuracy and may cause deformation and layer error, and surface deformations, usually caused by improper support removal (Pham and Ji, 2000).

2.2.3 Biomedical applications of additive manufacturing

Additive manufacturing processes have expanded their range of biomedical applications over the years. Applications range from using polymers, ceramics, and composites to fabricate scaffolds and anatomical models, to tissue engineering applications using hydrogels, chitin-based materials, polylactides, and other photocrosslinkable polymers for printing tissue (Melchels, Feijen and Grijpma, 2010)(Arcaute, Mann and Wicker, 2010). Vat photopolymerization has been used since early 2000 in the fabrication of custom molds for hearing aids (Gao and Jarng, 2009). The fabrication of hearing aid shells was adopted by additive manufacturing methods in the form of 3D rapid shell modelling Figure 2.1. 6.
Figure 2.1. 6 Hearing aids provided by Beltone (GN ReSound) with 3D printed custom shell casings.

This method combined scanning, modeling, and building steps in order to produce complex ear impression shells for use in hearing aids. Biomedical applications benefit greatly from the ability to design parts for AM in terms of complexity and customization since the human body is asymmetrical in nature. These application efforts have expanded to dental industries, such as Invisalign, and rapid prototyping for implants in biomechanical research. All the fabrication methods mentioned are executed accurately due to the ability to obtain patient specific imaging data. Having aids such as magnetic resonance imaging (MRI) 3D modelling, mathematical equations programs, and computed tomography (CT) scanning methods, have improved the accuracy in fabrication of these anatomical models.
Other biomedical applications using AM are those for fabrication of anatomical models. Due to a lack of imaging capabilities in past decades, fabrication of complex anatomical models was complicated. However, in manipulating medical imaging data, processes for reverse engineering and fabrication of these models has become more accurate (Cortez, Quintana and Wicker, 2007). Systems have been designed for fabrication of parts such as cardiovascular membranes, to be used by medical professionals in their practice. Additionally, with the freedom of design that AM allows, a focus for anatomical patient-specific design and fabrication later emerged (Arcaute et al., 2003).

2.3 CT and 3D scanning

2.3.1 CT scanning

Computed tomography (CT) scanning is a well-known method used in everyday healthcare scenarios. CT scanning methods have been around since 1963, when invented by Allan Cormack. However, commercialization of the method did not occur until later, when Sir Godfrey Newbold Hounsfield designed the first available commercial system (Leung, 1995). CT scanning uses an x-ray as the scanning source to capture 2-D cross sectional images. Software such as Materialise Mimics, exists to convert Digital Imaging and Communications in Medicine (DICOM) data into STL and other 3D object files. The x-ray procedure works by setting a pre-determined helical thickness. Helical thickness is defined as the thickness of each slice being scanned by the CT scanner. This helical thickness is pre-selected through software prior to performing a scan in accordance to the anatomical area of focus (Grieshaber et al., 2008). Selecting the helical thickness depends on the object being scanned as well as the scanning technology limitations and capabilities. For example, scanning a human ear and its ossicles, a type of bone inside the ear,
would require a smaller helical thickness as opposed to CT scanning a human leg, which contains larger bone sizes. Thus, CT scanning for anatomical modeling may be beneficial due its ability to produce DICOM data that can be converted into STL and other formats Figure 2.1. 7.

![Figure 2.1. 7 Workflow for taking DICOM data, processing, refining, and 3D modeling for printing. Used with permission (Bücking et al., 2017)](image)

While CT scanning may be beneficial, it is also considered an invasive method, and its use is recommended only if necessary. Using x-ray sources in CT scanning causes the emission of radiation, which when scanning a live body, can cause it harm if exposure occurs at high doses (Grieshaber et al., 2008). The cost of CT scanners is roughly $500,000 - $700,000, although that cost omits the cost for establishment of a CT scanning system, operating cost, and maintenance and data storage costs. Therefore, their application in reverse engineering and anatomical modeling
is not justified by the cost. In the case of producing individualized custom 3D models for medical modeling and reverse engineering, CT scanning is presented as the best option in terms of achieving accuracy in the 3D models. However, alternative methods for capturing the data can be considered.

2.3.2 3D laser contact and non-contact scanning

Scanning methods such as photocopying have been around since 1938 and have been used in many applications such as medical, reverse engineering, and more (Thompson, Maskery and Leach, 2016). Laser 3D scanning can be divided into two categories: contact and non-contact scanning. Contact scanners will use a touch probe to directly contact the surface of the sample, whereas non-contact scanners will use other scanning sources, such as a laser, to capture data points without coming into contact with the sample (Martínez and Cuesta, 2008). These scanning systems have evolved over the years, from fabrication of larger scanning machines to mobile hand-held scanners, which are the most frequently used today due to their ease of use (Kersten et al., 2016).
Point cloud data are points representing a location on the object being scanned. By placing multiple points throughout the surface of the part, a point cloud structure is created. 3D scanning methods capture point clouds that are mapped together to form a non-uniform rational basis spline (NURBS) surface. These surface models can be cleaned up to remove any excess or repeated points, also known as noise.

Contact laser scanning requires the use of touch probes to capture these point clouds. To increase the accuracy of the data being captured, touch probes can be interchangeable, allowing the use of smaller diameter probes to capture finer points. Non-contact laser scanning involves using a laser as the source for capturing the data points. While laser scanning can be as accurate as contact scanning, noise is more prevalent in laser scan data due to overlap in capturing the same regions in multiple scan sweeps. However, since all scan data requires post processing, clearing the scans of noise is possible.
Laser scanning can be a cost-effective alternative to CT and MRI scanning, which are two procedures that range high in cost. Additionally, the use of 3D scanning methods would be more affordable than CT and MRI scanning methods. Applications for the use of 3D scanning include forensic testing in crimes, physical anthropology, anatomical model measurements such as internal organs and bones, and documented conservation of anatomical parts (Sholts et al., 2010). 3D scanning systems can be expensive, although more affordable compared to CT scanners. Optical projection scanning systems range from $1,000 - $100,000 and laser scanners range from $25,000 - $1,000,000 (Ahmed et al., 2011).

Although 3D scanner systems may be considered a low-cost alternative to other scanning methods, they also come with limitations. A major limitation for 3D laser scanning is material being scanned. While some components are fabricated out of matte-like material, others are made with metal and resins, which are reflective in nature. The reflectiveness of the material can have an effect on accurate capturing of the data, however, resources such as talcum powder may be used to mitigate the reflectiveness of a component (Odeh et al., 2019). Another drawback of using 3D scan technology is the processing of data. 3D scan data is generally captured in multiple sweeps, meaning a part is scanned more than one time in order to capture all sides of a component. In performing multiple scan sweeps, data merging is followed in processing of the data, increasing the time it takes to process data into a printable form. Lastly, 3D scanning methods are susceptible to human error compared to CT scanning, requiring proper equipment use training, where scan quality and processing relies on the system user.
3.1 Introduction

Additive manufacturing (AM), also known as 3D printing, is often turned to when customization and complexity become a priority in design fabrication. AM capabilities were explored to replicate cavities, curves, and other details on the outermost portion of the ear, also known as the pinna (Figure 3.1). Preservation of ear pinnae geometries is crucial for potential use of AM models in sound and acoustic testing applications (Batteau, 1967). In combining scanning and reverse engineering methods to replicate organic components, choosing AM as the manufacturing method allowed for the potential to replicate these individualized complex and unique ear samples.

![Figure 3.1: Basic anatomy of the human ear.](image)

For the purpose of this experiment, all scanners used were non-contact scanners: a computed tomography (CT) scanner and two 3D scanners. A General Electric (GE) VCT 64-slice positron emission tomography/computed tomography (PET/CT) scanner was used. The CT scanner used a
motorized x-ray source with an 80 – 140 kVp peak, that rotates and captures data around the circular opening, with a 160 cm range for full body scan capability. The circular opening, also known as a gantry, is constrained in diameter size of 70 cm (FaroArm). The cost of this GE CT scanner is around $500,000 - $700,000. While the CT scanner used an x-ray source, the 3D scanners used a laser source to capture data located within a designated base as shown in the schematic in Figure 3.1. One of the 3D laser scanners was a FARO Technologies FARO 8-Axis Quantum ScanArm (FARO, Lake Mary, FL, USA) said to achieve accuracies of ± 25 µm at a scan rate of 280 frames/second. The laser used with this system is a Class 2M laser, emitting visible radiation of 400 to 700 nm with a power output below 1 mW as defines by ANSI Z136.1-2014. The cost of the FaroArm scanner is $58,464 (Appendix 1A). The other 3D laser scanner used was a NextEngine 3D scanner (NextEngine, Santa Monica, CA, USA). This system is a small desktop scanner said to achieve accuracies of ± 127 µm in Macro mode, and ± 381 µm in Wide mode (NextEngine 3D Scanner Technical Manual.pdf). This system uses a Class 1M laser, emitting radiation of 650 nm with a power output of 10 mW. The cost of this scanning system is $2,995; however, it excludes operating, software, and handling costs. After describing the three scanning systems, it is shows that the CT scanner would cost the most, followed by the FaroArm scanner, followed by the NextEngine Desktop Scanner.
In an effort to explore the best scanning methods for replicating complex ear models, various scanning options were evaluated for their potential to output accurate ear geometry point clouds that could be used to generate printable STL files.

Due to limitations in 3D laser scanning methods, a Scan-to-CAD processing software, Geomagic Design X (3D Systems, Rock Hill, South Carolina, USA), was used to clean up the data captured by the scanners. The software provided an automatic analysis and cleaning option; however, since these scan files can be complex in capturing the cavities of the pinnae geometry, manual cleaning through the software was also carefully conducted. The cleaning process of scan data is necessary for generating a 3D model. To generate the 3D model, the software offers an auto surfacing tool, which generates a non-uniform rational basis spline (NURBS) surface on either mechanical or organic 3D scans, thus producing 3D CAD files. These can be modified using other
software with Standard for the Exchange of Product (STP) model data and Initial Graphics Exchange Specification (IGES) file compatibility. An accurate model file relies heavily on the processing of the point cloud data captured by the scanners. To capture KEMAR silicone ear data and replicate it, the cleaning process was crucial in the post processing stage.

3.1.1 Background

The automation of laser scanning methods enabled the use of contact and non-contact scanning for inspection and reverse engineering applications in industry (Son, Park and Lee, 2002). Utilizing non-contact scanning methods to reverse engineer a complex geometry such as the ear can potentially impact current testing protocols for acoustics. A scanning process requires post processing; therefore, the use of expensive software may be necessary to generate scan data to use in testing. Reverse engineering procedures can be performed in a conventional manner by utilizing a caliper and other inspection tools. While portions of a KEMAR silicone ear can be reverse engineered conventionally, the intricate curves and curvatures of a pinna make it near-impossible to recreate them via this method. Therefore, CT and 3D scanning were the methods of choice for this effort. An automated scanning procedure requires positioning of the part, establishing the direction of the scan sweeps, and finally assigning the scan data to a coordinate system (Son, Park and Lee, 2002). While scanning systems are all setup differently, they all require determining a center of axis, such as a base for the sample to be placed on, or for the scanner itself to be in a stationary position. Determining an origin facilitates capturing of the data, as well as provides a guide for merging individual scans.

The use of AM in the hearing industry is not limited to replication of 3D geometries of a human ear as research in these areas can be extended to other applications such as improving
acoustic testing methods and rapid prototyping of ear and hearing protection models. CT scanning methods allow parameters, such as helical thickness, to be set prior to scanning. The helical thickness represents the thickness of each 2D image the CT scanner captures (Fahrni et al., 2017). While capturing 2D images of ear geometries can help map out a general outline and image of the shape and size of an ear, 2D imaging limits the information that can be gathered from these images. Since ears have spatial geometrical information, 3D modeling of CT scan data and 3D scanning methods are better suited to obtain the data in three-dimensional space and perform analysis of ear geometry samples in acoustic testing (Liu, Lu and Zhang, 2015).

3.1.2 Motivation

Utilizing additive manufacturing methods to fabricate complex geometries enables the ability to explore applications involving complex parts such as the human body. By studying several methods to scan the fabricated ear models, they can be analyzed and compared to nominal data to determine which method provides the highest accuracy. Focusing on CT scanning and 3D laser non-contact scanning, the scanning styles can also be compared to one another in terms of processing of data, cost, and efficiency. Additionally, scanning technologies can be used in combination in order to produce higher accuracy scan data. CT scanning may be a beneficial addition to achieving 3D scan data. Likewise, it may be beneficial to use 3D scanning methods to improve data captured with CT scanning. If the ear geometries can be successfully replicated with the highest accuracy, the printed models can be used in testing settings and other hearing industry applications. While ear geometries have an effect on testing based on the application, for this experiment, pinnae geometry accuracy was required in order to test at frequencies over 6kHz when pinna filtering comes into play. Another feature to preserve for this experiment was the ear canal
geometry, as the open space and relative dimension (about 7 mm) allows for test-fit success onto the KEMAR manikin head with microphone placement. In evaluating the accuracy of 3D scanning for the development of 3D printed anatomical models relative to scan data, it can be hypothesized that the FaroArm 3D printer will capture data more accurately due to the capability in range of motion and resolution. Additionally, based on previous work performed it can be hypothesized that CT scanning will be the favorable option for use in accurately replicating KEMAR silicone ears.

3.2 Methods

3.2.1 CT scanning of left and right KEMAR ears

To begin the process of replicating anatomical ear models, two samples of a silicone Knowles Electronics Manikin for Acoustic Research (KEMAR) ear (G.R.A.S. Sound and Vibration, Denmark) were CT and 3D laser scanned using three technologies. The two samples are labeled throughout as small right KEMAR silicone ear and small left KEMAR silicone ear (Figure 3.2.1). The silicone ears include a back interface and a pinna, which is said to have an effect in acoustic testing for frequencies above 6 kHz (Rice et al., 1992). In frequencies above 6 kHz, pinna filtering is considered, where sound hits a region of the pinna, creating reflection paths leading to the ear canal entrance (Rice et al., 1992) Without pinna filtering, the sound traveling to the ear canal can be hindered or interpreted differently.
Figure 3.2. 1 Left to right: Small left KEMAR ear, small right KEMAR ear.

For CT scanning of both left and right KEMAR ears, a 64-Slice GE VCT positron emission tomography/computed tomography (PET/CT) scanner (GE Healthcare, Chicago IL. USA) at a radiology center called Desert Imaging in El Paso, TX was used (Figure 3.2. 2).

Figure 3.2. 2 Desert Imaging PET/CT scanner.
A CT scanner allows for modification of its parameters through a compatible software by providing a range of different anatomical components of the human body to choose from. The first step for setting up the CT scan process was to define the ear parameters. Because the ossicles are the smallest bone in the body, the accuracy of the slicing was the most optimal for AM purposes as the helical thickness slice of 0.625 mm was the smallest option available. Once the anatomical section of the body was defined, other parameters were defined such as: the number of slices of Digital Imaging and Communications in Medicine (DICOM) data, which was set at the maximum, density adjustments, and pre-positioning of the bed where the samples were placed. All ear samples (left and right small KEMAR silicone ears) were placed on a towel on the PET CT scanner bed, and repositioning occurred to ensure that the ear samples were clearly visible and not cut off by the software. Once all the system settings were set; the slice scanning took place and DICOM data was generated. As DICOM data is represented in a 2D image format, post processing of the DICOM data was needed to generate a 3D model.

### 3.2.2 3D non-contact laser scanning of left and right KEMAR ears

The second method used to replicate the KEMAR ear samples was non-contact laser 3D scanning. For laser 3D scanning, two scanners were used: a CMM 8-Axis Quantum Faro® V2 and ScanArm (FARO Technologies, Lake Mary, FL, USA), and an Ultra HD desktop 3D scanner (NextEngine, Santa Monica, CA, USA). Prior to performing scans, both 3D scanners were calibrated depending on the system, in order to gather accurate results. Within each of their corresponding software packages, a calibration setup window was opened to perform this task. For the FARO arm, the calibration required a block that is provided with the product. The block is placed on a surface and the touch probe capability of the FaroArm is used. The calibration will
require the location of various points on the block using the touch probe attached to the arm. Once calibrated, regular use of the software can be continued. The NextEngine 3D scanner calibration requires the setup of the turntable at a specified range distance of 7.5”, 9.5” or 11.5”, based on user preference. Once placed, the software will begin focusing on the turntable based on the defined distance. Once the scanning system is able to focus, it will prompt a preview of the testing setup for use.

The FARO ScanArm is a stationary 8-axis arm that can obtain data through both contact and non-contact methods, using various diameter touch probes for contact and a laser for non-contact scanning. The FARO arm was placed in a stationary position to where the 8-axis arm could be extended to cover the table space the KEMAR ear samples were placed on. The scan arm was used to scan both right and left small KEMAR ear samples. A metal rod was placed to hold the ear samples upright in order to obtain a scan as shown in Figure 3.2.2.1.

Figure 3.2.2.1 Faro Arm 3D scanner and left KEMAR ear sample.
The samples were coated evenly with white talcum powder to avoid reflective light that might interfere with the laser and cause faulty data points and were individually placed within arm length’s reach. The ear samples were not moved during scan swipes; however, new individual scans could be taken by placing the ear samples in different orientations prior to scanning. Individual scans were later imported into a processing software where the data was meshed to generate better scan point clouds.

Data was gathered using the Geomagic Design X (3D Systems, Rock Hill, South Carolina, USA) Faro Arm plug-in. Design X was used to further refine the scanned data and process it to generate a usable STL file. To refine the scan data, it was first captured through the laser on the Faro and moved into the user interface. In the Design X user interface, the mesh buildup wizard was used to fill in cavities that the laser was unable to capture due to positioning issues and pinnae angles covering natural curvatures of the ear. Using this tool, all holes within the mesh were covered, and a water-tight mesh was produced. The software allows for auto surfacing of a water-tight mesh which generates NURBS point clouds that can be further processed into STP and IGES file formats for use in CAD software. After using the auto surfacing tool, both STP and STL files were exported from the software.

The Next Engine desktop Ultra HD 3D scanner also collected data points through non-contact laser scanning. This is a small desktop scanner that includes the body that shoots the laser as well as a platform on which the samples to be scanned are placed (Figure 3.2.2.2). Prior to scanning the KEMAR ear samples, the scanner was set up and calibrated using ScanStudio (NextEngine, Santa Monica, CA, USA), the NextEngine’s scanning software. The NextEngine scanner will sweep through the platform and calibrate the laser to focus on a specific distance chosen by the user. The software allows one to choose from three set distances, and a 7.5 in.
distance was chosen to fully capture the detail of the ear samples. After parts were placed, the
calibration was performed. Before placing each ear sample to run the individual scans, the samples
were coated with powder to prevent reflective light from affecting the laser scan and its ability to
capture point clouds. Each ear sample was placed and fixed using a T-bar tool, provided with the
scanner, that can be fixed onto the platform.

![Figure 3.2.2. 2 Next Engine desktop 3D scanner and left KEMAR ear sample.](image)

After the ear samples were placed and secured, they were not moved. Instead, the platform
rotated after each scan swipe, running a total of 6 scans, also known as divisions. The software
provided various options for the number of scans to be performed. The higher the number of scans,
the better the resolution of the scan outcome. In setting up the scan parameters, a 360-positioning
style was chosen in order to capture the complex geometry through various angles. A total of 6
scan swipes were taken as the samples were rotated. From the three ranges available, the macro
option was chosen, which defines a distance to place the object within. The platform was placed
at a distance of 7.5 in. from the front face of the scanner using a ruler. Once positioned at the specified distance, the ear sample was box selected to frame focus on the ear sample being scanned (Figure 3.2.2. 3).

![Figure 3.2.2. 3 Next Engine scan parameter setup.](image)

The first ear sample was placed, parameters were established, and a scan was performed. Scans are generally made up of multiple scan sweeps, meaning the laser travels across or around the target more than one time. After collecting all data scan sweeps, the data can either be merged, exported, or processed to generate a final scan file. ScanStudio includes a section within the software where post processing of the all the data can be done. However, to maintain consistency, the scan data was exported in STL file format and post-processed in a scan data processing software. The process of taking a silicone KEMAR ear and replicating an accurate STL file using three different scanning methods is described in Figure 3.2.2. 4. Each process requires its own software, steps, and post-processing methods in order to achieve a desired file.
Figure 3.2.2.4 Process for reverse engineering a small right KEMAR silicone ear and exporting a STP file.
3.2.3 Post processing of scan data

DICOM is the standard used to store and handle information in medical imaging. DICOM data can be converted by taking stacked 2D images captured and converting them into a 3D printable format (Kamio, no date). In order to interpret the data for AM applications, a medical imaging processing software known as Materialise Mimics (Materialise, Leuven, Belgium) was used to generate usable STL files for the small right and left KEMAR silicone ears that were CT scanned. Mimics was chosen as it has the capability of outputting data captured by a PET CT scanner, processing stacks of 2D images and generating 3D components. Each ear scan DICOM data was extracted separately from the software as an STL file for printing. CT scans can sometimes record extra point clouds if densities of other items within range are similar; therefore, any extra point clouds, also known as noise, were removed using Design X, a scan data processing software.

For the four samples captured through non-contact 3D laser scanning, small right and left KEMAR ears with the FaroArm and small right and left KEMAR ears with the NextEngine scanner, data was directly imported into the scan data processing software for cleaning. Design X allows for inspection of scan data to identify potential issues, noise, and unnecessary point clouds and conversion of scan to CAD. Using the software, a healing wizard was used to identify what parts of the ear data needed to be cleaned thus all identified issues were corrected. However, the data was cleaned manually in other areas where extra (unnecessary) points were captured outside of the geometry of the ear samples. Once the scans were cleaned and finalized, STL files were exported for printing purposes and STP files were exported for any necessary CAD modifications in the future (Figure 3.2.3.1, Figure 3.2.3.2).
Depending on the quality of the scanner and the number of scans needing merging, the time it took to process each scan varied. Therefore, cleaning of data captured with the CT scanner took significantly less time compared to cleaning of the data captured with the NextEngine 3D laser scanner. The average amount of time it took to clean the FaroArm and NextEngine 3D scans was...
3 to 4 and 7 to 8 hours, respectively. Once all of the holes were filled, an auto surfacing tool within the software was used to generate a NURBS point cloud of the scan. This generated a watertight mesh that could be converted into a solid 3D model, which could then be exported in a variety of file formats. For the purpose of this experiment, the formats exported were STP and IGES since they can be modified in CAD software.

### 3.2.4 CAD generation and scan data inspection methods

After processing of all point cloud and DICOM data, CAD STP and STL files were generated for the small left and right KEMAR ear models. Files in STL format provide limited capabilities for adding, removing, and modifying point clouds within the component. While software allowing for modification of STL files such as Materialise Magics (Materialise, Leuven, Belgium) and Autodesk’s Netfabb (Autodesk, San Rafael, CA, USA) exist, they generally do not provide the same editing capacity as that seen in CAD software when working with STP or IGES files. In order to generate CAD format files, the same scan data processing software was used.

Once all the scan data was successfully generated and cleaned, a method of inspection was required to ensure the accuracy of the data. To do this, a 3D metrology software called GOM Inspect (gom, Zeiss group, Germany) was used to validate the accuracy of the scan data captured by all 3 scanners used. To set this up, a left and right small KEMAR silicone CAD model, provided by G.R.A.S. Sound & Vibration was used as the base and all other models were compared to it. The following were compared to the CAD models provided: right and left small CT scanned KEMAR ear files, right and left small FaroArm 3D laser scan files, and right and left small NextEngine 3D laser scan files. By comparing the data from each of the scanning methods
previously mentioned, accuracies between the technologies used can provide insight as to whether these methods are a viable option for this application.

To begin inspection, a right small KEMAR silicone ear CAD file was imported into the software and aligned. GOM Inspect allows for proper alignment of data, creation of reference points, planes, and geometries. The alignment step allows for the inspection step to be performed. Within the software, the data was aligned using the 3-2-1 Alignment option, where three points on the X-plane, 2 points on the Y-plane, and 1-point on the Z-plane are selected to position the components along a coordinate system. Once the coordinate system is aligned to the first scan, the file to compare was imported and aligned to the coordinate system using the same 3-2-1 Alignment option. Using this method of alignment yielded deviations of under 0.5 mm between the two files being compared.

Once the alignment was complete, a surface comparison the CAD (small right KEMAR ear CT scan) was performed. A study comparing CT to 3D scan data of a skull found that measurement errors within a ± 2 mm range was acceptable and found error of ± 1.5 mm from their scans (Verhoff et al., 2008) (Stull et al., 2014). However, the ear geometry is smaller in size, requiring a smaller range of error. Another study comparing dimensional accuracy between a 3D printed component and processed DICOM data used a ± 1 mm range, reporting results with recorded error within a ± 5 mm range, as discrepancies are clinically negligible (Ibrahim et al., 2009). A range of deviations throughout important features on the parts and maximum/minimum deviations were defined and labeled within the surface comparison process. Once labeled, inspection reports were generated. The process mentioned above for inspection of the small right KEMAR ear CT data was repeated for the left small FaroArm scan data, and right and left small KEMAR ear Next Engine scan data.
In order to perform the 3D comparison to the CT scan data, a 3-2-1 Alignment was performed, aligning the imported data to a coordinate system. Once aligned, CAD data was imported and aligned to the previous alignment. Conducting a surface comparison on the CAD, the software allows for the construction of equidistant surface points that are evenly distributed across the surface of your components. The distribution of the surface point can be defined at a specified distance. In the scan comparisons performed, the distribution of surface points was set at 5 mm apart. When selecting the tool to create these equidistant points, the software will then generate a fitting plane, aligning to the profile of the components. Deviation labels will then be projected in the normal direction of the fitting plane. Aside from surface comparisons, GOM Inspect also allows for the segmentation of specific areas of interest. Once the specific area is chosen, equidistant points and deviation labels are projected only along the selected area. The way the software records these deviations is by computing a perpendicular distance between each point to the nominal data. In interpreting the data, deviations in positive values (red) determine that the CAD coordinates lie above the nominal data, whereas negative values (blue) determine that the CAD coordinates lie below the nominal data.

3.3 Results and discussion

3.3.1 Scanning of a small right G.R.A.S. KEMAR silicone ear

Using GOM inspect, surface comparisons were performed on all the scan files captured. In order to compare them to one another, CT scan files of the small right and left KEMAR silicone ears were used as nominal data. The 3D scans captured with the FaroArm and the NextEngine scanners were then individually compared to the nominal data. The CT and 3D scan data comparisons for small right and left KEMAR ears are shown in Figure 3.3.1 and Figure 3.3.2. The maximum allowable deviation was preset to ± 1 mm and the scale for deviation in the surface comparison analysis was set to ± 0.5 mm as suggested in Ibrahim et al., 2009, in order to evaluate each scanning methods’ capability for accurately replicating complex data such as the human ear.
Therefore, viewing differences with those parameters would help determine whether or not these scanning methods could be used in replicating these models.

Figure 3.3. 1 Small right KEMAR CT and 3D scan comparisons to G.R.A.S. KEMAR file.

The surface comparisons performed on the right small ear 3D scans are shown in Figure 3.3. 1. Performing a surface comparison on the CAD files, that is, the scan data captured with the 3D scanners, deviations were recorded from the nominal (CT scan) part to the actual (3D scan) part. The scale describing the deviations between CAD and nominal coordinates is shown to the right of each comparison.

The CT scan data took the shortest amount of time to post process, with about 30 minutes to an hour of cleaning up. The CT scan data was captured in 2D image slices, then converted into a 3D object in Magics software; therefore, data merging was not required. There were a few issues shown on the pinna portion, where In CT scanning, positioning of the samples on the bed can
affect the scan result, delivering data missing slices of the part. However, the CT scan data was improved by overlapping different CT scans of the same samples. Once overlapped and aligned, the CT scans were merged, improving the quality of the scan. The data showed the highest accuracy in capturing the complexities of the silicone ears; therefore, it was used as the nominal and the 3D scans were compared to it.

Although there were a few issues with the FaroArm scan, raw data did not require much time for cleaning. Post-processing of the scan data took about 3 to 4 hours as various scan sweeps needed to be merged together in order to capture the curves and cavities of the pinna as a whole. The FaroArm 3D scan showed an overall consistency in capturing data points throughout the surface. The surface comparison parameters were preset to a maximum and minimum deviation of ± 1 mm. A total of 112 points, placed 5 mm apart, measuring deviations recorded on the surface comparison were generated. After taking the absolute value of the recordings, an average deviation of 0.17 mm was recorded. The biggest differences in comparison with the CT scan data can be seen on the pinna portion of the scan right below the antihelix where some points seem to not have been captured. Other regions such as the concha and the ear canal entrance also showed the largest error compared to the CT scan. Other large errors can be seen on the surrounding flat surface, which could potentially be a result of poor data merging. Sections of the surface comparison shown in gray are regions out the ear model that do not fit within the allowable ± 1 mm error range used. These sections are primarily located within the concavities of the pinna. It can be concluded that the inability to capture these regions is due to the angle positioning of the scanner when being held.

The NextEngine scan required the most post-processing out of all the data obtained. Post-processing of the scan data took about 7 to 8 hours as the quality of the scan sweeps was not the best and more scan sweeps had to be merged than with the other scanning methods. The surface
comparison parameters were preset to a maximum and minimum deviation of ± 1 mm. A total of 112 points, placed 5 mm apart, measuring deviations recorded on the surface comparison were generated. After taking the absolute value of the recordings, an average deviation of 0.34 mm was recorded. The right ear NextEngine scan showed the biggest differences in comparison with the CT scan data. The NextEngine showed slightly larger deviations throughout the pinna compared to the FaroArm data, reporting deviations of + 0.66 mm and -0.61 mm. The regions with these recordings were also found beneath the antihelix and the concha. Due to lack of movement of the scanning systems on more than one axis, capturing data around the entrance to the ear canal and surrounding deep cavities required additional scan sweeps by repositioning the ear sample in different orientations. Additionally, the inability to move the scanners freely, posed an issue in capturing cavities throughout the ears.

3.3.2 Scanning of a small left G.R.A.S. KEMAR silicone ear

The left scan files generated with the three scanning technologies were created using the same methods for the small right ear. The CT scan data was also used as the nominal data and the 3D scans were compared to it for accuracy. The surface comparison parameters were preset to a maximum and minimum deviation of ± 1 mm. A total of 112 points, placed 5 mm apart, measuring deviations recorded on the surface comparison were generated. After taking the absolute value of the recordings, an average deviation of 0.22 mm was recorded. The locations for these larger deviations are shown to be within the flat surfaces surrounding the pinna. The pinna portion of the scan showed higher accuracy in comparison to the rest of the data points showing deviations under ± 0.20 mm. The FaroArm data captured shows deviations from the nominal outside the ± 0.5 mm scale, predominantly within the interfacing surface of the ear (flat surface).
Figure 3.3. 2 Small left KEMAR CT and 3D scan comparisons to G.R.A.S. KEMAR file.

The NextEngine 3D scan, shown on the right, showed the largest inconsistency in capturing data, even along flat surfaces. The surface comparison parameters were preset to a maximum and minimum deviation of ± 1 mm. A total of 112 points, placed 5 mm apart, measuring deviations recorded on the surface comparison were generated. After taking the absolute value of the recordings, an average deviation of 0.34 mm was recorded. The locations where these deviations were marked were not only within the curves and contours of the pinna portion of the ear, but also on the surrounding flat surfaces, showing deviations outside the scale of ± 0.5 mm. The left NextEngine surface comparison also showed regions in gray, meaning that the data points in those regions recorded deviations over the set max/min ± 1 mm range. The left ear 3D scanned data from both the FaroArm and the NextEngine 3D scanner showed that the largest area of error was within on the flat surfaces of the ear models compared to the nominal CT scan data.
3.3.3 Capturing complex geometries of pinnae using scanning methods

To further evaluate how well the 3D laser scanning systems captured curvatures and cavities, a front view of the pinnae is provided. The cavities and curvatures of the pinna were considered; therefore, replicating those features closely shows the potential in using 3D scanning methods for this application. The right FaroArm 3D scan shows deviations within ± 1 mm; however, it lies within the acceptable range for measurement error of ± 2 mm. From the FaroArm scan data, only a few sections of the pinna lied outside the ± 1 mm scale (Figure 3.3.2.) The FaroArm captured the cavities of the pinna, however, due to the limitation of rotation of the handheld scanner, the deepest cavities required more scan merging to obtain all the data points. The right NextEngine 3D scan showed the largest differences compared to the nominal. The flat portion of the ear captured was off by ± 0.15 mm in comparison to the data captured by the FaroArm; however, data captured on the pinna portion is less accurate than that of the FaroArm. The cavities of the pinna showed deviations lying outside the ± 1 mm range. In comparison to the FaroArm data, the NextEngine 3D scanner is not a suitable option for capturing the complex areas of the pinnae. Since the data that lies deeper into the cavities is the one that is harder to capture with either of the 3D scanning methods, it can be concluded that the tool to which the laser is attached limits successful capturing of the data within the pinna (Figure 3.3. ).
Figure 3.3. 3 Cavity differences on small right ear scan data comparisons.
Looking closely at the deviations between each right ear scan and the G.R.A.S. KEMAR scan data, Equidistant Deviation surface comparison points were recorded. A total of 112 points were generated, and each of the points were equally placed at a distance of 5 mm throughout the surface for each individual comparison. After capturing the values, the right ear FaroArm 3D scan recorded an average deviation of 0.17 mm, and the right ear NextEngine 3D scan recorded an average deviation of 0.34 mm. Based on the comparisons performed on the 3D scans in comparison to the CT scan data, both 3D scanners on average performed under the ± 0.5 mm desired threshold. However, the FaroArm performed better than the NextEngine desktop scanner. Looking closely at the front view of the surface comparisons, the FaroArm also captured the cavities better, recording deviations under ± 0.4 mm, whereas the NextEngine recorded deviations under ± 0.6 mm.
Figure 3.3. Surface comparison on CAD for right small ear NextEngine and FaroArm 3D scan data.
Equidistant Deviation surface comparison points were also generated for the left ear scan files compared to the CT scan data Figure 3.3. 2. A total of 112 points were generated and placed at an equal distance of 5 mm throughout the surface of the scan data. From this data, the left ear FaroArm 3D scan recorded an average deviation of 0.22 mm, and the left ear NextEngine 3D scan recorded an average deviation of 0.34 mm. Compared to the data captured for the right ears, the scans for the small left KEMAR ear had a larger difference. While this result could be due to human error, it is important to note that the left and right small KEMAR ears were different in thickness, size, and pinnae geometry. Overall, looking at the surface comparisons, it can be concluded that amongst the two 3D scanners tested, the FaroArm 3D provided greater results, resulting in smaller deviations from the nominal under ± 0.5 mm of -0.02 mm. The NextEngine
followed, recording deviations under ± 0.9 mm. However, the PET CT scanner still remains the nominal choice when comparing the three scanners.

3.4 Conclusions

Scanning is a useful method in reverse engineering applications, allowing for the replication of components and assemblies. Replication of a silicone KEMAR ear is possible due to the evolution of scanning methods such as CT and 3D laser contact and non-contact scanners. By using a combination of CT and 3D scanning methods, unique geometries such as an ear, can be replicated and reproduced. While 3D scanning may not be a stand-alone suitable option for this application, it can be used as a means to improve data captured by CT scanners as well as in reverse engineering efforts. Based on the cost outline mentioned in section 3.1, CT scanning is more expensive once equipment, operating, handling, and processing costs are considered; thus, 3D scanning methods can also serve as a low-cost alternative for capturing data. Whether CT or 3D scanning methods are used, each method requires post-processing of the data in order to generate usable STL, STP, and IGES files for 3D printing applications. Additionally, during post-processing, the data captured by the lower-cost 3D scanner took about twice as long to post-process compared to the higher-end 3D scanner option. The FaroArm surface comparison showed higher accuracies in capturing data in comparison to the CT scan of the right and left KEMAR silicone ears. Therefore, slightly more expensive 3D scanning technology options, such as a $58,464 FaroArm scanner may be more beneficial than a $2,995 NextEngine desktop scanner. Depending on the target application, CT and 3D laser non-contact methods can be used individually or in combination in the production of data.
Chapter 4: Technology comparison; technology and material matrix development

4.1 Introduction

Additive manufacturing can be further divided into 7 process categories: vat photopolymerization, material extrusion, material jetting, binder jetting, powder-bed fusion, directed energy deposition, and sheet lamination. The applications for each of these processes vary depending on capabilities such as material selection, build size, and cost, among others. While processes such as powder-bed fusion and directed-energy deposition have great potential in aerospace and automotive industries due to their ability to print metal, other processes like material extrusion and vat photopolymerization are used for applications such as bioprinting, food printing, and dental applications (Ngo et al.).

It was previously discussed that ears can be categorized as a complex geometry of the human body; therefore, additive manufacturing methods were sought out in an effort to replicate the unique geometries of KEMAR silicone ears. In choosing AM, the processes were further explored to choose the best suited for medical applications. Factors that were considered in narrowing down to a selection of processes included the following: printer build size, material selection, resolution, and cost. In an effort to replicate the ear geometry, accuracy and precision were priorities; hence, the selection of vat photopolymerization as it provides high resolution of 50 – 200 µm in prints according to Ngo et al. Vat photopolymerization is widely applicable to the fabrications of medical models and is as a good fit for this application as suggested in Marciniec and Miechowicz. A second process was selected with the intention of comparing it to vat photopolymerization in terms of the technology’s ability to accurately replicate an ear model. The second process chosen was that of material extrusion. This process has proven to be able to produce medical models with similar accuracy (under 0.5% mean error) to other industrial-grade
technologies in processes of PolyJet and Selective Laser Sintering printing (Petropolis, Kozan and Sigurdson, 2015). Within these process categories, a range of printers and materials with different build sizes and material capabilities were available. Additionally, a selection of two commercial-grade desktop systems from both process categories were chosen in order to evaluate the potential for a low-cost alternative fabrication method for these ear models. A technology matrix was developed comparing two AM processes, an industrial and desktop system within each process category, as well as a low-cost alternative comparison between two industrial systems and two desktop systems. Other factors affect print quality, for example, material extrusion industrial systems offer heated envelopes, which tend to promote better adhesion and prevent warping of the part. Most material extrusion desktop 3D printers, however, are open-source printers, and their exposure to environmental factors can affect the quality of the print.

4.1.1 Background

Fused Deposition Modeling (FDM) is a material extrusion process that uses a heating source to melt material most commonly presented in filament or pellet form. Within this process, thermoplastic material is deposited through a nozzle or an orifice onto a build platform, and layers are added upon one another to create a 3D geometry (Ngo et al.) (Figure 4.1.1). As the material is being deposited in a semi-melted form, it begins solidifying, and as new layers are added on top of one another, the 3D component will begin to take form.
This process allows for the modification of parameters such as layer thickness, layer width, component orientation, and temperature depending on the system. By modifying these parameters along with other factors, a desired .gcode, which is a readable file format that runs lines of code with coordinates indicating where material is to be deposited at specified parameters ((Duong et al., 2018)). Post-processing is required when using this process, for example, manual removal of any support material added in order to fabricate components. In comparing industrial vs. desktop systems used, the FDM Fortus 400mc offers a heated envelope, known to promote adhesion and improved print quality. The Lulzbot TAZ 6 does not provide that capability as printing parts in an open environment can have an effect on print quality.

Vat photopolymerization, also known as stereolithography, was the first commercially-available additive manufacturing technology, developed in 1986 (Ngo et al.). Over the years, the technology capabilities have evolved in speed, resolution, and fabrication methods; therefore, high accuracy in fabrication applications is now possible. This process uses a UV light to activate
polymer chains, also known as radicalization, of resin material thus causing it to solidify and create 3D components. This reaction continues as a new layer of fresh resin is placed onto a bed or platform until the 3D model is created (Figure 4.1. 2). This process also allows for modification of parameters like layer thickness, width, and orientation placement of the component. Once parts are printed, post-processing such as support removal, alcohol soaking, as well as part curing in an oven is necessary in order to achieve the desired surface finish. While the two processes mentioned above may have different methods for the creation of 3D printed models, their material and parameter capabilities make them suitable options for medical modeling applications. Medical modeling application requirements focus on features such as material selection, biocompatibility, dimensional accuracy, and sterilization compatibility, as they are heavily used in hospital environments (Marciniec and Miechowicz, 2004)
A medical application that can be further explored for additive manufacturing is that of hearing aids and hearing protection devices. The fabrication of hearing aids and shells has adopted stereolithography methods since 2000, with the creation of rapid shell modeling (Dodziuk, 2016). With AM applications in hearing aid fabrication, exploring 3D printing of complex geometries, such as a human ear, is another application that could potentially benefit from the technology. Hearing protection devices are used in industries such as military and aviation. In order to produce satisfactory products for use, acoustic testing methods seek to improve prototypes in order to produce suitable products.
4.1.2 Motivation

Introducing 3D printed components to a traditional acoustic testing setup can be beneficial in many ways such as: finding lower-cost alternatives for custom device testing through the use of available desktop systems with an ability to replicate unique features of the human ear. A focus in this field could promote research for improving current methods for applications in hearing protection and hearing assistive devices. This study allows for the use of various technologies, both industry as well as desktop systems, that can be compared to one another in terms of accuracy capabilities. Developing matrices for testing out various technologies and other factors such as material selection and resolution for replicating the ear models can help identify a technology that is best suited for this type of application. Additionally, these studies can also help identify the benefits and drawbacks of each technology involved in the study with respect to the hearing industry. Selecting technologies to be used, other comparisons can be made between industrial systems and desktop systems. While industrial systems can be used in medical modeling applications, replicating accurate 3D printed KEMAR models using desktop systems can also be explored. Companies are constantly improving their commercially available technologies to be used in industry, including industrial and desktop systems. With the development of new desktop systems, their use for medical modeling applications can be explored in terms of cost, dimensional accuracy, and print quality.

Sound localization is defined as the ability to localize where sound is coming from in space (Jin et al., 2000). In being able to localize sound, a human subject’s natural reaction is to turn their head towards the direction they hear the sound coming from. Human localization is important as it allows the listener to engage and react accordingly to the sound approaching them. It is much more important in scenarios such as a war zone or guiding traffic at airports. While localization is
achieved naturally by an individual’s ears, hearing protection in areas of high noise impact is necessary for the preservation of a person’s hearing capabilities. When wearing hearing protection devices, the pinna geometry, as well as the entrance of the ear canal are partially blocked off by the hearing protection, ultimately impacting frequency response. In frequency response testing, gain is the input level of sound which the microphone signal goes through first. To improve the use and capabilities of hearing protection devices, investigating ways to improve localization in testing methods can help better understand how it can be preserved or improved when using hearing protection devices.

Subjecting various AM technologies to this study enables the ability to explore materials available for 3D printing purposes. Some materials are meant for specific applications; however, AM allows for comparing fabrication methods of various materials without directly affecting the cost. The human body, in particular the ear, has very intricate features and textures throughout that play a part in how sound is perceived. This can inspire the development of a matrix involving materials that have similar properties to that of human skin. By testing out these different materials, sound testing data can be further analyzed to identify the different effects material may have on sound perception and sound localization. Therefore, material selection may be a beneficial factor to focus on in future studies due to the effect of material properties on sound perception (Kuru et al., 2016). Based on previous literature assessing the capabilities of material extrusion and vat photopolymerization systems, it can be hypothesized that 3D ear models printed using vat photopolymerization systems will perform better in acoustic testing due to their higher resolution and smaller layer thickness. In the case of comparing industrial systems and desktop systems, it can be hypothesized that industrial prints will perform better in acoustic testing.
4.2 Methods

4.2.1 Silicone insert design and printed ear samples

In order to fabricate the KEMAR ear samples, the data captured with the PET/CT scanner (described in Chapter 3) was processed and converted into standard tessellation language (STL) files for printing. Using these models, two design ideas were presented, one with a single material design and another with a multi-material design assembly. Design 1 (D1) was a CT scan replica of the right and left silicone ears, those which include the back portion of the ear scan that interfaces with the KEMAR manikin (Figure 4.1.2.1). This design was not modified, only cleaned after scan data was collected and processed through Materialise Magics (Materialise, Gilching, Munich). However, this design presented issues as the materials selected for D1 were rigid. Due to the rigidity of the back interface of the printed ear samples, a tight assembly of the printed samples into the KEMAR manikin interface was not possible. The interface on the KEMAR manikin is predesigned to fit the silicone ears fabricated by G.R.A.S. which are molded out of a semi-flexible material (Figure 4.1.2.1).
The main goal in interfacing between the KEMAR ear and the manikin head was to be able to create a tight seal in the joining of the two, avoiding any possibility for sound leakage during testing. D1 did not meet the design requirements that would allow for this tight seal when inserted into the manikin head. The issues that D1 presented inspired a redesigning period, creating a second design called Design 2 (D2), whose primary focus revolved around the preservation of the pinnae geometry on both left and right small KEMAR ears.
D2, shown in Figure 4.1.2. 2, shows modifications to the portion of the ear scan that does not involve the pinna. It incorporates a two-part assembly, the pinna, printed out of the chosen technology using the same materials that D1 was printed with, and a pocket, molded out of flexible silicone material. The pinna CAD was modified to fit snug into the silicone pocket by adding material to the outline of the pinna geometry. This extra material is then to be inserted into a molded silicone pocket generated to fit the pinna. The silicone pocket mimics the original silicone ears that were scanned, having that back interface on them that assembles with the KEMAR manikin head. In creating the silicone pocket, a mold fitting the ear parameters was designed. The
back portion of the interface of the silicone ears, shown in Figure 4.1.2. 3, was added to the mold design to allow the curvatures on the flat surface of the KEMAR silicone ears to be molded.

Figure 4.1.2. 3 Mold CAD design silicone pocket assembly of Design 2 for printing KEMAR ears.

Before molding the silicone pockets, material selection was explored and narrowed down to the following: AeroMarine Food Grade 40 durometer and Food Grade 30 durometer platinum-based mold making rubber. According to Falanga and Bucalo, the hardness range of skin surrounding the human ear can be classified within the range of 25 to 45 durometer. A design consideration required that the printed ear model was to seal into the manikin head interface. This seal was necessary in order to ensure the proper position of the ear model, as well as prevent any sound leaking from the manikin during testing. To develop a printed ear model that sealed on the
manikin, two different durometer silicone rubber materials were chosen to mold the silicone pockets for the printed ear samples. The two silicones were chosen due to their hardness being similar to that of skin, as previously mentioned, as skin-like and skin models allow the simulation of skin behavior (Dabrowska et al., 2016). To avoid slippage or a detached printed assembly, various silicones were selected for molding the silicone pocket needed to provide some rigidity by securely attaching onto the KEMAR manikin head interface. With the pockets being made out of semi-flexible material, a seal element between the 3D printed ears and the interfaces on the manikin head was presented (Figure 4.1.2. 4).

Figure 4.1.2. 4 Molded silicone pockets, insert of Formlabs on KEMAR (top, Shore 40, bottom, Shore 30).
To create the silicone pockets, the designed molds were 3D printed out of two industrial technologies: a 3D Systems (3D Systems, Rockhill, SC, USA) Viper SLA printer and a Stratasys Fortus 400mc printer. Post-processing such as UV curing and manual support removal was required for the fabricated molds. The Shore 40 durometer material was used to create a right and left silicone pocket out of the mold fabricated with the Viper SLA. To avoid adhesion to the mold, a CRC boron nitride mold release (CRC, Horsham, PA, TX) was applied to all three parts of the mold and left out to dry for 10 minutes. Once dry, the silicone mixture was prepared. To prepare the mixture, the Shore 40 mold making rubber was mixed with an AeroMarine Food Grade Catalyst at a 10:1 mix ratio. A plastic cup was placed on a scale and 100 g of the liquid Shore 40 rubber material were added, then, 10 g of the catalyst were added and the two were hand mixed with a spatula. The selection of the two silicones was based off the KEMAR manikin silicone ears being Shore 55 and the similarities to that of skin material. After thorough mixing, the mixture was placed in a vacuum for 5 minutes to rid it of any air bubbles.

Using a 5 mL syringe, the mixture was transferred from the mixing bowl and inserted into an assembled mold through the pour hole. A few issues in the creation of the first set of silicone pockets pointed out the mold needed to be held at an angle in order for the material to spread evenly throughout the smaller cavities. Since the material was not fully spreading throughout the mold cavities, the mixture was transferred and inserted until it began pouring out of the designed escape holes. To ensure enough material rested within the mold, excess material oozed out of the mold until it was free of any air bubbles. This process was repeated to create the left silicone pocket out of the mold fabricated with the Viper SLA. Two additional silicone pockets for small left and right KEMAR ears were made out of the Shore 30 durometer rubber (AeroMarine 30 durometer food grade rubber) using the molds printed on the Fortus 400mc printer.
Figure 4.1.2. 5 Print assembly for right and left KEMAR ears into anthropometric manikin.

Having the back portion of the KEMAR ears made out of flexible material allowed the ear assemblies to be inserted into the interface and be flush with the contour of the manikin head (Figure 4.1.2. 5). In this experiment, a factor for replicating these silicone samples was the ability to preserve the pinnae. Different design modifications were implemented in order to compare the interfacing of the ear samples and the original silicone KEMAR ears to the manikin head. The silicone pocket and printed ear assemblies were each inserted into the manikin head to ensure the pockets conformed to the KEMAR manikin head like the silicone ears did.

4.2.2 Technology matrix development and breakdown

Technologies available for additive manufacturing applications range from low-cost options used in home projects, prototyping, and education up to higher end options used in
applications such as production for aerospace and automotive industries. By developing a matrix of technologies to use for the fabrication of the small right and left KEMAR ear STL files, the matrix was setup by dividing the chosen technologies into industrial (high cost) and desktop systems (low-cost). Additionally, the matrix also divided the technologies into the following process categories: vat photopolymerization and material extrusion. To print out the STL files generated from CT scan data in chapter 3, four systems were chosen: a 3D Systems’ Viper SLA printer (3D Systems, Inc., Rock Hill, SC, USA), a Formlabs Form 2 desktop printer (Formlabs Inc., Somerville, MA, USA), a Stratasys Fortus 400mc FDM printer (Stratasys, Ltd., Eden Prairie, MN, USA), and a Lulzbot TAZ 6 desktop printer (Aleph Objects Inc., Loveland, CO, USA) (Table 4.1.1). The Viper SLA and the Form 2 are printing technologies that fall under the vat photopolymerization process of additive manufacturing. The differences between the two is that the Viper SLA is an industrial system and the Form 2 is a desktop system. The other two technologies fall under the material extrusion process of AM, with the Stratasys Fortus 400mc FDM printer developed for industry and the Lulzbot TAZ 6 printer developed as a desktop system.

Table 4.1.1 AM technology matrix for fabrication of ear samples.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Industrial</th>
<th>Desktop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vat photopolymerization</td>
<td>3D Systems’ Viper SLA system</td>
<td>Formlabs Form 2 desktop printer</td>
</tr>
</tbody>
</table>
To fabricate the ear samples, the STL files for the small left and right KEMAR ears were imported into corresponding slicer software for each technology in order to prepare a .gcode file. To prepare a .gcode file for the Viper SLA, a slicer software was used to set parameters and position the ear samples on the bed platform. Printing with the Viper SLA, the ear samples were individually printed at a layer thickness of 0.07 mm out of Somos NeXt material (DSM, Heerlen, Netherlands). In preparing a .gcode file for the Form 2, slicer software Preform (Formlabs, Somerville, MA, USA) was used to set parameters and position the ear samples at an angle on the build platform. Ear samples were individually printed on the Form 2 out of Tough resin at a layer thickness of 0.10 mm (Table 4.1.2).

To prepare a .gcode file for the Fortus 400mc prints, slicer software Insight 3D (Smd3D, Calicut, India) was used to set parameters and position the ear samples on the bed platform. Each ear sample was individually printed out of polycarbonate (PC) at a layer thickness of 0.127 mm. Lastly, to prepare a .gcode file for the Lulzbot TAZ 6 printer, slicer software known as Simplify 3D (Simplify 3D, Cincinnati, OH USA) was used to set parameters and position the ear samples on the bed platform. Each ear sample was printed out of acrylonitrile butadiene styrene (ABS) at a layer thickness of 0.125 mm (Table 4.1.2). In choosing the build orientation for the samples, each individual ear was placed with the back interface resting on the build plate in order to minimize support material surrounding the pinnae. Average build time for each ear sample printed was about
2 hours. The build time varied depending on pre-printing preparation, failed prints, and other troubleshooting events.

Table 4.1. 2 Fabrication parameters for AM technologies.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Technology</th>
<th>Layer thickness</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vat photopolymerization</td>
<td>Viper SLA</td>
<td>0.07 mm</td>
<td>Somos NeXt</td>
</tr>
<tr>
<td></td>
<td>Form 2</td>
<td>0.10 mm</td>
<td>Tough resin</td>
</tr>
<tr>
<td>Material extrusion</td>
<td>Fortus 400mc</td>
<td>0.127 mm</td>
<td>PC</td>
</tr>
<tr>
<td></td>
<td>Lulzbot TAZ 6</td>
<td>0.125 mm</td>
<td>ABS</td>
</tr>
</tbody>
</table>

4.2.4 Anechoic chamber setup and testing

Traditional testing methods exist for sound and acoustic response. An anechoic chamber is a room that is setup to block out and absorb reflections of sound or electromagnetic waves. To subject all 3D printed components to testing methods, an anechoic chamber setup was used at Beltone headquarters (GN ReSound, Glenview, IL) (Figure 4.2.4. 1).
A schematic provided by Beltone represents the general specifications for the anechoic reverberant chamber. Anechoic chambers are commonly used to test hearing aid and hearing equipment capabilities used in applications such as: medical care, aviation, and military. Prior to any testing, the chamber was setup with sound equipment. The setup included the following: an anthropometric manikin (KEMAR), two samples of a KEMAR silicone ear (G.R.A.S. Sound and Vibration, Denmark), eight 3D printed replicas of the KEMAR silicone ears, microphones, speakers, wiring, and software.

In this testing setup, the KEMAR manikin is positioned at the center of a turn table inside an anechoic chamber. In maintaining the speaker in a static position, the manikin used for testing rotates along a horizontal plane for 360° in a clockwise direction. Prior to testing, calibration of the setup was performed. To capture the data, software Soundcheck 17 (Listen Inc., Boston, MA, USA) was used. Maintaining the speaker aligned to the horizontal plane, frequencies were
measured along a range of angles, also known as azimuth. Azimuth can be defined as the angle provided by the sound source, relative to the position of the center of the manikin head along one plane (Middlebrooks, 1991). In using anechoic and semi-anechoic chambers, design and dimensions of the room are important as they affect testing capabilities. Conventional anechoic chambers handle various sound sources from moving microphones in order to evaluate signal (Kim, 2012). The testing setup used for the KEMAR silicone ears and printed samples included the measurement parameters in (Table 4.2.4. 1).

Table 4.2.4. 1 Measurement parameters of anechoic camber setup for testing KEMAR and D1 printed ear samples.

<table>
<thead>
<tr>
<th>Measurement parameters</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input:</td>
<td>4s Pink Noise @75 dBSPL/Freq. Log Sweep @</td>
</tr>
<tr>
<td></td>
<td>80dBSPL</td>
</tr>
<tr>
<td>Field:</td>
<td>In Situ</td>
</tr>
<tr>
<td>Distance (Source Speaker – DUT):</td>
<td>1 meter</td>
</tr>
<tr>
<td>Measurement system:</td>
<td>SoundCheck 17, Full Analysis</td>
</tr>
<tr>
<td>Source speaker:</td>
<td>Tannoy VX6</td>
</tr>
<tr>
<td>Anechoic room:</td>
<td>GN ReSound, Glenview, IL</td>
</tr>
<tr>
<td>Anechoic room LxWxH:</td>
<td>280&quot; (L) x 184&quot; (W) x 129&quot; (H)</td>
</tr>
</tbody>
</table>
4.3 Results and discussion

4.3.1 Silicone pocket analysis

Design 2 of the fabrication of 3D printed ear samples included a silicone pocket molded out of rubber material. When molding these pockets, two different durometer options were made in order to test out the flexibility of the material and the sealing capabilities onto the KEMAR head interface. Shore 40 silicone was molded out of a 3D printed stereolithography mold and pink-like silicone pockets were created. Shore 30 silicone was molded out of a 3D printed FDM mold and purple-like silicone pockets were created. From initial observation, differences in the surface texture of the silicone pockets can be seen (Figure 4.3.1. 1). Since the material extrusion mold was printed at a larger layer thickness than the vat photopolymerization mold, 0.127 mm and 0.07 mm respectively, it can be concluded that the surface texture on the purple silicone pockets was a result of the technology used to print the molds. Although both silicone pockets molded out of different technology prints were successful, the Shore 40 silicone pocket sealed into the KEMAR manikin head. Additionally, through test-fitting procedures, it was noted that the Shore 30 silicone pocket began to wear as constant use of it began to tear it due to its hardness.
The two different molds were assembled onto the printed ear samples and subjected to acoustic testing. All testing on the 3D printed samples was performed by Srdjan Petrovic, acoustics engineer, at GN facilities in Glenview, IL. For testing, the printed ear and silicone pocket assembly was inserted onto the KEMAR manikin head. Based on data captured, similarities amongst both molded pocket types could be observed at 90° (Figure 4.3.1. 1a). However, the molds showed the largest gain differences at 180°, marked in orange arrows, with the samples in the pink molds showing gain differences of up to 5 dB at a frequency of 6.50 kHz and 6 dB at a frequency of 8.18 kHz (Figure 4.3.1. 1b). In contrast, the samples in the purple molds showed gain differences of up to 10 dB at a frequency of 6.88 kHz and up to 9 dB at a frequency of 7.72 kHz.
Figure 4.3.1. 2 Mold comparison: Shore 40 (pink) vs. Shore 30 (purple) mold at 90° and 180° (3 to 10 kHz).

Figure 4.3.1. 2 shows a data comparison between each printed sample with two different molds at 270° and 360°. While differences were noted between the two molds, they did not have a large effect at these two angles like Figure 4.3.1. 1b showed at 180°. Both mold tests show a difference in gain response after surpassing a frequency of 7.72 kHz for the right ear samples. The pink mold shows a large gain difference of 13.49 dB at 9.72 kHz. The purple mold shows a similar pattern, recording a gain difference of 13.94 dB at the same frequency. While multiple tests for the samples may provide more accurate data, the differences in this test can be due to a misalignment between the right printed samples and the silicone pockets that show error as the frequency increases. Overall, the purple mold samples showed the largest difference in gain response compared to the pink mold samples. This observation is more apparent in the data captured at 180°, as data captured at 270° and 360°, Figure 4.3.1. 2a, Figure 4.3.1. 2b, showed the
smallest differences in gain response under ±1 dB. The gain response behavior for the purple mold printed samples shows gain response differences of up to 10 dB. The 3D models in the purple mold showed a difference of 1.66% in gain response behavior compared to the models in the pink mold. In an effort to be as accurate as the KEMAR silicone ears, the pink molds, Shore 40 silicone, would be a more suitable option to replicate these models. In order to evaluate the mold accuracies fabricated with the two manufacturing systems, multiple mold prints are required in order to perform a thorough analysis.

4.3.2 Accuracies between material extrusion processes

The two material extrusion printers whose accuracies were compared were an FDM Fortus 400mc and a Lulzbot TAZ 6. Although different layer thickness parameters were used with each printer due to machine capability, similarities and differences between them and the original small KEMAR silicone ears were explored. The data recorded shows gain response over a frequency range of 3 to about 10 kHz at 4 different angles: 90°, 180°, 270° and 360° (Figure 4.3.). The data represented by the solid lines are printed samples using the pink silicone pocket and the one represented by the dotted lines are those printed using the purple silicone pocket. This data compares both material extrusion process printed ear samples as well as the G.R.A.S. silicone KEMAR ears that are regularly used for testing. Both of the printed samples performed similarly during testing. Figure 4.3. a shows gain response at 360°, where sound is approaching the manikin head directly from the front. At 360°, the smallest deviations in gain response were recorded for the printed samples compared to the silicone KEMAR samples. At 90° and 270°, slightly larger differences of up to 1 dB can be seen (Figure 4.3. b, Figure 4.3. d). However, past a frequency of 8.66 kHz, both left and right printed samples show a larger difference in gain response compared to the silicone KEMAR ears.
Over a frequency range of 3 to about 10 kHz, both printers recorded a similar gain response compared to that captured by the KEMAR silicone ears. However, large differences were evident, specifically, at 180 degrees, where sound approaches the manikin from the rear (Figure 4.3. c). The highest differences in gain response are typically shown when sound is traveling to the manikin positioned at the origin from the rear. This is expected as localization within these frequency ranges can be harder to achieve, due to physical components blocking or deviating the sound (Middlebrooks, 1991). At this angle, differences in gain response were twice as large for the Lulzbot prints compared to the Fortus 400mc prints.

![Figure 4.3. Material extrusion technologies gain response at a) 90°, b) 180°, c) 270°, d) 360° (3 to 10 kHz).](image)

Figure 4.3. 2c shows that the biggest differences in gain response are coming from the small right and left Lulzbot ear samples. The right Lulzbot printed ear sample shows a gain difference of over 5 dB compared to the original KEMAR ear at a frequency of 6.50 kHz. Past this frequency, both Lulzbot printed samples deviate in gain response from the silicone KEMAR ears at around an
average of 3 dB. In contrast, the FDM printed samples only showed about a 1 dB difference compared to the KEMAR ears at a frequency of 6.50 kHz and remained within a 1 dB range as the frequency increased. While factors such as ear sample placements and alignment may have contributed to the differences in gain response, it can be concluded from data that the Fortus 400mc printer of the material extrusion processes performed better than the Lulzbot TAZ 6 desktop system as the TAZ 6 printer showed gain differences of up to 5 dB compared to the KEMAR silicone ears.

### 4.3.3 Accuracies between vat photopolymerization processes

The two vat photopolymerization printers whose accuracies were compared were a Viper SLA and a Formlabs Form 2. Although different layer thicknesses were used for the prints due to machine capability, similarities and differences between the printed samples and the silicone KEMAR ears were apparent. The data shown in Figure 4.3. 3 Vat photopolymerization technologies gain response at a) 90°, b) 180°, c) 270°, and d) 360° (3 to 10 kHz).

compares the vat photopolymerization printed samples to the original small KEMAR silicone ears at angles of 90°, 180°, 270°, and 360° within a frequency range of 3 to about 10 kHz. The data captured at 360°, shown in Figure 4.3. a, showed the smallest differences in gain response in both printed samples compared to the silicone KEMAR ears, showing gain differences of less than 0.1 dB. Similar to the results captured by the material extrusion tests, at 90° and 270°, Figure 4.3. 3b, Figure 4.3. 3d, differences of up to 1 dB can be seen between the vat photopolymerization printed samples. After a frequency of 8.66 kHz, larger differences in gain response can be seen. Among the vat photopolymerization printed samples, the right Viper SLA ear and the right
Formlabs ear showed the biggest difference in gain response compared to the original KEMAR silicone ears at 180° (Figure 4.3. c).

Figure 4.3. 3 Vat photopolymerization technologies gain response at a) 90°, b) 180°, c) 270°, and d) 360° (3 to 10 kHz).

The right Viper SLA printed ear showed the largest gain difference of 10 dB compared to the KEMAR silicone ear at a frequency of 6.88 kHz. As the frequency increased from that point, gain differences ranged from 5 to 10 dB. The right Form 2 printed ear showed a gain difference of 9.2 dB compared to the right KEMAR silicone ear at the same frequency. However, the left printed ear samples showed significantly smaller differences, with the left Viper SLA ear showing a gain response difference of 4.3 dB at a frequency of 8.18 kHz, and the left Form 2 ear showing the largest gain response difference of 5 dB at a frequency of 8.18 kHz. While all left printed samples performed similarly to the silicone KEMAR ears, both right ear prints performed significantly different at 180°. Since the left ear samples printed with the same technologies showed greater accuracy in gain response, it can be suggested that the differences in both of the right ear prints
can be due to a misalignment in positioning or an error within the assembly where the printed ear sample and the silicone pocket are assembled together.

4.3.4 Accuracies between material extrusion and vat photopolymerization processes

Comparing the printed samples amongst AM processes could help determine the appropriate technologies to use for these applications. El-Katatny et al. provided evidence of high accuracy when using material extrusion techniques in fabricating anatomical models; therefore, a comparison between material extrusion and vat photopolymerization processes was performed. The differences between both process capabilities can be seen at 180°. While both VP right ear samples printed showed a large difference compared to the silicone KEMAR ears, the overall pattern of gain response was more accurate that the one shown in the material extrusion prints (Figure 4.3.4.1).

![Figure 4.3.4.1 Material extrusion vs. vat photopolymerization processes at 180° (3 to 10 kHz).](image)

The material extrusion process shows a gradual difference in gain response past a frequency of 4.60 kHz. As frequency increases after, the gain response between printed samples only shows larger differences in gain response. In contrast, most of the printed samples using the vat
photopolymerization technique show similarities in gain response throughout all frequencies. However, two printed right samples show the largest differences in gain response compared to the silicone KEMAR ears. These differences can be assumed to be caused by the silicone pocket molded out of the Shore 30 rubber. The left ear prints do not show similar differences to those of the right ears; therefore, it can be concluded that the issues in assembly are only present in the right silicone pockets and not the left ones. Due to this, the right SLA and right Formlabs ears can be treated as outliers. All systems showed averages of under 5 dB gain differences among all printed samples. The Lulzbot TAZ 6 right and left ear samples showed gain response differences of up to 10 dB, which was twice as much as all other printed samples. Additionally, at frequencies over 8.18 kHz, vat photopolymerization prints maintain differences of under 5 dB, whereas material extrusion prints begin to show larger deviations of over 5 dB. Therefore, vat photopolymerization technologies achieved more consistent accuracies in testing compared to material extrusion technologies.

### 4.3.5 Accuracies between industrial and desktop systems

Looking at the matrix development, another reason for choosing the four technologies was to be able to compare industrial systems to desktop systems. The graph shown in Error! Reference source not found. represents gain response for the KEMAR silicone ears, the vat photopolymerization industrial system prints from the Viper SLA, and the material extrusion industrial system prints from the FDM Fortus 400mc. In comparing the three, the right Viper SLA printed ear at 180°, Figure 4.3.5. 1c, showed the largest gain difference of 10 dB at a frequency of 6.88 kHz compared to the KEMAR silicone ear, whereas the right FDM Fortus 400mc printed ear only showed a gain difference of 1.5 dB at the same frequency. Although the Viper SLA print
reached a gain difference of 10 dB, it maintained an average 5 dB difference as the frequency increases. As mentioned in the previous comparison discussing vat photopolymerization prints, the right Viper SLA print shows this large difference due to the silicone pocket it is assembled to. Overall, all prints fabricated using industrial system techniques showed similar behavior when capturing sound compared to the silicone KEMAR ears.

Figure 4.3.5. 1 KEMAR vs. right and left printed samples using industrial AM systems.

The graph shown in Figure 4.3.5. 2 represents gain response for the original KEMAR ears, the material extrusion desktop system prints from the Lulzbot TAZ 6, and the vat photopolymerization desktop system prints from the Formlabs Form 2 printer. Comparing the three, the desktop systems showed gain response differences throughout the angles recorded. Sound coming from the front at 360°, Figure 4.3.5. 2a, showed gain differences of less than 0.5 dB throughout all frequencies. However, at 90° and 270°, Figure 4.3.5. 2b, Figure 4.3.5. 2d, the desktop systems showed gain differences as large as 5 dB compared to the KEMAR silicone ears.
The larger gain differences were recorded for the right ear samples at these angles. In comparing the printed samples to the KEMAR silicone ears, the small right printed ears showed the largest gain differences at 180° (Figure 4.3.5. 2c). The small right Formlabs printed ear shows the largest gain response difference of 5.69 dB at a frequency of 7.72 kHz. The small left Lulzbot printed ear shows the largest gain difference of 3.59 dB at a frequency of 9.72 kHz compared to the KEMAR silicone ears.

While the technologies from both processes were successful in replicating the KEMAR silicone ears, an overview of the data suggest that the industrial systems performed more effectively than the desktop systems using the Shore 40 silicone pockets with less flexibility (Figure 4.3.5. 3). This conclusion can be supported with findings in gain response behavior to be ± 1 dB throughout the four angles for vat photopolymerization processes. However, the right SLA ear at 180° showed gain response differences of over 5 dB compared to the silicone ears. Similarly,
the right desktop system Form 2 ear, shows gain response differences of over 5 dB at frequencies higher than 7.29 kHz. Looking further into data captured, it can be suggested that using AM for fabricating KEMAR ear replicas can be beneficial when performing acoustic tests below frequencies of 6 kHz. Data recorded was most similar between printed samples and the silicone ears throughout a frequency range of 3 to 6 kHz. Larger gain differences are more apparent once the frequency surpasses 6 kHz. Pinnae begin filtering sound above frequencies of 6 kHz and play an important role in resolving front and back ambiguity (Oldfield and Parker, 1986; Butler, Humanski and Musicant, 1990). In order to determine the use of 3D models in acoustic testing of higher frequencies, > 6 kHz, where pinna filtering comes into play, further testing and data recording over larger frequency scales (3 kHz to 20 kHz) can be explored to observe the behavior.

Figure 4.3.5. 3 Industrial vs. desktop systems compared to KEMAR.
4.4 Conclusions

The 3D printed ear samples were assembled into the molded silicone pockets and placed into an interface on the KEMAR manikin head. After insertion, each pair, right and left, of printed samples and the KEMAR silicone ears were subject to acoustic testing. From the data gathered, a comparison of processes and capabilities was drawn. It can be concluded that AM models behave similarly to silicone ear models when capturing sound. In replicating, accuracy becomes important, therefore choosing the right technology for manufacturing is needed. Using the material extrusion process, replicating the ear geometries was possible. The FDM system was able to replicate accurately, capturing of the sound posed similar to that of the original KEMAR silicone ears. While the Lulzbot TAZ 6 prints also achieved similar response, they showed various and larger differences in the way the sound was being captured. Therefore, the FDM Fortus 400mc has the capability for replicating the KEMAR silicone ears with greater accuracy.

Using the vat photopolymerization process, replicating ear geometries was possible, however, the SLA system was able to achieve similar gain response behavior of 1-3 dB differences compared to the Formlabs desktop system. While vat photopolymerization is said to provide high accuracy prints (George et al., 2017), the behavior in capturing sound over frequencies of 3 to 10 kHz shows more inconsistencies with prints fabricated using this process using the P30 silicone pocket. While differences may be due to alignment or unaccounted for changes in positioning of the samples, another reason for said inconsistencies may be due to the silicone pocket assembling methods. Although vat photopolymerization can achieve and replicate complex ear geometries, material selection and assembly efficacy should be further explored in order to dismiss any effect they may have during these testing procedures.

Next, using the selected technology, a comparison between industrial and desktop systems was done. Overall, both categories performed similarly in replicating the KEMAR silicone ears. While the industrial systems provided better data in terms of gain response during testing, using the desktop systems under circumstances involving cost would be a great alternative to fabricating
these components. In order to fully determine which of the processes would deliver a more accurate printed replica, further studies involving prints with the same parameters such as material, layer thickness, etc. would provide a more concise conclusion.

Lastly, the implementation of a different design to create a better sealing component into the KEMAR manikin head allowed for the molding of two different silicones. In molding these silicones whose main difference is the durometer, the molds in assembly with the printed ears were also tested and compared. The flexibility difference between the two different silicone pockets did not seem to have an effect on the gain response over a range of frequencies. The only major differences between the two silicone pocket types were observed when sound was traveling to the manikin from the rear, around 180 degrees. Those major differences can be attributed to a lack of localization in higher frequencies, however, the purple silicone pocket showed differences in gain twice as large compared to those captured using the pink silicone pocket. The differences captured can be attributed to the fabrication process of the molds used to create the silicone pockets. Further testing and evaluation is required to come to this conclusion.
Chapter 5: Application of AM in designing individualized custom headsets and printed ear canals

5.1 Introduction

5.1.1 Background

The human ear is a very complex geometry, both in the way it looks as well as the way it works. Every intricate feature that a human ear possesses plays a part in the way that it perceives sound. The perception of sound is not only dependent on ear geometries, cavities, and curves, but other factors such as the neck, head, and torso can also influence how sound enters the body (Burkhard and Sachs, 1975). An important component to how sound enters through the ear canal is the outer portion of the ear, also known as the pinna. The pinna is said to influence the perception of sound, localization, and spectral cues at higher frequencies (Middlebrooks, 1992) (Figure 5.1.1. 1). This concept is crucial for military applications, for example, as users often employ hearing protection with noise cancelling features which can hinder their ability to localize sound.
Applications of additive manufacturing methods quickly evolve and expand with the introduction of cutting-edge technology. An industry that has implemented AM methods since the year 2000 was that of hearing aids, using AM to produce the shell material casing out of stereolithography systems (Dodziuk, 2016). With the use of AM, the ability to generate complex and unique design concepts becomes possible; therefore, applications involving complexity and customizability benefit the most from additive manufacturing. Due to this, complex geometries such as the human ear, can be further explored through AM methods.

As testing methods for acoustic knowledge and enhanced sound experiences have been around throughout the years, new sound equipment and an improvement in testing protocols have evolved. The evolvement of testing methods increases as new technology is created that requires testing. Having accurately replicated a KEMAR ear sample, other design concepts such as the development of a 3D printed headset can also be explored. By taking advantage of freedom of
design with AM, the design development of a 3D printed headset that could be used to improve various parameters in acoustic testing began. In addition to headset design and fabrication, other factors that could benefit from AM would be replicating ear canals, as they are also complex in shape. The ear canal is necessary in sound perception as it provides the pathway for sound registration to the brain. As sound travels through reflection paths and towards the ear canal, sound waves, also known as vibrations, occur once the tympanic membrane (TM) is reached (Kuru et al., 2016). Anatomical replicas and models of the middle ear have been done, such as in Feng and Gan, where the models were used for measuring acoustic characteristics.

5.1.2 Motivation

Headphone designs that are commercially available today are generic and usually presented in three different forms: circumaural (on-the-ear) headphones, supra-aural (over-the-ear) headphones, and earphones, earpieces, and earbuds. The first two require a headband to assemble to and be securely placed around the head. The last category of headphone design is the most innovative one today, ranging from generic wired-in ear buds, to fully customized wireless earpieces. Each form has similar features, such as providing sound and form-fit capabilities. Each behaves differently in terms of how sound is perceived. Sound perception is a complex process, taking place at the moment it leaves the source up until it hits a person’s ear canal. Many factors can affect sound perception such as: neck length, hair length, torso size, and ear pinnae cavities (Burkhard and Sachs, 1975).

To further the range of applications for AM in the hearing industry, the design and development process for a headset device is presented. The motivation for designing and fabricating a headset using AM methods allows for freedom of design, meaning there is potential
for the fabrication of complex designs that could potentially be used in acoustic testing settings. Using AM methods allows the headset to accommodate for designs that are uniquely made for each individual set of ears. Like the ear models, the printed headset can also be used to test out machine capability, accuracy, complexity, and material selection. Gathering the knowledge captured through literature review on the effect of the pinna on sound perception and localization, it can be hypothesized that the use of AM customized fabrication methods has the potential to develop designs that can be used in acoustic testing application, further improving methods for human sound perception, and sound localization in hearing aids and hearing protection devices.

5.2 Methods

5.2.1 Headset design

Headphone types and applications were briefly investigated in order to understand their functions. A headphone set used in testing by GN ReSound (GN ReSound, Glenview, IL) was provided by the company to use as a guide to design a new headset for 3D printing. After investigating which headphone type was best suited for acoustic testing applications, it was determined that the supra-aural (over-the-ear) headphone design was the right focus for this experiment. A 3M™ PELTOR™ Tactical Sport™ Communications Headset (MT16H210F-SV, 3M, Maplewood, MN, USA) was reverse engineered to generate individual designs of the ear muffs. The earmuffs were designed as a three-part assembly: the muff, an assembly ring, to be used for connecting the printed muff to the third component, and a cushion with foam inserts. In an effort to drive the design towards its use in testing for sound localization, the previously CT scanned ear pinna model was attached to the exterior portion of each earmuff (Figure 5.2.1.1).
To place the ear strategically, a CMM FARO 8-axis ScanArm (FARO Technologies, FL, USA) was used to scan the head of the KEMAR manikin. Once the manikin head was scanned, the STL file was imported into Autodesk’s Fusion 360 (Autodesk, San Rafael, CA, USA) software and aligned to a coordinate system. The head scan allowed for the alignment of the muffs onto both sides of the head at an angle of 2.5° from the vertical axis. Once the muffs were aligned, the previously generated ear CAD models were individually imported into the workspace and aligned onto each muff (Figure 5.2.1. 2). In order to have the ear model be flush with the outer face of the muff, the combine tool was used to cut out any portion of the muff interfering with the cavities of the pinna. This tool allowed the joining of both components, cutting out unnecessary material, while preserving the pinnae geometries. The right and left KEMAR ear scans are different, therefore the process of using this boolean operation within Fusion 360 was not repeatable and each ear had to be placed and joined to the muff separately.
In order to be able to 3D print the muffs and assemble them to the headband from the 3M™ PELTOR™ Tactical Sport™ Communications Headset (MT16H210F-SV, 3M, Maplewood, MN, USA), the interface portion of the headset was reverse engineered using a caliper tool and based on the printing technology, a 0.250 mm clearance was used in design. Implementing clearances and other design strategies into the muff design prepared it for printing using the 3D Systems’ Viper SLA in the Somos NeXt (DSM SOMOS 11122XC) material. Prior to printing, the CAD file was exported from Fusion 360 as an STL file and analyzed using Materialise Magics (Materialise, Leuven, Belgium), an STL editor software. Using Magics allowed the muff STL file to be analyzed through cross section inspection to fix any discrepancies not visible to the naked eye. Once the STL file was finalized, various parameters were identified regarding the build orientation, material selection, and layer thickness. The main hypothesis posed behind designing a headset with ears positioned on the external portion of the muff was that the ear canal geometry open to the outside...
would serve as a natural driver of incoming sound into the ear canal of the KEMAR silicone ear lying below as shown in Figure 5.2.1. 3. With the natural sound driver on the exterior portion of the headset design, its potential in maintaining hearing protection while improving sound localization could be further explored.

5.2.2 Printed ear canal design and application

The ear canal, better known as the external acoustic meatus or external auditory meatus can be divided into three different categories: outer ear, middle ear, and inner ear. The tympanic membrane, more commonly known as the eardrum that lies between the outer and middle ear, is a factor in the passing of sound through the ear canal until it is registered in the brain. The tympanic membrane, or eardrum, results in vibrations when sound waves are traveling through the ear canal. Once the sound reaches the eardrum, the middle ear bones conduct the sound to the fluids of the inner ear (Sheean et al., 2008).

While the main objective of the design and development of the printed headphones with the pinnae geometry on the exterior portion was to maintain hearing protection while improving sound localization, further design iterations introduced that of a printed ear canal (PEC). This printed ear canal was designed as an addition to the headset in use for acoustic testing. The design development for the PEC required a number of design considerations. Several things such as the length of the ear canal, diameter variations, as well as confinement, all play a part in how the sound reaches a listener’s cochlea. In order to generate a printable PEC, further research on the anatomy of an ear canal led to the development of anatomical design considerations (Table 5.2.2. 1).

<table>
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</tbody>
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90
<table>
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<th>Ear alignment on muff exterior</th>
<th>Alignment between ears (earmuff ears to KEMAR ears)</th>
<th>Align to 3D scan of KEMAR manikin head.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ear canal length</strong></td>
<td>Distance from entrance of ear canal up to the cochlea.</td>
<td>25 – 27 mm length.</td>
</tr>
<tr>
<td><strong>Ear canal inner diameter (ID)</strong></td>
<td>Ear canals vary in diameter size throughout.</td>
<td>5 – 7 mm inner diameter. In actual ear canal, up to 13 mm.</td>
</tr>
<tr>
<td><strong>Ear canal outer diameter (OD)</strong></td>
<td>Accounts for thickness of the PEC.</td>
<td>Flexibility with OD size, empty space allows for an OD of &gt; 7 mm.</td>
</tr>
</tbody>
</table>

Table 5.2.2.1 Design requirements for a printable ear canal (PEC).

Table 5.2.2.1 describes the initial design requirements that were addressed prior to the fabrication of a PEC. For example, the average length of a human’s ear canal is about 25 mm (Stinson and Lawton, 1989), therefore when designing the PEC, a controlled length of about 25 – 27 mm was used. In order to replicate the ear canal in a print with high accuracy, a chain of design iterations, technologies, and material selection were explored.

Several factors were considered when choosing a design and material for fabricating the PEC. The first consideration was the material. Although, ear plugs tend to be made out of flexible material, for the purpose of the first prototype being tested on KEMAR itself, a rigid material sufficed. The PEC underwent a series of design iterations, starting off as a single piece component, then eventually became a multiple piece assembly (Figure 5.2.2.2). In order for the PEC to work, the electronic components of a hearing aid were introduced into the design of the PEC. The hearing aids used to generate design considerations were in-the-canal (ITC) or in-the-ear (ITE) hearing aids provided by Beltone, GN ReSound (GN ReSound, Glenview, IL). The hearing aids are composed of 3 main electronic components: a digital signal processor (DSP), a microphone, and a transmitter (speaker). Two components, the microphone and the transmitter, were soldered onto
the DSP and powered by a Zinc-based 312 battery (Figure 5.2.2.). A wiring schematic for connecting the electronic components was provided by GN (GN ReSound, Glenview, IL, USA).

Figure 5.2.2. 1 Electronic components of a Beltone ITC hearing aid.
The first printed prototype was a single part assembly that resembled an ear plug, commonly used for noise reduction or noise cancelling purposes. This PEC was fabricated in order to validate the ability to 3D print small components that require fine details. For prototyping, as mentioned above, the PEC was printed out of black resin on a Form1+. Since the technology used was an older model from what was commercially available during the time the experiment took
place, the quality of the prints could have been improved with an updated Formlabs desktop printer. Using the Form1+, the prototype prints were accurate enough to test form and fit.

Due to the fine details and small parameters of the electronic components, a 3D Systems’ Viper SLA printer was ultimately chosen to fabricate the PEC components. When designing the parts, clearances in the XY and XZ were determined based on the printer’s capabilities. Once the second design iteration was finished, a few of the models were printed out of a Formlabs Form1+ with clear resin, and other PEC components were also printed on the Viper SLA out of Somos NeXt resin for high accuracy prints. In order to ensure that all the components assembled, Fusion 360 was used to assemble and test-fit all parts to the assembly (Figure 5.2.2). Furthermore, testing of
the printed headset was performed using methods mentioned in section 4.2.4 Anechoic chamber setup and testing).

5.3 Results and discussion

5.3.1 Headset prototype testing data analysis

The first headset prototype was assembled and shipped to GN for testing using the same reverberant anechoic chamber used in Ch. 4. The testing was performed on a 3D printed assembled headset, not including PEC samples. Prior to testing of the headset, the system setup was calibrated, and the individual KEMAR silicone ears were inserted into the manikin head for testing. The data captured by the KEMAR ears (unaided) are reflected in the graphs shown in Figure 5.3.1. 1. The headset was then placed and tested the same way as the KEMAR ears and data was captured. The graphs below show a comparison in gain response between the KEMAR ears (unaided) and the ears on the headset over a frequency range of 1 to 15.4 kHz. Higher frequencies were included for the testing of the headset in order to observe the effects of pinnae on localization when using headphones or other hearing protection devices. Overall, the headset showed similarities in gain response at 90°, 180°, and 270° compared to the KEMAR silicone ears. At 90° and 270°, Figure 5.3.1. 1a, Figure 5.3.1. 1c, the similarities between gain response were expected due to the alignment of the ear canal of the muff to the ear canal of the KEMAR silicone lying beneath. Furthermore, the data recorded at 180° was also comparable showing minimal changes for localization capabilities (Figure 5.3.1. 1b).
The placement of the pinnae on the external portion of the muffis seemed to have an effect on gain response as the higher frequencies (7.2 to 15.4 kHz) still showed similarities between the headset and the KEMAR silicone ears. Gain response recorded from the headset at 90° and 270° showed gain differences between 5 and 10 dB. However, after testing, it was reported by GN ReSound that volume space between the entrance of the ear canal of the printed headset and that of the silicone ear could have potentially had an effect on gain response. This could be attributed to sound bouncing within the blank space between the two points before reaching the ear canal of the silicone ears. Gain response recorded from the headset at 180° showed gain differences of under 5 dB compared to the silicone ears. This result showed potential in the design, as sound being introduced from the rear is difficult to capture similarly to the silicone ears. In order to improve data captured, the removal of the blank volume space addressed could further validate results. In turn, the addition of the PEC to close off the pathway from one ear canal to another can further analyze the effects of blank space and noise bounce on the ability of the manikin to capture the sound fully.
5.3.2 Applications in headset design

Using the generated STL files from scanning methods in Ch. 3, a headset was designed, and 3D printed. However, improvements in design iterations quickly began by investigating better suited printable materials for the muffs. Other important design changes were made, such as ensuring that the ear geometry was flush with the muff exterior face. Since sound is affected by outside factors such as the pinnae, neck, head, and torso, cavities and curvatures should have an effect on the reflection paths created that move the sound into the ear canal. Therefore, a headset 2 design was generated and printed using a clear resin on the 3D Systems’ Viper SLA printer, as it provides resolutions of 50 – 200 µm, even in complex geometries (Melchels, Feijen and Grijpma, 2010) (Figure 5.3.2. 1). While headset 2 has not yet been tested to prove this hypothesis, future work in this application will validate and provide feedback for the initial headset design and its efficiency and potential application in testing.

Figure 5.3.2. 1 Headset 2 design right muff and assembly ring printed out of clear resin on Viper SLA system.
5.3.3 Applications in ear canal and hearing aid testing

In order to improve the PEC design and fabrication, consideration of the capabilities in providing consistency and reproducibility in vat photopolymerization micro precision printing as proven in Davoudinejad et al was done. The electronic components found inside a hearing aid are small in nature, varying in sizes under 5 mm x 7 mm. The size of these components is due to ITC hearing aids resting inside the ear, accommodating to individual pinnae shapes. In choosing a technology that not only provided the necessary resolution, but also precision, the dimensions of the components within were able to be replicated with high accuracy. Additionally, freedom of design allowed for integration of curves and contours to the PEC that an anatomical ear canal usually possesses. The first printed ear canal (PEC) was designed with a continuous inner diameter of 7 mm, as this mimic the average diameter size of a human ear canal (Figure 5.3.3. 1, Figure 5.3.3. 2) (Stinson and Lawton, 1989). However, improvements in design have progressed into working prototypes for both the left and right ears, to ultimately be used in testing.
Figure 5.3.3. 1 First printed ear canal (PEC) iteration with embedded electronics.
Newer iterations of the PEC are currently being fabricated and assembled in order to be tested by GN. As concluded in Stinson and Lawton, if the headset and the PEC are utilized for testing at higher frequencies (> 8kHz), implementation of specific ear canal geometries will be necessary. In recreating ear geometries, semi-flexible materials should be considered and also tested for their effect on sound distribution.

5.4 Conclusions

Applications of AM methods in medical modeling, hearing, and hearing protection devices inspired the design and fabrication of a headset design and a printed ear canal using a Viper SLA vat photopolymerization printer. In fabricating these components, freedom of design allowed for customization of the headset in regard to pinnae geometry and of the printed ear canal to support the housing of electronic components regularly found inside an in-the-ear (ITE) hearing aid. In
printing these two parts, new design iterations were set forth in order to accommodate for any
design considerations provided by experts. The first headset design (headset 1) was sent to GN
ReSound for testing. It was hypothesized that placing KEMAR pinnae geometries on the external
portion of the headset design, the printed pinnae would filter sound similarly to the silicone pinnae.
Results obtained from GN ReSound show that the printed pinnae on the headset did behave
similarly to the pinnae on the manikin head. It was also discussed that blank space on the inside of
the muff could result in noise bouncing. To mitigate this, a closed ear canal pathway by adding
flexible tubing was suggested.

Gathering from preliminary testing results in the headset 1 design, it can be concluded that
positioning of the pinnae geometry on the exterior portion of the headset allows for similar gain
response compared to the silicone ears attached to the KEMAR manikin head. This is a topic to
further investigate as it can potentially provide a path to redesigning hearing protection devices
with sound localization capabilities. By testing newer design iterations and implementing a printed
ear canal (PEC) to seal the pathway from one ear canal to the other, any sound traveling from the
muff into the PEC should be filtered, therefore, gain response with the use of hearing protection
can be enhanced. As more feedback is provided by experts, newer iterations of the headphones
and the PEC have been fabricated using vat photopolymerization printing technologies.
Furthermore, testing capabilities amongst desktop and industrial systems can provide insight
towards finding the technology best suited for these applications.
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8.


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Appendix

Appendix Figure 4.1 Lulzbot printed ear samples 2D polar plots
Appendix Figure 4.2 FDM Fortus 400mc printed ear samples 2D polar plots
Appendix Figure 4.3 Formlabs Form 2 printed ear samples 2D polar plots
Appendix Figure 4.4 Viper SLA printed ear samples 2D polar plots
2D Polars: TX White Ears (2) Blue Mold_SN: NA__Eng:
S. Petrovic, Date: 11/15/2019

Right Ear_Clockwise_Plot
adjusted for right side

Measurement System:
SoundCheck 17, Seq: Full Analysis 3

Input: 75dBSPL Pink
Noise, 4 seconds, 1m
Appendix Figure 4.5 Original KEMAR silicone ear samples 2D polar plots
Appendix Figure 4.6 Headset 1 printed samples 2D polar plots (R/L ears)
Appendix 1A Quote for cost of FaroArm scanning system
FARO Technologies Inc
250 Technology Park
Lake Mary FL 32746-7115
Phone No: ___________________________
Fax No: ___________________________
Email: Hafeez.Hussain@faro.com

Remit to: FARO Technologies, Inc.
P.O. Box 116908
Atlanta, GA 30322-6908

Quotation No: 20205466
Quote Date: 09/05/2018
Expiration Date: 09/28/2018
Regional Manager: Jonathan Yoder
Account Manager: Derrick McBreairty
Sales Support: Hafeez Hussain
Ship: Ground
Payment Terms: Net due in 30 days with approved credit
Delivery Terms: EXW Origin
Delivery Date: 4-6 Weeks

Bill To: University of Texas -El Paso
Ship To: University of Texas - El Paso
500 W University Ave Dept OF
500 W University Ave Dept OF
Mechanical Engineering
Mechanical Engineering
El Paso TX 79968-8900
El Paso TX 79968-8900
US
US

QUOTE FOR DEMO EQUIPMENT IS BASED ON INVENTORY AVAILABILITY. DEMO UNITS ARE SOLD AS IS, ON A FIRST COME, FIRST SERVE BASIS AND CANNOT BE RESERVED.

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Geomagic Design X is the industry's most comprehensive reverse engineering software, combines history-based CAD with 3D scan data processing so you can create feature-based editable solid models compatible with your existing CAD software. This package includes maintenance which provides you a full year of technical support and upgrades. (Educational Pricing) (Qty 1-4)

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<td>1</td>
<td>TR-GEO-DX-CL</td>
<td>Geomagic Design X-Training-Classroom Geomagic Design X training for 3 days and 1 student.</td>
<td>1,500.00</td>
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Geomagic Design X

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<th>Item No.</th>
<th>Description</th>
<th>Unit Price</th>
<th>Ext. Price</th>
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<tr>
<td>1</td>
<td>GEO-DONGLE</td>
<td>Geomagic Dongle Required for offline dongle license option.</td>
<td>500.00</td>
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PURCHASE AGREEMENT AND CONDITIONS OF SALE Customer will pay any federal, state and local taxes. All conditions of sale, service and warranty as described in FARO standard purchase conditions currently on file with FARO are made as part of this Quotation and are incorporated herein by reference (02FRM522). PLEASE REFERENCE FARO QUOTE NUMBER ON ALL DOCUMENTS. BY REFERENCING FARO QUOTE, CUSTOMER AGREES TO SAID TERMS AND CONDITIONS AS LISTED ON FARO QUOTATION.
<table>
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<tr>
<th>Qty</th>
<th>Item No.</th>
<th>Description</th>
<th>Unit Price</th>
<th>Ext. Price</th>
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</thead>
</table>
| 1   | 15532    | FaroArm Portable Folding Tripod  
     Designed specifically for the FaroArm, the folding tripod includes stabilizing struts that mount to the actual work surface, retractable wheels, ring mount for FaroArm, wheeled soft bag and heavy-duty shipping case.  
     Dimensions: Height 31" to 41" (0.7m to 1.0m), maximum spread 54" (1.4m). (Replaces 14422) | 5,850.00 | 5,850.00 |
| 1   | 20700    | Design ScanArm 9 Ft (2.7m) 7 Axis  
     Design ScanArm, 9 ft. (2.7m), 7 Axis. FARO’s dedicated reverse engineering measurement system featuring a built-in laser scanning probe and High Definition scanning technology with superior precision, high speed and resolution. Includes: Arm, calibration kit, base plate, 6mm probe, cables, mounting c-clamps, heavy-duty case and One (1) year Standard warranty. | 42,740.00 | 42,740.00 |

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Total in USD: 42,492.60
Vita

Alejandra Belmont was born and raised in El Paso, TX. Alejandra received her high school degree and continued her undergraduate education at The University of Texas at El Paso as an Academic Scholarship recipient. During her undergraduate studies, she took on teaching and leadership roles for peer-led team learning initiatives on engineering curriculum math courses as well as general chemistry courses. She received her B.S. in Engineering Leadership from UTEP in 2018 with a minor in Chemistry and a minor in Biomedical Engineering. Prior to her work at the W.M. Keck Center for 3D Innovation, Alejandra participated in research laboratories for biomechanical gait studies as well as immunology studies involving rodents and 3D printed hydrogels. She began working for the W.M. Keck Center for 3D Innovation as an undergraduate student, creating content for a 5-course certificate program in 3D Engineering and Additive Manufacturing. As a graduate student, her job description included conducting trainings on Design and Additive Manufacturing for SOCOM, AMRDEC, CERDEC, and NSRDEC and other DoD contractors. Aside from involvement in educational training, she also conducted research in additive manufacturing projects involving accurate replication of anatomical models, like the human ear, and applications in acoustic testing for manufacturing individualized custom hearing devices for sound localization and spectral cue preservation.

Contact Information: abelmont2@miners.utep.edu