THE USES OF 3-DIMENSIONAL PRINTING TECHNOLOGY IN ORTHODONTIC OFFICES IN THE UNITED STATES

by

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DEDICATION

I dedicate this thesis to my loving grandmother, Lola Johnson, who taught me how to give gratitude, remain humble, and show patience. To my mother, Joi Moore, for your support and encouragement. To my siblings Zipporah, Ephraim, and Olivia. Thank you for always being there for me.

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ABSTRACT

Introduction: The purpose of this study was to examine the use of orthodontic 3-dimensional printing technology in the US, whether that is in an in-house or outsourced capacity. To understand why orthodontists are, or are not, incorporating 3-dimensional printing technology in their practices. To identify the popularity of various software, applications, uses, pitfalls, and benefits for 3-dimensional printing by practicing professionals and any association of these experiences with practice or professional demographics.

Methods: A survey questionnaire was delivered on a secure online platform, RedCap. A pilot survey was given to the orthodontic faculty of Case Western Reserve University. IRB approval was gained. A 14-34 item survey with branching logic, so irrelevant questions were unseen, was distributed to the American Association of Orthodontists Partners in Research, to orthodontic groups on Facebook, and handed to individuals during in-person orthodontic meetings. A sample size target of 500 was the goal. IBM® SPSS® version 27 was used to analyze the data. Descriptive statistics were used to analyze the frequency of responses. Association between participant demographics and in-

house 3D printing was assessed using a chi-square test of independence. Statistical significance was defined as p-value ≤ 0.05.

Results: A total of 518 responses were recorded. The highest number of responses came from the age group of 36-45 and those who have been in practice for more than 10 years. Majority of the respondents were practice owners (60.8%), working in private practice (82.6%), and practicing primarily in a suburban area (62.8%). The majority of respondents of the survey treats 45-60 patients daily. Respondents were even distributed throughout the United States. An estimated 53% of the orthodontists reported that they have had training in 3-dimensional printing. Most people who received training in 3-dimensional printing taught themselves. If an orthodontist has had experience in 3-dimensional printing then majority only have 1-2 years of experience. About 73% of orthodontists use 3-dimensional printing applications in some capacity whether that is in an outsourced or in-house capacity. Digital light processing was the most known type of 3-dimensional printing. Out of the orthodontists that answered this survey, 46.9% had a 3-dimensional printer in their office. 21.0% had one printer ranking the highest out of the other options. The most used printer was the SprintRay (46.9%). Printing models for plastic retainers was the most popular use of

a 3-dimensional printer in a practitioner's office (90.9%). It was reported that roughly 57% of orthodontists in this survey use 3-dimensional printing technology for in-house and outsourced aligners. The most popular used software to making in-house aligners was uLab. The main reason orthodontists initially incorporated 3-dimensional printers into their office is because of self-research or self-interests. Practitioners with a 3-dimensional printer were very pleased with it as 96.3% reported it meeting their expectations. The main reason the printer met their expectations was due to the ease of workflow. Out of the orthodontists that did not use 3-dimensional printing in any capacity (141) in their offices, 33.3% said it was because they weren't the decision maker in their office. The next two reasons were even at 27% in that the orthodontist either had a training deficit in digital workflow or had a lack of interest in 3-dimensional printing. 39.3% of the 141 said they were interested or planned to implement 3-dimensional printing into their office in the future. There were chi-square tests of independence performed on the data to see which associations existed and how 3-dimensional printing impacted those associations. The strongest statistical associations with utilizing an in-house 3D printer are seen with patient load, practice type, years since residency, and orthodontist's

position. Increasing patient load and being in a private practice increases the likelihood of having a 3D printer.

Conclusion: Close to 3/4 of orthodontists use 3D printing technology in some capacity in the US. Some of the major factors that influenced orthodontists to incorporate 3D printing technology into their office were: self-interest and research. Some of the major factors that has prevented orthodontists from not incorporating 3D printing technology into their office were: Space for equipment/ventilation, digital workflow training deficit, lack of manpower. DLP, SprintRay, uLab, were the most popular in their respective categories. Orthodontists use their 3D printer mostly to make plastic retainers from printed models. Orthodontists using 3D printing were mostly happy with the ease of workflow and patient comfortability. Orthodontists who were displeased with 3D printing didn't like how time consuming it was. The strongest statistical associations with utilizing an in-house 3D printer are seen with patient load, practice type, years since residency, and orthodontist's position. Increasing patient load and being in a private practice increases the likelihood of having a 3D printer.

Review of Literature

History of Three-Dimensional Printing

Three-dimensional printing, also referred to as additive manufacturing, is performed by layers sequentially deposited on top of one another to eventually form an object. Three-dimensional printing has exponentially advanced since the advent of three-dimensional printing in 1983 by Charles W. Hull. Today, it is considered by many experts to be the next industrial revolution and ultimately supersede many current techniques of fabricating materials.

Before Hull invented his apparatus in 1980, Dr. Hideo Kodama filed for the first three-dimensional printing patent; however, it was never commercialized due to incomplete specification regarding the patent. Dr. Kodama was part of the Nagoya Municipal Industrial Research Institute and published an article detailing how "a solid model is fabricated by exposing liquid photo-hardening polymer to ultraviolet rays, … stacking the cross-sectional solidified layers."[1] Dr. Kodama never finished the specifications for his patent and that is the reason that it was never commercialized. Additionally, Jean-Claude Andre, Olivier de Witte, and Alain le Mehaute were part of a French team that made objects and pursued a patent that was later

abandoned. Although incomplete, the attempted patents for three-dimensional printing developed the framework for Hull to develop what we now know today as three-dimensional printing.

Charles Hull was born May 12th, 1939 and received his degree in engineering physics from the University of Colorado. Hull successfully designed the first commercial rapid prototyping technology. The unique design adopts the use of concentrated ultraviolet light and ultraviolet curable plastic to produce three-dimensional parts from computer files. The first form of three-dimensional printing was done by stereolithography apparatus (SLA).[2] SLA uses a photopolymer resin to strike the pattern of ultraviolet light, solidifying and attaching to what came before it. After a layer is complete, the part would drop down right below the surface in a bath of liquid plastic, resulting in each printed layer equidistance from the light source. Repeatedly, a new thin layer of liquid is selected, cured, and attached.

The term "three-dimensional printer" was first coined by four students at Massachusetts Institute of Technology (1993). This name was adopted by 3D Systems, a company co-founded in 1986 by Hull and (Unknown). 3D Systems produced the first machine for rapid prototyping and the first three-dimensional printing company in the

world. By 1987, the first stereolithography printer was commercialized. In addition to this revolutionary feat, the company also commercialized the "Standard Tessellation Language" or "Standard Triangular Language" (STL) file format that permits computer-aided design (CAD) software data to be translated for three-dimensional printers. The STL file format describes the surface of an object as a triangular mesh—a representation of a three-dimensional surface in triangular facets. Tessellation is a term used for breaking the geometry of the triangular mesh? surface into a series of small triangles, or other polygons. Without the STL file, three-dimensional printing would not be possible. Today 3D Systems is still as innovative as it was in the late 1980s.

Simultaneously, another emerging three-dimensional technology was invented in the late 1980s. A University of Texas' student by the name of Carl Deckard brought a patent for the Selective Laser Sintering technology in 1988. In contrast to Hull's design, Deckard's three-dimensional printing technique uses powder polymers to fuse them together locally by a laser. Nylon is commonly used in SLS and can make more complex shapes than SLA.[14]

Rapid prototyping went through many advances and out of that came additive manufacturing. In 1989, Scott Crump invented Fused Deposition Modeling (FDM) and commercialized it in 1990 by using Stratasys. This is the three-dimensional printing that most people using the technology would be familiar with today. Crump first created this technology to build his daughter a toy frog using a glue gun and a mixture of polyethylene and candle wax. The FDM design allows a user to first create a three-dimensional model in a three-dimensional modeling program. It subsequently saves the model as an STL file and the printer's interfacing software converts the file and slices the model into sections, simultaneously determining how the layers will be printed. After that phase is complete, the model is sent to the three-dimensional printer and build material is extruded through a heated nozzle layer by layer until the part is complete. This type of three-dimensional printing is the most common used today and is usually colloquially referred to as "desktop 3D printers."

These first three-dimensional printers introduced the preliminary technology required for the more advanced three-dimensional printing we see today and the foreseen future. In the 1990s, other three-dimensional techniques such as MIT's three-dimensional printing technique based on inkjet printers in 1993. This printing approach is

known as Binder Jetting. In that same year, Royden Sanders, developer of Solidscape, designed a wax three-dimensional printing known as The Model Maker. The Model Maker was later introduced in 1994 by Solidscape. This machine initially three-dimensionally printed jewelry.

Various other attempts of creating a three-dimensional printer occurred latter in the 1990s. In 1997, Arcam, the only manufacture of Electron Beam Melting (EBM) three-dimensional printers, was created. Arcam, at the time, specialized in metal three-dimensional printing machines. The following year, Objet Geometries founded their Polyjet printing technology. It was at this time that 3D printing started to move beyond solely producing polymers, and began transitioning into meaningful a asset of progress in fields such as biomedical engineering. For example, an incredible and life changing event happen in 1999 at Wake Forest Institute for Regenerative Medicine when scientist managed to three-dimensionally bioprint synthetic scaffolds of a human bladder.

The start of the new millennium introduced the first multi-color three-dimensional printer. 3D Systems emerged as a leader in the SLS market, setting the standard for SLA and SLS. In 2004 and 2005, the first self-replicating three-dimensional printers was created. It was called

the RepRap project which is short for replicating rapid prototyper. This project would foster the idea that three-dimensional printing could be affordable and done at home. Thus, interest in lower cost three-dimensional printers skyrocketed worldwide.

The year 2008 was a year that led to the creation of many innovative techniques and structures in the three-dimensional printing world that continue to impact design today. In this year, the self-replicating 'Darwin' RepRap 3D printer was designed. This discovery led to cheap and easy three-dimensionally printing from home. This was a first of its kind and wasn't as robust or expensive as its predecessor. Thingiverse was created that year as well. Thingiverse allowed designers to upload their 3-dimensinoal printer models built on various three-dimensional software for others to download for free and print at home. This is now in the top 700 most popular websites in the United States. The first three-dimensional printed prosthetic also made its debut in 2008, leading to the first printed and functionally prosthetic. . Finally, Statasys invented bio-compatible material that made three-dimensional bioprinting more widely available.

In 2012, B9Creator created a three-dimensional printer that used Digital Light Processing (DLP) technology. This introduced the era of

laser- and DLP-based SLA printing techniques. Digital Light Processing (DLP) is the newest and has the best finish quality of the previous three printing styles.[3] DLP-based 3D printing technology comes from the image projection technology developed by Texas Instruments in the 1980s.[4] This method uses a set of chipsets based on optical micro-electromechanical technology to process working light sources to photosensitive materials. The main functional part is a digital micro mirror device (DMD) which consists of a group of micron-sized, controllable mirrors. The mirrors rotate to control the path of light and then project it onto the photosensitive resin during working.[5] The projection of an image that is composed of small square pixels called "voxels" passes through an optical lens and cures the photo-curable polymer resin.[6] DLP printers can produce very intricate designs, are usually faster than its counterparts, and are more cost effective.

From 2013 to present, there have been several new additions to three-dimensional printing. For instance, in 2013, Cody Wilson printed the first three-dimensional hand gun. By 2014, NASA was three-dimensionally printing in outer space. This paved the way for future space manufacturing and the capability to aid future astronauts to fabricate tools in space. 2015 had two major players. The first was when Carbon 3D was introduced. This would allow three-dimensional

printers to become a lot faster. The second thing was the metal three-dimensional printer. Created by Desktop Metal's Production System, the metal 3-dimmensional printer allows for the printing of metal parts to be fabricated within minutes. 2016 was the year the first full-color three-dimensional printer was announced by HP. Also, in that year, a company by the name of Ultimaker produced a desktop three-dimensional printer that took the world by storm. LCD printing became available in 2018 and three-dimensional printer cost decreased drastically. You could now get a three-dimensional printer for under $500. There were many patents that expired in 2019 and many open source projects that were taking place. At this time, there were over 170 three-dimensional system manufactures across the globe. These companies include: 3D Systems, Stratasys, Fusion3, Formlabs, Desktop Metal, Prusa, and Voxel8, among many others.[2], By 2019, the scope of 3-dimmensional printing had scaled so large that Apis Cor had built a huge three-dimensional building in Dubai. They were also the same company to build a house in 24 hours. three-dimensional printing in construction was a $70M industry in 2017, but it is suggested that it will be worth $40bn by 2027. Today there are seven different types of three-dimensional printers: Fused deposition modeling (FDM), Stereolithography (SLA), Digital Light Processing (DLP), Selective Laser

Sintering (SLS), Selective laser melting (SLM), Laminated object manufacturing (LOM), and Digital Beam Melting (EBM).[7]

Industries using three-dimensional Printing

Three-dimensional printing has come a long way since the mid-1980s. There has been an astronomical increase in technology and how three-dimensional printing is done today. three-dimensional printing has grown to impact almost every major industry globally and it is changing how the world manufactures things. For instance, the construction industry has immensely benefited from three-dimensional printing. 3D printing has impacted the construction workforce where now, the roles of skilled builders and concrete homes are becoming less and less necessary with the introduction of this new technology" or something like that. The automobile industry is also using three-dimensional printing. New car parts are being printed and even entire cars and boats can be manufactured. Not only can three-dimensional printing produce motor vehicles, but even what we wear. There are three-dimensionally printed clothing, shoes, and jewelry. Clothing is printed with flexible filaments such as thermoplastic polyurethane. Footwear such as sneakers and flipflop sandals are also being three-

dimensionally printed. Custom STL files can be used to fabricate jewelry that are high in quality. Beyond construction, automobiles, and textiles, the engineering industry is using rapid prototyping to 3-dimentionally print. Furthermore, three-dimensional printing is even being used in the food industry. FDM three-dimensional printers are used to extrude special pastes. Chocolate, pizzas, and even meat can be printed. For example, vegan compounds can be printed to mimic the texture of meat. The gun industry has also taken advantage of this technology. 3-dimmensional printed guns are made from filament and a couple of tiny metal parts. During the COVID-19 pandemic, masks and face shields were even fabricated from three-dimensional printers due to factory workers not being able to work in the normal working conditions. Ultimately, the rapid development of three-dimensional printing technologies has led to new applications in the area of healthcare and medicine. Specifically, these areas include dentistry, orthopedics, cardiovascular, pharmaceutics, neurosurgery, engineered tissue models, medical devices, and anatomical models.[8] Welshman Stephen Power was the first person to receive a three-dimensionally printed skull bone implant. Metal three-dimensional printers can make sterile and implantable joints, bone segments, and even entire bone structures to perfectly fit the patient.[15] Aside from

bones, other organs such as hearts, lungs, kidneys, and more are now printed. Hearing aids can also be printed with three-dimensional printing, resulting in a much better fit for the patients allowing patients to hear more efficiently. Now, almost 100% of hearing aids are produced by this method.

Three-dimensional Printing in Dentistry

Even before three-dimensional printing was invented, the dental industry used digital dentistry dating far back as 1971. In dentistry, digital methods such as scans and computer-based analysis was used for diagnosis and surgeries. three-dimensional printing arose in dentistry in the 1990s and the dental field took full advantage of this three-dimensional printing technology. In 1999, the first three-dimensional printer was used to treat a patient with a cleft palate to place a custom implant.[9] The modern advancement in digital dentistry to integrate these tools has restructured dental practices by paving the way for computer-aided design (CAD) technology and rapid prototyping.[44] Three-dimensional printing has many advantages in process engineering, with applications in dentistry ranging from the field of prosthodontics, oral and maxillofacial surgery, and oral

implantology to orthodontics, endodontics, and periodontology.[11] Although this was a great implementation to the dental field, three-dimensional printing had a slow start due to the cost and the availability. It has since become more popular due to the affordability and access to own a printer. Now three-dimensional printing has been vastly implemented into all specialties in dentistry.

To create functional three-dimensional materials used in dentistry, a special wand called an intraoral scanner is used to scan a patient's teeth to recreate the exact replicas for necessary replacements. [16]. Intraoral scanners were first introduced in the 1980's close to the same time that computer-aided design/manufacturing (CAD/CAM) and chairside economical restoration of esthetic ceramics (CEREC) technologies. Intraoral scanners were first used in restorative dentistry to capture direct impressions of certain areas in the mouth. As time went on and technology advanced, intraoral scanners gained the ability to record full dental arches. By 2008, a company by the name of Cadent released the first intraoral scanner suitable for orthodontics called the iTero. This invention led to many other types of intraoral scanners which in turn created less use for conventional alginate and polyvinyl siloxane impressions.[17-19] The wand of the intraoral scanner has a built-in light source and sensor. Structured light

is projected from the wand onto the structures in the month. The light is then reflected back into the sensor of the wand. The data captured by the sensor is processed by the software and rendered as a three-dimensional model. Similarly, intraoral scanners can be used to digitize existing study models.[20-23] Part of the reason why three-dimensional printing is possible in dentistry is because of these intraoral scanners. three-dimensional modeling and scanning provide a more comfortable clinical experience for the patient. It also provides efficiency and accuracy and helps create a custom fit for the patient.

The rise of three-dimensional technology has drastically changed the face of dentistry in the last 10 years. Because it is an adaptable technique, it allows the fabrication of personalized dental devices and aids to patients in dental offices. Its efficiency, reproducibility, speed, and accuracy all at an affordable price are all reasons why it has gained popularity at an exponential rate.[25]

The applications that three-dimensional printing can create can range from several different categories. One of the most used applications for three-dimensional printing in dental offices are dental models. The models can be used as study models or active models. It has been studied that three-dimensionally printing dental models are

more accurate than alginate models.[28] A very common material used to three-dimensionally print dental models is polymethylmethacrylate resin (PMMA). This material helps shorten the lead time and can make multiple copies without any errors in anatomy.[40, 41] It has been studied and determined that three-dimensionally printed dental models are suitable for diagnosis and treatment planning.[40, 42, 43] In addition to dental models, three-dimensional printing can be used for dental implants. With scans of the mouth and jaw, the exact geometry of how an implant needs to be made can be calculated. After a scan is made, dentist can begin printing the necessary replacement and initiate testing it for the patient prior to any surgical intervention.[16] This lessens repeated impressions and diminishes cost and time wasted. Furthermore, it has been proven that three-dimensional printed implants without spikes and conventional threaded implants show comparable implant stability measurements.[24] Dentures are also three-dimensionally printed in dentistry. This can be done with both removable and partial dentures. This changed the antiquated fashion of grabbing a model off the shelf and having it fit the patient's mouth. Now, dentures are customizable. With dental resin arising to become the material to print dentures, the cost of dentures has drastically fallen. Now dentures can be made as quick as in two appointments

compared to the 5 or more appointments it used to take. Digitized impressions act as the primary step in a digital work flow when creating a three-dimensional denture.[25] The digitized scan creates a digital file, STL file, that can be quickly sent to CAD software to design the denture.[25, 26] The digitalization of the conventional impression is followed by CAD design of the denture using a CAD software program. The CAD software then helps with the positioning of teeth and modeling the denture base with high-level accuracy and detail. Teeth can be chosen from a vast digital library of existing denture teeth to suit the patient.[25, 27] Dental crowns are a very versatile dental procedure and an area where three-dimensionally printing could be useful. Crowns can be used on root canal treated teeth, in place of a missing tooth when placing a bridge, or on a tooth that has been fractured. Crowns are even used to restore implants. Because crowns are used in many different situations in dentistry, it is apparent that three-dimensional printing has impacted the process of receiving this type of restoration tremendously. The metal framework that is necessary for a porcelain fused to metal bridge can now be printed with complete accuracy. Same-day veneers can be easily made with this technology, therefore reducing chair time for the doctor and patient. The Stratasys Polyjet printer can fabricate esthetic try-in crowns

or bridges from light-polymerizing resins.[29] This helps a patient see exactly what the final restoration will appear in the patient's mouth. Therefore, if any fine tuning of the restoration needs to be done then it can be made at that moment rather than sending it back to the lab for changes. Because there are less errors with margins and this reduces the failure rate, the reliability of three-dimensional prosthetics supersedes that of the traditionally machined crowns.

Surgical guides can also be three-dimensionally printed. Surgical guides duplicate the precise surfaces of the patient's intraoral cavity and aids the oral surgeon to place the implant or implants into the bone with peak accuracy. The guide helps the implant to be placed in the proper angle, location, and even can assist in sinus lifts. A surgical guide helps prevent against oral health complications and can aid in avoiding any potential lawsuits.[31] There are several different ways that implant surgical guides are made. Certain guides are fabricated to place only a single implant, while others are designed to place multiple implants,[32, 33] implant-fixed partial dentures,[32, 34] and implant-retained overdentures.[32, 35] There are three ways to prepare the guide holes for the construction of the surgical guides. These include the following: free-hand, milling, and the use of computer-aided design/machining (CAD/CAM).[32, 36-39] In the past, dental laboratories

had to fabricate surgical guides from impressions taken chairside. With the advent of this new three-dimensional printing technology, there is no need for these antiquated impressions. They now can use the CAD/CAM technology to three-dimensionally print these creating many added benefits to the patient and clinician.

Three-dimensional Printing in Orthodontics

Three-dimensional printing plays more of a major role in the orthodontic specialty than it does in the general dentistry sector. With more advanced technology becoming available, printing is becoming easier. Three-dimensional printing is accurate and causes more comfort to patients. It was predicted that three-dimensional printing would become the future of orthodontics and play a significant role in many offices.[10] From 2015-2020, three-dimensional printing has exponentially grown in orthodontics. This has changed how many orthodontists structure their offices and perform tooth movement. In orthodontics, three-dimensional printing is commonly done by digital light processing (DLP), low force stereolithography (LFS), stereolithography (SLA), or material jetting technology. Although these

are the most popular ones used, there are other ways applications are printed three-dimensionally.

A common use for three-dimensional printing in orthodontics is to help create retainers. Retainers are needed after a patient has undergone orthodontic treatment. It is imperative to hold the teeth where they were moved to prevent relapse. Many authors have agreed that long-term immovability is closely connected to the type of removable retention appliance.[45-51] The first clear retainer, the Essix, was created by Dr. John Sheridan in 1993. It was coined the first true clear aligner. Its name came from an acronym for S-Six or Sheridan's Simple System for Stabilizing the Social Six.[53] The traditional way of fabricating a clear retainer is to use an alginate impression to pour up a model. You then take that model and use a piece of thermoplastic to create a vacuum formed aligner. With the new CAD/CAM software, this can be eliminated. Now, retainers can be three-dimensionally printed. These retainers are just as reliable as conventional vacuum formed aligners.[52] The major difference is that three-dimensionally printed retainers are made faster. This saves chair time for the patient and the orthodontist.

Another very popular application for three-dimensional printing in orthodontics is aligner therapy. Clear aligner therapy has increased tremendously over the past 10 years. Moving teeth without brackets and wires is a concept that started in the 1940's. In 1945, an orthodontist by the name of Harold Kesling announced his "tooth positioning appliance". The device was invented to be used as a finishing appliance after full fixed, orthodontic treatment was complete. This device could achieve good root parallelism in extraction cases, establish proper axial inclination and interdigitation, and even de-rotate teeth. The device was intended to be delivered as soon as the patient was de-banded. The patient had to wear the appliance for four hours during the day and while they slept. The device, if worn properly, would complete its results in a month's time.[54] Even though Dr. Kesling was the first to create a device like this of any kind, two students from Stanford University would get the credit for inventing aligner therapy. In 1997, Zia Chishti and Kelsey Worth invented the world's first complete clear aligner system. They called it and it conceptualized a series of clear plastic aligners that could move teeth of adults discreetly. The company that blossomed out of this creation was called Align Technology. Align started producing and selling Invisalign in 1999. When Invisalign launched their campaign for

three-dimensional aligner therapy, this brought attention to three-dimensional printing and all of the advantages that it has. They were the first company to initiate the use of CAD/CAM software for tooth movement.[55] Invisalign® was the first[56, 57] and is the current largest provider of custom-made clear aligners for orthodontic tooth movement.[58] Invisalign uses a biocompatible polyurethane resin and uses 3D System's Stereolithography (SLA) 3D printers.[60] This company has offered their services to orthodontists and dentist for roughly 25 years, initially only focusing on cases with mild spacing or crowding.[59]

In addition, indirect bonding trays can now be three-dimensionally printed. The indirect bonding technique was first developed by Silverman and Cohen[61, 62] to heighten patient comfort and condense chair time. The original method indirect bonding was performed by using cement for attaching brackets to the stone model, some type of sealant as a clinical adhesive, and thermoplastic trays for the transfer of the brackets. It was in 1979 that the "custom composite base technique" was invented which is still the most widely accepted technique used today.[61, 63] Over the years the same technique has been modified to increase bond strength and to decrease bond failures. One modification was done by mixing the universal and catalyst resins outside of the mouth and directly applying it to the

bracket. This enhanced bond strength and made it comparable to direct bonding.[61, 64] The next hallmark enhancement came in 1990 when light-cured resins were used for indirect bonding.[61,65] When technology skyrocketed and computers entered the realm of orthodontics, this caused an incredible enhancement to the indirect bonding technique. Several companies started offering three-dimensional CAD/CAM created techniques for the manufacturing of indirect bonding trays. Companies such as SureSmile[61, 66] and Insignia[61, 67] both fabricate these types of three-dimensionally printed bonding trays. The way this method works is by first using an intraoral scanner to scan the teeth to create a three-dimensional image. That image is then used for a digital set-up and the brackets are placed in the ideal region on each tooth. Finally, the customized transfer trays for indirect bonding are created and a customized archwire is assembled.[61] I bonding trays have become so popular because it eliminates the timing it takes to decide on where to place the bracket on each tooth.[68] It also reduces chair time up to 30 minutes in comparison with the conventional way of bonding brackets.[69]

There are several other applications in orthodontics that three-dimensional printing can be used for. Some orthodontists have integrated this technology to fabricate orthodontic expanders and

others use it to make functional appliances. Metal appliances can be three-dimensionally printed using selective laser sintering (SLS). This is a tremendous advantage because it reduces time in the lab to make near impossible appliances. It also eliminates the need to place separators in patients' mouths to make room for bands. The three-dimensionally printed metal "bands" actually overlay the teeth removing the need for interproximal space between teeth. The most common three-dimensionally printed appliance is the hyrax rapid palatal expander. Even though these printed appliances cost more to the orthodontist, it can save chair time, reduce patient's discomfort, and decrease the number of appointments for the patient.[70] Mouth guards and occlusal splints can also be made from this technology. Furthermore, temporary anchorage device templates, when three-dimensionally printed, can assist with the accuracy of TAD placement.

A nuance that has just recently been discovered is the three-dimensionally printed bracket. During the last 100 years, orthodontic brackets have advanced from basic tooth attachments to exceedingly variable fixed appliances with pre-adjusted prescriptions.[70, 71, 72] Now brackets can be tailored to specifically fit each patient's malocclusion. This reduces the time spent bending wire to make precise movements of teeth. The first 3-dimentionally printed

bracket was created by a company named LightForce Orthodontics. The company was founded in 2015 by Alfred Griffin III. He hypothesized that three-dimensional printing technology would be able to fabricate patient specific brackets. This dream came into fruition when the first bracket was developed. The bracket is customized and is patient-specific. It is made of polycrystalline alumina ceramic in the form of a twin bracket with idealized geometries. This allows for highly proficient tooth movement.[70] Orthodontic cases can now be finished with precision and with a reduced treatment time.

Three-dimensional printers used in orthodontics

Three-dimensional printing has infiltrated the orthodontic field by storm. More and more orthodontic applications are being fabricated using this technology. In the past, three-dimensional printers were large and bulky and very expensive. Today, printers have reduced dramatically in size and pricing. Now there are three-dimensional printers that are used inside of orthodontic offices and some that are used strictly outside of orthodontic offices in orthodontic laboratories. There are numerous of companies that have taken advantage of this technology by developing their own printers.

EnvisionTEC, founded by Al Siblani, introduced its three-dimensional printer in 2002. This company produced the first digital light processing (DLP) three-dimensional printer, which is the most popular method to printing in dentistry and to make jewelry.[76]

A popular in-house three-dimensional printer is the Formlabs printer. Founded in September of 2011 by three MIT Media Lab students, this was the very first easy-use and affordable desktop-sized printer[73] This three-dimensional printer used the stereolithography technology where liquid resin is cured into a solid material by the application of laser light.

Another three-dimensional printer used in orthodontics is the SprintRay. It was founded in 2014 at USC Marshall School of Business by Hossein Bassir, Jing Zhang, and Amir Mansouri.[74] It uses the DLP technology.

Anycubic three-dimensional printers were founded in 2015 by two childhood friends, James Ouyang and Lu Ouyang. This is now one of the most popular three-dimensional printer brands worldwide.[75] Like the SprintRay, Anycubic printers use DLP technology to fabricate it's prints.

Another popular brand used in orthodontics is the EPAX three-dimensional printer. Founded in 2016 by William Dai, it uses DLP technology and is also a desktop printer.

Additionally, a three-dimensional printer by the name of Juell 3D was founded in the same year. Like many three-dimensional printers used in orthodontics, it uses DLP technology. This printer is one of the fastest on the market today. It can produce orthodontic models in as less as 18 minutes.[77]

3D Systems was founded in 1983 and has evolved dramatically ever since. In orthodontics, it has developed a three-dimensional printer, Nextdent, that can print orthodontic applications directly to applications such as orthodontic models, splints, retainers, and indirect bonding trays. This printer has been fabricating these applications since 2017.[79]

Software used in orthodontics for in-house aligners

In order to print on three-dimensional printers, software needs to be used to create the necessary model so that applications can be fabricated. Alternatively, applications can be printed directly from STL

files. There are several different kinds of software out there that can create such applications. Numerous programs are capable of initiating innovative techniques in orthodontics such as creating orthodontic study models, fabricating indirect bonding trays, and making models to fabricate in-house aligners. In-house aligners stem from clear aligner therapy that first was discovered by Invisalign. Digital clear aligner therapy has led to creating aligners directly in orthodontic offices.[86] Creating your own in-house aligner therapy requires several accessible equipment in your armamentarium including a digital scanner, aligner planning software, three-dimensional printer, and a thermoforming machine.

There are a vast number of aligner planning software that an orthodontist can use some of which include but are not limited to Archform, uLab, SureSmile®, Ortho Insight 3D®, Ortho Analyzer. Archform was founded in 2017 and is a teeth-aligner software designed to import three-dimensional scanned modes, create, design and purchase aligners or 3-dimensinal in-office printing. The software detects open intra-oral scans and caps them, using machine-learning for accurate tooth segmentation and offering numbered aligners and automated attachments.[79]

Amir Abolfathi and Charlie Wen founded uLab Systems in 2015. The orthodontic aligner movement planning software allowsSTL files to be automictically labeled, trimmed, and exported to a three-dimensional printer. Once the printer the STL files are arranged in the print tray, the software is compatible with the leading printers and thermoformers. This allows orthodontists to print same day aligners and start treatment effectively and efficiently.[87]

SureSmile® technology was discovered and developed by OraMetrix, a company that was founded in 1998 by Dr. Rohit Sachdeva and Friedrich Riemeier. SureSmile® and OraMetrix introduced Elemetrix in 2015. Elemetrix was a newly designed digital treatment planning platform. It expanded the orthodontic treatment options that were available which included clear aligners. This paved the way for advances in aligner design incorporating control, accuracy, and clinical efficiency.[80] In 2018, Dentsply Sirona acquired OraMetrix[81] leading to the rebranding of Elemetrix to the name of SureSmile® Ortho. After the new name, new innovations were added to their aligner system. These features included cut-outs that could correct mild class II and class III occlusion cases. Furthermore, automated pontics and variable trim lines were added to allow for more flexibility and convenience for patients.[82, 83] SureSmile® Ortho

allows you to create do-it yourself (DIY) aligner, staging packages allowing the orthodontist to create a staged model sequence. An intraoral scan is first taken and uploaded. After it is submitted, a diagnostic model with segmented teeth will be generated and the movement of teeth can take place. Attachments can be added automatically based on the prescribed movements or manually based on the clinician's preferences. After tooth movements are finalized, the aligners can be fabricated by exporting the STL files and printing the staged models.

Ortho Insight 3D® was created by Motion View Software, LLC in 2012. The original company designed orthodontic software and was the first to integrate cephalometric tracing predictions with the morphing of digital photographs.[84] Today, the company offers the Ortho Insight 3D®, Facial Insight 3D, and Ortho Share 3D software. Furthermore, it produces a three-dimensional scanner and printer to use in conjunction with this software. This is how the clear aligner therapy service is fabricated.

Ortho Analyzer® is a product of a company out of Denmark called 3Shape. The company manufactures three-dimensional scanners and CAD/CAM software solutions. 3Shape was founded by

Tais Clausen and Nikolaj Deichmann, two graduate students from Denmark. In 2009, the company introduced its first orthodontic software allowing labs and practices to take full advantage of digital technology. They introduced the TRIOS intraoral scanner in 2011 and became one of the premiere leaders in CAD/CAM for laboratories.[85] 3Shape offers a variety of software solutions. The one that helps with fabricating in-house aligners is the Clear Aligner Studio along with Ortho Analyzer software.[86]

Surveys in Research

Surveys and questionnaires are used in research as an instrument consisting of a series of questions for the purpose of gathering information from respondents.[88] The first questionnaire was invented by Sir Francis Galton, a British anthropologist, explorer and statistician in late 1800.[89,90] It is important to note that the questionnaire forms the backbone of any survey and the success of it lies in the designing of a questionnaire.[89] A questionnaire is simply a list of mimeographed or printed questions that is completed by or for a respondent to give his opinion.[89,91] A questionnaire is the direct means of obtaining quantitative primary data. It allows quantitative data to

be collected in a standardized way so that the data are internally consistent and coherent for analysis. A questionnaire should always have initial considerations, question content, phrasing and response format, question sequence and layout, pretest (pilot) and revision, and then you develop the final questionnaire.[89] Four types of questionnaire designs exist for a survey.[89, 92] They consist of contingency questions, matrix questions, closed-ended questions, and open-ended questions. The way a questionnaire should be written is it should be composed of a simple and a specific language, it should demand one answer in one dimension, it should yield a truthful and accurate answer, it should accommodate all possible contingencies of a response, it should have mutually exclusive response options, it should produce variability in response, and it should minimize social desirability. Three aspects of a questionnaire are the general form, question sequence, question formulation, and wording. There are different ways to have a questionnaire answered which include face-to face interview, telephonic interview, mail questions, and internet questions. Questionnaires should be tested for reliability and validity. There is inter-interviewer reliability, test-retest reliability, and internal consistency reliability.[89] It is important to check four types of validity in questionnaires.[89, 93] There is content validity, face validity, criterion

validity, and construct validity. It is value to recognize poor questions through pretesting. There are several things that indicate that there are errors in the early drafts of a questionnaire.[89, 94] Note if there is a lack of order in the answers, all or none responses, high proportion of don't know or do not understand answers, high proportion of refusal to answers, and substantial variation in answers when order of questions has been changed.[89] Surveys can be valuable in research if constructed the proper way. Surveys can find out important information that can easily be computed and interpreted.

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STATEMENT OF THESIS

- **Objective**: The purpose of this study is to examine the use of orthodontic 3-dimensional printing technology in the US, whether that is in an in-house or outsourced capacity and to understand why orthodontists are, or are not, incorporating 3-dimensional printing technology in their practices. Finally, to identify the popularity of various software, applications, uses, pitfalls, and benefits for 3-dimensional printing by practicing professionals and any association of these experiences with practice or professional demographics.

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THE USES OF 3-DIMENSIONAL PRINTING TECHNOLOGY IN ORTHODONTIC OFFICES IN THE UNITED STATES

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Introduction

Over the last several decades, technological advancements have shaped orthodontics and dentofacial orthopedics into the effective, innovative field it is today. Three-dimensional printing, also referred to as additive manufacturing, is the result of layers of material sequentially deposited on top of one another to eventually form an object. Three-dimensional printing has exponentially advanced since the advent of three-dimensional printing in 1983 by Charles W. Hull. He is credited to have successfully designed the first commercial rapid prototyping technology and later became the prominent founder of 3D Systems in 1986.

The first form of three-dimensional printing was done by stereolithography apparatus (SLA)[2] and commercialized in 1987, which was created by Hull. SLA uses a photopolymer resin to strike the pattern of ultraviolet light, solidifying and adding to the structure that came before it. After a layer is complete, the developing structure drops down right below the surface into a bath of liquid plastic, resulting in each printed layer equidistance from the light source. Repeatedly, a new thin layer of liquid is selected, cured, and attached. Simultaneously, another emerging 3-dimensional technology was invented in the late 1980s. A University of Texas' student by the name

of Carl Deckard brought a patent for the Selective Laser Sintering (SLS) technology in 1988. In contrast to Hull's design, Deckard's 3-dimensional printing technique uses powder polymers to fuse them together locally by a laser. Nylon is commonly used in SLS and can make more complex shapes than SLA.[14]

In 1989, Scott Crump invented Fused Deposition Modeling (FDM) and commercialized it in 1990 by using Stratasys. This is the 3-dimensional printing technology that people are most familiar with today. Crump first created this technology to build his daughter a toy frog using a glue gun and a mixture of polyethylene and candle wax. The FDM design allows a user to first create a 3-dimensional model in a 3-dimensional modeling program. It subsequently saves the model as an STL file and the printer's interfacing software converts the file and slices the model into sections, simultaneously determining how the layers will be printed. After that phase is complete, the model is sent to the 3-dimensional printer and build material is extruded through a heated nozzle layer by layer until the part is complete. This type of 3-dimensional printing is the most common used today and is usually colloquially referred to as "desktop 3D printers."

In 2012, B9Creator created a 3-dimensional printer that used Digital Light Processing (DLP) technology. This introduced the era of

laser- and DLP-based SLA printing techniques. Digital Light Processing (DLP) is the newest technology and has the best finish quality of the previous three printing styles.[3] DLP-based 3D printing technology comes from the image projection technology developed by Texas Instruments in the 1980s.[4] This method uses a set of chipsets based on optical micro-electromechanical technology to process working light sources to photosensitive materials. The main functional part is a digital micro mirror device (DMD), which consists of a group of micron-sized, controllable mirrors. The mirrors rotate to control the path of light and then project it onto the photosensitive resin during working.[5] The projection of an image that is composed of small square pixels called "voxels" passes through an optical lens and cures the photo-curable polymer resin.[6] DLP printers can produce intricate designs and are usually faster and more cost effective than its counterparts.

Before 3-dimensional printing was invented, the dental industry used digital dentistry dating far back as 1971. In dentistry, digital methods such as scans and computer-based analysis was used for diagnosis and surgeries. 3-dimensional printing arose in dentistry in the 1990s and the dental field took full advantage of this seemingly novel technology. The modern advancement in digital dentistry to integrate these tools has restructured dental practices by paving the way for computer-

aided design (CAD) technology and rapid prototyping.[44] For example, in 1999, the first 3-dimensional printer was used to treat a patient with a cleft palate to place a custom implant.[9] Three-dimensional printing has many advantages in process engineering, with applications in dentistry ranging from the field of prosthodontics, oral and maxillofacial surgery, oral implantology, orthodontics, endodontics, and periodontology.[11] Although this was a great asset to the dental field, the implementation of 3-dimensional printing in dentistry has had a slow start due to the cost and the availability. It has since become more popular due to the increased access and affordability of a printer. Now 3-dimensional printing has been vastly integrated into all specialties in dentistry.

Three-dimensional printing plays more of a major role in the orthodontic specialty than it does in the general dentistry sector. With more advanced technology becoming available, printing is becoming easier. Three-dimensional printing is accurate and causes more comfort to patients. It was predicted that 3-dimensional printing would become the future of orthodontics and play a significant role in many offices.[10] From 2015-2020, 3-dimensional printing has exponentially grown in orthodontics, changing how many orthodontists structure their offices and perform tooth movement. In orthodontics, 3-dimensional printing is commonly done by digital light processing (DLP), low force

stereolithography (LFS), stereolithography (SLA), or material jetting technology. Although these are the most popular ones used, there are other ways applications are printed 3-dimensionally.

Three-dimensional printing has infiltrated the orthodontic field by storm. More and more orthodontic applications are being fabricated using this technology. In the past, 3-dimensional printers were large and bulky and very expensive. Today, printers have reduced dramatically in size and pricing. Now there are 3-dimensional printers that are used inside of orthodontic offices and some that are used strictly outside of orthodontic offices in orthodontic laboratories. There are numerous of companies that have taken advantage of this technology by developing their own printers. Some printer to note are: EnvisionTEC, Formlabs, SprintRay, Anycubic, EPAX, Juell 3D, and 3D Systems.

In order to print on 3-dimensional printers, software needs to be used to create the necessary model so that applications can be fabricated. Alternatively, applications can be printed directly from STL files. There are several different kinds of software that can create such applications.

Ultimately, there are numerous software programs that exist today capable of initiating innovative techniques in orthodontics such

as creating orthodontic study models, fabricating indirect bonding trays, and making models to fabricate in-house aligners. For example, in-house aligners stem from clear aligner therapy that first was discovered by Invisalign (1997) and digital clear aligner therapy has led to creating aligners directly in orthodontic offices.[86] However, it is evident that accomplishing these novel orthodontic techniques requires access to personal printer and software. In the case of creating your own in-house aligner therapy, an orthodontist requires equipment in their armamentarium including a digital scanner, aligner planning software, 3-dimensional printer, and a thermoforming machine. There are a vast number of aligner planning software that an orthodontist can use some of which include but are not limited to Archform, uLab, SureSmile®, Ortho Insight 3D®, Ortho Analyzer.

This revolutionary technological advance in orthodontics is shaping the way treatment is being performed. Orthodontics has shifted from using alginate impression material to then pour up the impression with stone in order to fabricate a cast. With this new technology, the patient's dentition is scanned and then 3-dimensionally printed. This is only one of the many examples of how 3-dimensional printing is changing how orthodontics is being done. Since this is a blossoming advance in this field and still in its infancy stages,

many practitioners haven't made the leap of faith to switch over from analog to digital. This study will gather a baseline of who is using this technology and in what capacity the technology is being used. Demographically, has the technology infiltrated most regions of the United States and what associations exist? Are both young and seasoned orthodontists using this technology? Have many orthodontists started using their printers to making clear aligners in-house or are orthodontists using this technology for outsourced aligner therapy? If this technology is being used, this study will determine the popularity of software, applications, uses, pitfalls, and benefits for 3-dimensional printing.

Material and Methods

This descriptive study was approved by the Case Western Reserve University (CWRU) Institutional Review Board (IRB) (Appendix 1). The survey was created on a secure online survey platform called RedCap. The data for this study was collected from orthodontists practicing in the United States. Data was collected from February 1st through June 30th. A 14-34 item descriptive survey was created to ask practicing orthodontists in the United States their experience with 3-dimensional printing. The survey was made to evaluate the use of

orthodontic 3-dimensional printing in the United States, whether it was in-house or outsourced; to evaluate the rationale on why orthodontists are incorporating 3-dimensional printing technology or not; to discover the popularity of software, applications, uses, pitfalls, and benefits for 3-dimensional printing; and to determine if demographics have an association between the use of 3-dimensional printing in orthodontic offices. The survey begins asking orthodontists demographic questions to gain a baseline of who is answering the survey. It then goes on to ask about their experience with 3-dimensional printing. The survey ends if the orthodontist doesn't have 3-dimensional printers in their office. If they have printers, the survey branches to ask in-depth questions about the number of printers their office has, what are the uses of their printers, what type of software they use, the applications they use for their printers, and questions about their 3-dimensional laboratory. The survey was distributed by three methods. The first method was via the American Association of Orthodontics Partners in Research program, which is comprised of American and Canadian orthodontists. The program selects orthodontists at random from a database and sends a link to the randomly selected members welcoming them to complete the questionnaire. About 1/3 of the orthodontists registered to the American Association of Orthodontists receives the link to this email,

which is roughly 2,200 orthodontists. The second method was through an orthodontic Facebook group called Orthodontic Pearls. Finally, surveys were handed out during in-person meetings by distributing business cards with QR codes which links the scanner to the survey. The data was then compiled to determine the uses of 3-dimensional printing in the United States. IBM® SPSS® version 27 was used to analyze the data. Descriptive statistics were used to analyze the frequency of responses. Association between participant demographics and in-house 3D printing was assessed using a chi-square test of independence. Statistical significance was defined as p-value ≤ 0.05.

Results

A total of 518 responses were recorded. No responses were eliminated from data analysis. The highest number of responses came from the age group of 36-45 (32.8 %) and those who have been in practice for more than 10 years (51.2%). Majority of the respondents were practice owners (60.8%), working in private practice (82.6%), and practicing primarily in a suburban area (62.8%). The majority of respondents of the survey treats 45-60 patients daily (31.5%). Most respondents lived in the southeastern part of the United States (26.0%). These states include: WV, VA, KY, AR, LA, TN, NC, SC, MS, AL, GA, FL.

An estimated 53% of the orthodontists that participated in this survey reported that they have had training in 3-dimensional printing. Most people who received training in 3-dimensional printing taught themselves (24.0%). If an orthodontist has had experience in 3-dimensional printing, then majority only have 1-2 years of experience (29.3%). About 73% of orthodontists use 3-dimensional printing applications in some capacity, whether that is in an outsourced or in-house capacity. Digital light processing was the most known type of 3-dimensional printing (35.1%). Out of the orthodontists that answered this survey, 46.9% had a 3-dimensional printer in their office. 21.0% had one printer ranking the highest out of the other options. The most used printer was the SprintRay (46.9%). Printing models for plastic retainers was the most popular use of a 3-dimensional printer in a practitioner's office (90.9%). It was reported that roughly 57% of orthodontists in this survey use 3-dimensional printing technology for in-house and outsourced aligners. The most popular (59.7%) used software to making in-house aligners was uLab.

The main reason orthodontists initially incorporated 3-dimensional printers into their office is because of self-research or self-interests. Practitioners with a 3-dimensional printer were very pleased

with it as 96.3% reported it meeting their expectations. The main reason the printer met their expectations was due to the ease of workflow.

Out of the orthodontists that did not use 3-dimensional printing in any capacity (141) in their offices, 33.3% said it was because they weren't the decision maker in their office. The next two reasons were even at 27% in that the orthodontists either had a training deficit in digital workflow or had a lack of interest in 3-dimensional printing. 39.3% of the 141 said they were interested or planned to implement 3-dimensional printing into their office in the future.

There were chi-square tests of independence performed on the data to see which associations existed and how 3-dimensional printing impacted those associations. There were several demographics that were statistically significant with the influence of 3-dimensional printing. The strongest statistical associations with utilizing an in-house 3D printer are seen with patient load, practice type, years since residency, and orthodontist's position. Increasing patient load and being in a private practice increases the likelihood of having a 3D printer. In contrast, the type of community and the region you practice in doesn't have a significant association with 3-dimensional printing.

Discussion

Our survey was answered by 518 practicing orthodontists in the United States and the obtained data represented the opinions of these practitioners. The majority of the respondents were found to be practice owners, practicing in the suburbs, and graduated from their respective residency programs over 10 years ago. The majority of the respondents have had training in 3-dimensional printing either by self-teaching, in their residency program, or by continuing education. In contrast, most of the respondents have had less than two years of experience with 3-dimensional printing. The survey was answered by an evenly distributed part of the country. Our study found that almost 50% (47%) of the practicing orthodontist respondents had at least one 3-dimensional printer in their office compared to a study by Poulos et al. in 2021 which stated that 39% of practicing orthodontists had a 3-dimensional printer. This discrepancy may be due to having over six times more responses than the previous survey. To the best of our knowledge, this was the first study to delve deeper into 3-dimensional technology practices in the orthodontics office solely in the United States.

Our study looked to focus on who was using 3-dimensional printing technology, whether that is in in-house or outsourced method.

Over 72% of respondents use 3-dimensional printing technology in some fashion in their office. There are several different types of 3-dimensional printers and our respondents had the opportunity to select from a various list. Digital light processing printers were the most commonly known type of printer, followed by the stereolithography apparatus. Out of the ones who had a 3-dimensional printer in their office, SprintRay was, by far, the most widely used printer by the participants of this study in their current practices. While uLab was the most commonly used software to print in-house aligners. Printing models for plastic retainers was the most popular application used by orthodontists with their 3-dimensional printer as most were using their 3-dimensional printer daily. Orthodontists with an in-house 3-dimensional printer were using in-house and outsourcing their aligner therapy a little more than half of the time. In contrast, one sixth of orthodontists were printing all of their aligners in their office. The major application that practitioners without a 3-dimensional printer carried out by outsourcing was aligner therapy.

The study also wanted to determine why orthodontists are, or are not, incorporating 3-dimensional printing technology in their practices. Most orthodontists that were using this technology were motivated because of self-interest or completing their own research. The majority

of orthodontists using this technology felt that there were minor to very little challenges to find the workspace to use the 3-dimensional printers and to train staff is using this technology. This last point is important because over 75% of staff operates the 3-dimensional printing technology. Out of the practitioners that weren't incorporating 3-dimensional printing in their office, most weren't the decision maker in their practice. Out of the decision makers, the leading reasons not to incorporate this technology was because of lack of interests, having the lack of training with this 3-dimensional printing, or difficulties with finding the space for ventilation.

Almost every respondent using 3-dimensional printing technology was happy with their experience. The most common reasons that 3-dimensional printing met their expectations was because of the ease of workflow, comfortability to the patient, and it being more accurate. Out of those who felt that 3-dimensional printing hadn't met their expectations, the main reason was because they felt it to be more time consuming than conventional methods of orthodontics.

Of the orthodontic specialists who did not currently practice 3-dimensional printing technology, greater than 1/3 (39%) expressed that they are very likely to incorporate 3-dimensional printing in their

practices in the future. Reinforcing advantages and eliminating challenges associated with 3-dimensional printing technology as identified in this study may present opportunity for more orthodontists who wish to adopt this technology. One of the limitations of our study is the minimal response rate. The survey questionnaire was sent to 2,200 active U.S. members of the American Association of Orthodontists (AAO). And also distributed to orthodontists at orthodontic meetings and via orthodontic Facebook groups. The AAO active members have been randomly divided into 3 groups of 2,200 members in each group. Such surveys are typically sent to only one group of 2,200 members by the AAO to avoid "survey fatigue". A reasonable explanation to the low survey response rate can be due to decreased interest in the orthodontists to participate in the survey. Orthodontists who are occupied in their practice may have inadequate time to respond to such surveys. With utilizing a social media group like Facebook, some practitioners may not view these groups on a daily basis and may have missed the posting to fill out the survey. Survey fatigue can also a reason. It can be conjectured that the results of our study could be the same or have varied results if the response rate was higher. The low response rate to such a survey study is outside the control of the investigators or the survey distributor (AAO). Future studies with a higher

response rate need to be done in this area of research to better understand the factors influencing orthodontists' preference of adopting 3-dimensional printing technology in their office. Lastly, survey bias could play an important barrier in the response rate. If a practitioner viewed the title of the survey and saw "3-dimensional printing", they could have not answered if they felt it didn't concern them. Leading to a biased data set, with respondents who participated in 3-dimensional printing in their office.

Future studies could take a closer look at whether 3-dimensional printing is more cost effective when completing it by an in-house or in an outsourced manner. Furthermore, a study to discover whether general dentist or orthodontists are incorporating 3-dimensional printing technology in their offices more.

Conclusion

- Within the limitations of this study, it can be concluded that close to 3/4 of orthodontists use 3-dimensional printing technology in some capacity in the US

- Some of the major factors that influenced orthodontists to incorporate 3-dimensional printing technology into their office were: self-interest and research
- Some of the major factors that has prevented orthodontists from not incorporating 3-dimensional printing technology into their office were: Space for equipment/ventilation, digital workflow training deficit, lack of manpower
- DLP, SprintRay, uLab, were the most popular in their respective categories
- Orthodontists use their 3-dimensional printer mostly to make plastic retainers from printed models
- Orthodontists using 3-dimensional printing were mostly happy with the ease of workflow and patient comfortability
- Orthodontists who were displeased with 3-dimensional printing didn't like how time consuming it was
- The strongest associations with utilizing an in-house 3D printer are seen with patient load, practice type, years since residency, and orthodontist's position.
- Increasing patient load and being in a private practice increases the likelihood of having a 3D printer.

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APPENDICES

Appendix A: IRB Approval

IRB Administration Offices
UH IRB Phone: 216.844.1529
CWRU IRB Phone: 216.368.6925

EXEMPT DETERMINATION

Principal Investigator:	Juan Palomo
Title:	The Influence of 3-D Printing Technology on Orthodontic Offices in the US
IRB Number:	STUDY20210785
IRB Office:	CWRU IRB
Approval Date:	8/13/2021
Effective Date:	8/13/2021
Exemption Category:	(2)(i) Tests, surveys, interviews, or observation (non-identifiable);
Documents Reviewed:	• YJS CWRU Exemption Protocol , Category: IRB Protocol; • Thesis Survey, Category: Other; • Thesis Informed Consent, Category: Consent Form; • Facebook approval doc, Category: Contract/Agreement; • AAO permission , Category: Letter of Cooperation; • Facebook approval doc, Category: Contract/Agreement; • Recruitment Material.pdf, Category: Recruitment Materials

The IRB determined that this protocol meets the criteria for exemption from IRB review.

Ongoing IRB review and approval by this organization is not required. This determination applies only to the activities described in the IRB submission and does not apply should any changes be made. If you wish to make changes to this protocol, please submit a modification.

The UH IRB operates under HHS Federalwide Assurance (FWA) number 00003937 and IRB registration numbers 00000684, 00001691 and 00008600. The CWRU IRB operates under DHHS FWA00004428 and IRB registration number 00000683.

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