TESTING THE SHEAR BOND STRENGTH OF THREE-DIMENSIONAL PRINTED BRACKETS ON ENAMEL

By

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DEDICATION

I dedicate this thesis to my loving grandparents John H. Jones Jr and Lillie Belle Robinson, who instilled in me to always work hard, stay focused and trust in the Lord. To my father, John H. Jones III for being my biggest inspiration and hero and for always believing in me. To my mother, Rosalyn C. Jones for the unwavering love. To my sister, Sopheia, thank you for all of your love, support and encouragement.

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ABSTRACT

Introduction: The aim of this study was to test the shear bond strength of three-dimensional (3D) printed CAD/CAM brackets and 3D printed twin brackets in comparison to traditional metal and ceramic bracket systems. This will allow us to evaluate how much shear stress they can withstand.

Methods: For this in vitro study, a total of 55 extracted and discarded premolars were collected from patients whose teeth were being extracted according to their treatment plans. The protocol for this study was approved by the Institutional Review Board (IRB) of Case Western Reserve University School of Dental Medicine (STUDY20221520). The Fifty-five extracted and discarded premolars were divided into five groups with 11 teeth each. Group 1 was direct bonded with LightForce brackets (Polycrystalline Alumina); Group 2 was direct bonded with 3M Unitek Victory Metal brackets; Group 3 was direct bonded using 3M Unitek Victory Clarity brackets; Group 4 was direct bonded using Braces on Demand 3-D printed brackets in A1 denture resin (Formlabs); Group 5 was direct bonded using Braces on Demand 3-D printed brackets in BioMed Clear resin (Formlabs). All teeth were mounted in acrylic resin prior to being bonded with brackets. The debonding force was measured using the Instron Universal Testing Machine. The descriptive data analysis, the Shapiro-Wilk test for normality, and the graphs suggested approximately normally distributed data in all groups. Multiple range testing shows that there are three distinct homogenous ranges or groups from the data collected. We can conclude from this that there is a statistical difference between the brackets.

Results: Multiple range testing shows that there are three distinct homogenous ranges or groups from the data collected. We can conclude from this that there is a statistical difference between the brackets. The ANOVA table decomposes the variance of the data into two components: a between-group component and a within-group component. Since the P-value for that test is less than 0.05, there is a statistically significant difference between the means at the 5% significance level.

Conclusion: Multiple range testing shows that there are three distinct homogeneous ranges or groups for the data collected, leading to the conclusion that there is a statistical difference between the brackets.

REVIEW OF LITERATURE

Timeline/History of brackets in Ortho

With all of the modern advancements and technology in the field of orthodontics, it is quite easy to forget the prehistoric techniques from which orthodontic treatment stemmed from. From the Ancient Egyptians, Greeks, Etruscans and Romans, ancient cultures have experimented with methods to achieve straight teeth by mechanisms placed on the teeth. Mummies and artifacts have been found showing evidence of orthodontic devices such as wires and animal intestines. Esthetic and straight teeth were so highly regarded by the Etruscan civilization in Italy that the deceased were buried with dental devices to ensure that their teeth would be preserved in the afterlife[1]. In the 1700's, Pierre Fauchard, known as "the father of orthodontics" invented devices for expanding the mouth and fixing the alignment of teeth. Fauchard noted that children's teeth were more relatively straightforward to correct than adults. Ettiene Bourdet later built a foundation on this observation along with helping people to extract crowded teeth for a better smile. Various appliances, elastics, wires and devices were used until 1880 when J.N. Farrar came up with the proposal to straighten teeth at specific force intervals[2]. This thought process birthed modern braces. In 1819, Christophe-Francois Delabarre created the wire crib which was a precursor to today's dental brace. E.G. Tucker was the first to use rubber bands in orthodontics after the creating of rubber by Charles Goodyear in the middle 1800's (Acceledontics). By the time it was the 1900's, dentists were using metal bands, rubber bands, x-rays and impressions in their orthodontic practice to properly align teeth. In the early 1900's, Edward Angle, known as "the father of modern orthodontics" created a system for classifying misaligned teeth and created the term

malocclusion. In 1916, Dr. Angle coined the term “bracket” when he introduced his ribbon arch appliance. Brackets were defined as “a simple, rigid, L shaped structure, one arm of which is fixed to a vertical surface, the other projecting horizontally to support a weight, as a shelf”. He played a very significant role in developing and evolving bracket types from the pin and tube appliance to the ribbon arch bracket mechanism and finally to the edgewise bracket. Brackets have tremendously evolved since their introduction and over the past century. Their evolution has increased the efficiency of tooth movement, decreased time in treatment as well as reduced chair time.

Types of Brackets and its Components

Dental materials and supplies used for braces were unregulated in the first half of the 20th century (Acceledontics). Dentists preferred working with gold due to its flexible properties however it was an expensive material to obtain. Silver was not as easy to manipulate as gold, however it was better than the alternatives of ivory and wood. In the 1950’s, stainless steel was available for usage however it was deemed a controversial choice of material for braces until it gained acceptance in the 1970’s. Stainless-steel became the most frequently used metal by dentists due to its flexibility and affordability for the patient. In the initial days of fixed-appliances the brackets were welded to gold or stainless-steel bands. Prior to starting treatment, the orthodontist would need to create adequate space surrounding each tooth to accommodate the fit of the bands. These spaces were then closed before the completion of treatment. Banded type appliances frequently caused trauma to the gingiva when being fitted and decalcifications

under the bands were a risk[3]. The components of a modern orthodontic bracket are the slot or tube, tie wings, hooks for an elastic and a retentive mesh backing for bonding.

During the 1970's, Lexan plastic was utilized to construct anterior brackets for patients who demanded improved esthetics. This improved polycarbonate material was more rigid and less predisposed to wear and tie-wing fracture. Nevertheless, it still was not as durable or reliable as stainless steel. The demand for increased esthetics led to the development of a variety of bracket systems to make braces less visible.

This pressure resulted in the development of lingual orthodontics along with additional labial appliance systems made of ceramic, plastic and even resin. In the 21st century, self-ligating brackets became a popular treatment option for eliminating the need to use elastomeric o-ties and steel ties with wires. Self-ligating brackets were acclaimed to reduce patient discomfort, decrease treatment time and be an improvement for oral hygiene. Customized brackets for tooth movements have also been an innovation in the more recent years. Dynamic bracket customization allows for the function of the bracket to be enhanced as needed during the course of treatment. The customization allows for assessment of changes three-dimensionally (3D) via the use of intraoral scanning, cone-beam computed tomography (CBCT), 3D photography and computer-aided design and computer-aided manufacturing (CAD/CAM) technologies [4].

Evolution of Bonding in Orthodontics

In the mid 1960's orthodontists Dr. George Newman and Professor Fujio Miura, chair of the Orthodontics department at Tokyo Medical and Dental University in Japan introduced

bonding orthodontic brackets directly to enamel (Gange, S56). Both orthodontists had the same vision of developing an adhesive that would bond plastic brackets to enamel directly. These adhesives would be strong enough to withstand the forces of occlusion and mastication during treatment along with stresses from the archwire while also maintaining control biomechanically. It was also critical that such adhesives allowed for debonding of the brackets without causing appreciable damage to the enamel. The 1970's was a time of major orthodontic breakthroughs. Braces advanced from the metal bands wrapped around each tooth to adhesives that were being discovered to bond brackets onto teeth.

In the early 1970's, Miura innovated a technique for bonding polycarbonate plastic brackets to phosphoric-acid etched enamel using a restorative filling material that was developed by Mashura and his co-workers at Tokyo Medical and Dental university (Gange, S56). The adhesive that was developed consisted of a monomer, methyl methacrylate and polymer, polymethyl methacrylate. The catalyst was tri-n-butylborane. In his investigation of the newer bonding materials to the dentine, Mashura was able to confirm the existence of chemical bonding between the tri-n-butylborane resin and the collagen in dentine [5]. A finding of Miura was that the bond strength decreased with time as a result of exposure to fluids in the oral cavity. Additionally, mastication and the metal archwires used with plastic brackets resulted in broken tie wings and deformed archwire slots.

Although this system had its drawbacks, it was still a popular technique as an alternative to bands being cemented around each tooth. It fueled the research to develop stronger adhesives. The end goal in mind was to have the ability to develop bondable metal brackets (Gange, S56).

Newman continued to pursue his work with epoxy resins while Retief et al from South Africa fabricated an adhesive to bond metal brackets that was based on research conducted by Bowen on epoxy resins[6] . Epoxy resins are synthetic materials manufactured from by-products of the petroleum industry (Retief). The Epoxy resins did not undergo polymerization shrinkage significantly when setting, maintained the same coefficient of thermal expansion as enamel, and were cross-linked to minimize water absorption. These characteristics produced the required strength to resist the forces associated with mastication and mechanics of braces. The properties of an ideal dental adhesive are as follows: It should rapidly set at or close to natural body temperature, shrinkage should not occur during setting, the cured resin should have sufficient cross-linking to minimize water absorption, it should be strong enough to resist the forces acting on it, it should have a coefficient of thermal expansion which approximates that of tooth structure, it should be non-toxic to the pulp and other oral tissues, it should not deteriorate in the oral environment, a lasting bond should be produced between the enamel and dentin (Retief). The final challenge was increasing the strength of the brackets so that they could withstand the forces of the three-dimensional mechanics associated with orthodontic treatment.

Retief et al collaborated with 3M Unitek to create a mesh grid that would be welded onto a flattened stainless steel material with a metal bracket welded to it. The primary disadvantage to that design was that the weld spots on the mesh base prevented the adhesive from flowing between the mesh and the foil pad properly, which resulted in a decrease mechanical retention. Over time and with additional research performed, this bracket design improved. By the 1970's, metal brackets were welded to a perforated base which enabled the

adhesive to become interlocked and provide mechanical adhesion. The primary complaint associated with these brackets with the perforated base was that the adhesive that covered the perforations was affected by the environment of the oral cavity causing it to often become stained and discolored over the duration of orthodontic treatment (Gange, s57).

Visible light-cured restorative materials were introduced to dentistry in the early 1980's. This restorative material gained popularity in orthodontics and was used for bonding brackets, lingual retainers and bands. This material was ideal to work with due to its unlimited working time. The catalyst for these adhesives was camphorquinine which has the ability to cure in the visible light range (440-480nm) when utilizing a quartz-tungsten-halogen light. The key element to using these types of materials is achieving proper light penetration under the base of the metal bracket. The catalyst absorbs the photons that are emitted from the curing light. For success with this system it is essential that as many photons as possible contact the paste directly. There are three fundamentals to complete light polymerization. They are intensity, proximity and duration. It is imperative to keep these elements in mind when curing the composite under a metal bracket.

Retrospectively looking at where orthodontics started, the changes and evolution has been substantial. Starting from brackets welded to fixed metal bands around teeth to having the ability to move teeth with the use of clear removable plastic aligners. Dramatic progress also has been seen in the bonding of orthodontic attachments. Comparing the messy, slow-setting, weak powder and liquid adhesives for bonding brackets to enamel, to single-paste, quick-setting adhesives that adhere to both enamel and non-enamel surfaces. The power to bond fixed appliances to dentin, amalgam, porcelain, and zirconia with the new-generation

primers has made orthodontic treatment more effortless for the operator and mores esthetic for the patient.

History of testing shear bond strength in dentistry

A plethora of direct restorative materials have been utilized in dentistry over the years. As the demand for more esthetic restorations has gained popularity, composite material has gained attention in restorative dentistry. Despite the fact that esthetics is a key characteristic for dental materials, specifically, care should be granted to the mechanical properties and bonding longevity of different restorative materials. Despite the many advances made in adhesive technology over the last 50 years, the bonded interface itself continues to be the weakest point of an adhesive restoration[7] . Thorough testing should be completed to determine the efficacy of bonded interfaces. The functionality of dental materials should be assessed by different testing techniques. One of these methods is the evaluation of the ability of a material to bond to a substrate through different bond strength tests [8]. Shear bond strength (SBS) testing is one of the most commonly used methods for measuring bond strength. The ease of preparing specimens, having a simple testing protocol, and lower incidence of pretest failure are some advantages of performing shear tests.

Shear bond strength is a measure of the resistance of a material to dislodge against a shearing mode of loading. Testing the shear bond strength is done to assess different dental adhesive systems that bond composite resin to the tooth. SBS differentiates from tensile bond strength which refers to the utmost stress a material can withstand before displacement occurs. Tensile and shear bond strengths refer to the resistance of the composite resin to forces of mastication when it is bonded to the tooth[9]. Bond strength has the tendency to increase with

smaller bonding areas along with the use of high elastic modulus composites. Stress concentration at the bonded interface is more severe in regards to shear compared to tension[10]. The measurement of a material's shear or tensile strength may not be completely suggestive of how durable it is. There have been discussions regarding the success of a material's bond to the tooth lies at the interface between the tooth and the material, and not the inherent properties of the material itself.

Laboratory testing can gather data rapidly regarding a specific guideline or property. It allows the ability to measure one specific parameter while maintaining all other constant variables. The relationship between bond strength test results and the reliability of clinical performance for dental adhesive has been looked at as questionable however there is evidence to prove that clinical reliability can be estimated based on laboratory results[11].

Clinical trials are considered the gold standard to evaluate adhesive dental restorations. The setback regarding clinical trials is their inability to identify the exact reason of failure due to the simultaneous homogenization of differing complex stressors on restorations within the oral cavity. Additionally, due to the rapid and continual fabrication of new materials, there is an increasing dependence on learning the properties of these dental materials from laboratory testing. Gathering the evidence clinically takes a longer amount of time and new materials may be on the market by the time these results have evolved. The amalgamation of these instances leads to the justification of laboratory testing being able to predict the data of in vivo clinical performance (Ismail, et al).

Studies utilizing finite element analysis demonstrated that conventional, or macro, shear bond strength tests result in a non-uniform and heterogenous stress pattern[12].

Microshear bond strength tests were created due to the need for novel methods to overcome these limitations. Microshear bond strength tests, test specimens with small bonding areas (i.e., less than 1 mm^2) Earlier shear test methods used large bonding areas; however, higher bond strength and incidence of adhesive failures were observed with smaller bonded areas (Ismail, et al). Micro-bond strength tests are categorized into three types: micro-shear, micro-tensile and micro-push out tests based on the stresses that are exerted on the test specimens.[13]

Despite there being multiple studies that have investigated the bond strength of various interfaces, so far, there is no standardized protocol recommended for evaluating bond strength. Failure mode analysis can provide information regarding weaknesses in different testing methods to improve their reliability. This allows for results that represent the actual strength of adhesive junction.

The measurement of a material's shear or tensile strength is not entirely suggestive of how durable it is. It has been argued that the success of a material's bond to the tooth is at the interface between the tooth and the material. A lot of factors dictate the shear or tensile strength of the resin.

Testing shear bond strengths of brackets

Various types of malocclusions can benefit from orthodontic treatment, which nearly takes 2 years or more to complete. Debonding of brackets during the treatment delays its completion and negatively affects the quality of the treatment outcome[14]. Fixed orthodontic treatment outcomes rely on the integrity of the orthodontic bracket-adhesive system. To withstand accidental bracket failures, there are many studies that focus on the bonding ability

of the various orthodontic adhesives, brackets, surface conditioning and methods for bonding. These studies are typically either in vitro or ex vivo done in the laboratory for mechanical testing or in vivo analysis of clinical bracket failure rates. Mechanical tests are usually done by the universal testing machine that applies either tensile or true shear load on the brackets. This machine is known for its accuracy and precision. However, it cannot exactly imitate the process of clinical debonding. This is because brackets face combined forces in all directions while functioning and in clinical debonding[15].

Test parameters that may influence bond strength include enamel type, the storage medium of the specimen and pretreatment of enamel surface. Bond strength testing is also affected by the test mode used, such as tensile or shear testing. Different outcomes seen in vitro bond strength studies might be because of the possibility of an unidentified combination of physical and mechanical properties related to the testing surfaces (Jain, et al.)

For an orthodontic bracket to work efficaciously it must be able to withstand normal masticatory forces without dislodgement. The maximum occlusal force for children with normal facial height between the ages of 6-11 is approximately 5.01kg and adults with normal facial height is approximately 13.5 Kg. Regarding values of shear bond strength, it has been reported in the literature that values have ranged from 3.2 MPa to 41.3 MPa (Jain, et al.) The ideal range for shear bond strength is within the range of 5.8-7.9 MPa. This range is considered to be the gold standard. Values below this range could increase the risk of bracket failure during treatment and values above this range increases the risk of damage to surface enamel during debonding[16]. During bracket removal bond failure may occur in the bracket/adhesive interface (adhesive), in the adhesive/enamel interface (adhesive), in the adhesive layer

(cohesive), or both (adhesive and cohesive). Failures in the adhesive/enamel interface can lead deleterious effects such as having enamel fragments removed along with the bracket base resin. Consequently, many authors suggests that orthodontists should use a technique that promotes failure in the bracket/adhesive interface in order to prevent damage to the tooth structure [17].

There are several studies that have investigated various factors of the bracket base component and how it effects bond strength. These factors include bracket base surface area, mesh wire gauge, the number of mesh layers and the design of the retention base. An investigation by MacColl *et al.* Looked at the effect of bracket base surface area on SBS by comparing different base sizes[18]. It was concluded there were no differences in SBS for surface area within the range of 6.82-12.35 mm2. However, significant reduction in SBS was observed if the surface area was below 6.82 mm2 (MacColl, et al)

Additional crucial factors that affect bond strength are the bracket base design, bracket surface characteristics, and bracket bonding area. Custom brackets are a newer technology within the more recent years. These types of brackets are fabricated specifically based on the diagnostic set up and treatment plan for the patient. There are various types of customized bracket bases, such as composite resin base, occlusal clasp extension, surface treatment with sandblasting, and an encircled bracket base design. The size of the customized bracket base also differs depending on the morphology of the tooth. With regard to customized bracket systems, due to the absence of substitute brackets, a custom bracket must often be rebonded when a failure occurs. It is necessary to have a vigorous bonding ability in customized bracket systems in order to ensure their long-term performance clinically[19].

Studies regarding how bracket base design influences the strength of the bracket-cement interface by Knox *et al* investigated differingf bracket base designs including 60-, 80-, and 100- gauge single mesh bases, a double mesh base, and integrated metal base[20]. In this study, it was concluded that the bonding agent has a significant effect on the shear bond strength. It was also concluded that specific base designs may allow for both enhanced adhesive penetration or penetration of the curing light. An investigation by Pham *et al.* in 2016 investigated the effect of bracket pad shape on shear bond strength on enamel of bovine teeth. It was concluded that the bracket base shape has an effect on shear bond strength[21]. Lastly, a study by Wang *et al.* investigated the influence of retention base design on shear bond strength. The retention base designs that were evaluated consisted of retention groove, circular concave, single mesh and double mesh layers with variable sizes. This study deduced that retention base design of a bracket could affect SBS[22].

The demand for esthetic brackets was the catalyst for the culmination of a plethora of bracket design types with varying shapes, sizes and material used. The need for esthetic orthodontic treatment, particularly requested by adults, resulted in the development of the first ceramic brackets in the late 1980's. Since then, new technologies for manufacturing esthetic brackets have been developed (Da Rocha et al.) Traditionally, options for bracket style or appliance design were very limited for both patient and the provider. Recently, the orthodontic market has experienced immense growth in the development and production of orthodontic appliances designed to esthetically appeal to patients. There are substantial differences in what patients indicate as the most attractive appliances. In 2009, Rosvall *et al.* investigated to quantify laypersons' assessments of attractiveness, acceptability, and value of orthodontic appliances [23].

Fixed orthodontic appliances work by transferring the forces from the wires to the teeth. There are a number of factors that can influence the attachment bond strength and clinical success. The most paramount attachment-related factor is the attachment bonding surface (ABS) morphology. The degree of contact between the ABS and bonding materials is dependent on the ABS morphology and bonding material characteristics such as viscosity and wetting ability. Additionally, the morphology of the ABS can influence the resin thickness, flow of resin, air escape and penetrability of light in light-activated bonding materials. Initial attempts to enhance bond strength include increasing the macroscopic area of the ABS and improving the ABS adaptation on the tooth surface. Extension of the ABS in the incisal-gingival direction in attachments with a gingival offset feature is an additional method to increase the bonding surface area. When the area is even, the ABS shape does not have a significant effect on the bond strength. Hygienic and aesthetic concerns have led to the fabrication of fixed attachments reduced in size and consequently has caused a reduction in macroscopic ABSs. The reduction of the macroscopic ABS area increased the importance of its design and its microscopic area for maintaining an ideal bonding strength. Bonding mechanism of attachments may be either chemical, mechanical or have the properties of both. Since most ABSs do not have chemical bonds to resins, mechanical retention due to the design of the ABS plays a critical role in the success of bonding. Mechanical retention occurs by producing surface roughness to enlarge the surface area and the development of undercuts for the resin to interlock and penetrate after polymerization effectively [24].

History of 3D Printing

Three-dimensional printing, also known as additive manufacturing, is performed by the process of sequentially depositing layers on top of one another to eventually form an object. Three-dimensional printing has exponentially advanced since the innovation of three-dimensional printing in 1983 by Charles W. Hull. Today, it is considered by to be the next industrial revolution.

Prior to Hull inventing his apparatus in 1980, Dr. Hideo Kodama filed for the first three-dimensional printing patent. However, it was never commercialized due to an incomplete specification regarding the patent. Dr. Kodama was part of the Nagoya Municipal Industrial Research Institute. He 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."[25] Dr. Kodama never finished the specifications for his patent and subsequentially it was never commercialized. Jean-Claude Andre, Olivier de Witte, and Alain le Mehaute were members of a French team that fabricated objects and pursued a patent which was also later abandoned. Although these three-dimensional patent attempts were incomplete, they developed the framework for Hull to develop what we now know today as three-dimensional printing. Charles Hull received his degree in engineering physics from the University of Colorado. He was the first to successfully design commercial rapid prototyping technology. This design adopts the utilization of concentrated ultraviolet light and ultraviolet curable plastic to produce three-dimensional parts from computer files. The initial form of three-dimensional printing was done by stereolithography apparatus (SLA).[26] SLA utilizes a photopolymer resin to strike the pattern of ultraviolet light followed by solidifying and

attaching to what came before it. Once a layer is complete, the part would drop down slightly below the surface in a bath of liquid plastic. This resulted in each printed layer equidistance from the light source. A new thin layer of liquid is selected, cured, and attached repeatedly until completion.

The inception of the term "three-dimensional printer" was coined by four students at Massachusetts Institute of Technology (1993). This name was then adopted by 3D Systems. This was a company co-founded in 1986 by Hull and (Unknown). 3D Systems fabricated the first machine for rapid prototyping and became the first three-dimensional printing company in the world. By the year 1987, the first stereolithography printer was commercialized. Additionally, the company also commercialized the "Standard Tessellation Language" or "Standard Triangular Language" (STL) file format that allows 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 which is a representation of a three-dimensional surface in triangular facets. Without the STL file, three-dimensional printing would not be possible.

3D Printing in Dentistry

Even before the advent of three-dimensional printing, the dental industry used digital dentistry dating back to 1971. In dentistry, digital methods such as intra-oral scans and computer-based analysis were used for diagnoses and surgeries. Three-dimensional printing arose in dentistry in the 1990s and the dental field took full advantage of this technology. In the year 1999, the first three-dimensional printer was used to place a custom implant in a patient with cleft palate.[27] The modern advancements in digital dentistry to utilize and integrate

these tools has reconfigured dental practices by paving the way for computer-aided design (CAD) technology and rapid prototyping.[28] Three-dimensional printing has many advantages in process engineering. It is able to be applied in a number of dental fields ranging from prosthodontics, oral and maxillofacial surgery, and oral implantology to orthodontics, endodontics, and periodontology.[29] The dental field has immensely benefitted from implementation of three-dimensional printing. However it did have a slow start due to the price point and the availability. Since then, it has 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 fabricate functional three-dimensional materials used in dentistry, an intraoral scanner is used to scan a patient's teeth. This allows for recreation of the exact replicas for necessary replacements. [30] Intraoral scanners were first introduced in the 1980's around the same time computer-aided design/manufacturing (CAD/CAM) and chairside economical restoration of esthetic ceramics (CEREC) technologies were introduced. Intraoral scanners were initially used in restorative dentistry to capture direct impressions of specific areas in the mouth. As technology advanced, intraoral scanners became able to record full dental arches. By 2008, a company called Cadent released the first intraoral scanner suitable for orthodontics. This intra-oral scanner was 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.[31],[32],[33] The wand of the intraoral scanner has a light source and sensor that is built in. Structured light is projected from the wand onto the different structures in the mouth. Then the light is reflected back into the sensor of the wand. The data captured by the sensor is

processed and rendered as a three-dimensional model. Intraoral scanners can also be used to digitize existing study models.[34],[35],[36],[37] A large reason that three-dimensional printing is possible in dentistry is due to the utilization of intraoral scanners. Three-dimensional modeling and scanning provide a more enjoyable and comfortable clinical experience for the patient.

The rise of three-dimensional technology has dramatically altered the dentistry in the last 10 years. Due to it being an adaptable technique, it allows the fabrication of personalized dental devices to patients in the dental office. Its efficiency, reproducibility, speed, and accuracy at an affordable price arereasons why it has gained popularity at a rapid rate.[38]

The applications that three-dimensional printing are capable of creating range from several different categories. One of the most common uses for three-dimensional printing in dental offices are dental models. The models are able to be used as study models or active models. The literature state that three-dimensionally printed dental models are more accurate than alginate models.[39]It has been studied and determined that three-dimensionally printed dental models are suitable for diagnosis and treatment planning.[40],[41],[42]In addition to dental models, three-dimensional printing can be used for the fabrication of dental implants. The exact geometry of how an implant needs to be made can be calculated using scans of the mouth and jaw. Once a scan is completed, the dentist can begin printing the replacement and test it for the patient prior to any surgical intervention.[43]This decreases the amount repeated impressions aling with diminishing cost and time wasted. Additionally, the literature states that three-dimensional printed implants without spikes and conventional threaded implants show comparable implant stability measurements.[44]Dentures are also able to be three-dimensionally printed in dentistry. This applies to both removable and partial dentures. With dental resin

available as the material to print dentures, the cost of dentures has fallen and become much more affordable. Digitized impressions act as the primary step in a digital work flow when fabricating a three-dimensional denture.[45] The digitized scan creates a STL file, that can be rapidly sent to CAD software for denture design.[46] The CAD software utilizes high-level accuracy and attention to detail to help with the positioning of teeth and modeling the denture base. Teeth can be selected from a digital library of existing denture teeth to suit the esthetics and wishes of the patient.[47] Dental crowns are another area where three-dimensional printing can be utilized. Due to crowns being used in many different situations in dentistry, it is evident that three-dimensional printing has largely impacted the process of receiving this type of restoration. The metal framework for a porcelain fused to metal bridge can be printed with complete accuracy. Same-day veneers can be easily fabricated with this technology. This truly reduces chair time for the doctor and patient. The Stratasys Polyjet printer is able to fabricate esthetic try-in crowns or bridges from light-polymerizing resins.[48] This allows for a patient to see exactly how the final restoration will look in their mouth. This allows for any fine tuning of the restoration to be done at that moment rather than sending it back to the lab for changes. Due to less errors with margins, this reduces the failure rate. Three-dimensional prosthetics reliability and accuracy surpasses that of the traditionally machined crowns.

Surgical guides can also be three-dimensionally printed. The guide helps the implant to be placed in the proper angle and location. A surgical guide helps prevent against oral health complications and can aid in avoiding any potential lawsuits.[49] There are several different ways that implant surgical guides are fabricated. There are three ways the guide holes can be prepared for the construction of the surgical guides. These include: free-hand, milling, and the

use of computer-aided design/machining (CAD/CAM).[50],[51],[52],[53] In the past, dental laboratories had to fabricate surgical guides from chairside impressions. They are now able to use the CAD/CAM technology to three-dimensionally print and fabricate them.

In today's orthodontic work flow, three-dimensional printing plays a major role. With more advanced technology becoming readily available, printing has become more attainable. Three-dimensional printing is very accurate and causes more comfort and efficiency for patients. It was predicted that three-dimensional printing would become the future of orthodontics.[54] From the years 2015-2020, three-dimensional printing has rapidly grown in orthodontics. This has changed how many orthodontists structure their office work flow and achieve 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 a plethora ways to print three-dimensionally.

One of the very common uses for three-dimensional printing in orthodontics is for the fabrication of retainers. Retainers are necessary after a patient has undergone orthodontic treatment. It is imperative to hold the teeth where they were moved to prevent relapse after debond. The traditional way of fabricating a clear retainer was to use an alginate impression to pour up and cast the model. You then proceed to create a vacuum formed retainer using the model and a piece of thermoplastic. Now, with the use of CAD/CAM technology, retainers can be three-dimensionally printed. These retainers are just as reliable as conventional vacuum formed aligners.[55] The major difference is that three-dimensionally printed retainers are made faster which saves chair time for the patient and the orthodontist.

Another popular application for three-dimensional printing in orthodontics is for the fabrication of aligners for use in aligner therapy. Orthodontic treatment via clear aligner therapy has tremendously increased over the past 10 years. Moving teeth without the traditional use of brackets and wires is a concept that begain in the 1940's. In 1945, Dr. Harold Kesling announced his "tooth positioning appliance". This device was invented to be utilized as a finishing appliance following the completion of full fixed orthodontic treatment. The device was intended to be delivered as soon as the patient was de-bonded. The patient was instructed to wear the appliance for four hours during the day and at night time as they slept. If worn properly the device would complete its results in a month's time[56.] Although Dr. Kesling was the first to create such a device, two students from Stanford University would receive the credit for inventing aligner therapy. In 1997, Zia Chishti and Kelsey Worth invented the world's first complete clear aligner system. The company that evolved from this innovation was called Align Technology. Align began producing and selling Invisalign in 1999. They were the first company to begin using CAD/CAM software for tooth movement.[57] Invisalign® was the first[58],[59] and is currently the largest provider of clear aligners for orthodontic tooth movement.[60]

Another technological innovation in orthodontics that three-dimensional prtiners can be used for are indirect bonding trays. The indirect bonding technique was first developed by Silverman and Cohen[6162] to increase patient comfort and decrease chair time. In 1979 the "custom composite base technique" was invented which is still the most widely accepted technique used today. [63]Over the years the same technique has been modified and improved to increase bond strength and to decrease bond failures. When technology skyrocketed in the

realm of orthodontics, this caused an incredible enhancement to the indirect bonding technique which piqued the interest of many orthodontists. Several companies began offering three-dimensional CAD/CAM created techniques for the manufacturing of indirect bonding trays. Indirect bonding trays have become popular due to the elimination of the time it takes to decide where to place the bracket on each tooth and can produce more accurate positioning.[64] It also reduces chair time up in comparison with the conventional way of bonding brackets.[65]

There are several other applications in orthodontics that three-dimensional printing can be utilized for. Some orthodontists have integrated this technology in the fabrication of appliances such as expanders or functional appliances. Metal appliances can be three-dimensionally printed using selective laser sintering (SLS). This is a major advantage because it reduces the time in the lab making appliances. Additionally, it eliminates the need to place separators in patients' mouths to make room for bands. The three-dimensionally printed metal "bands" overlay the teeth. This removes the need for interproximal space between teeth. The hyrax rapid palatal expander is the most commonly three-dimensionally printed appliance by orthodontists. Although printed appliances are of higher cost to the orthodontist, it can save chair time, reduce patient's discomfort, and decrease the number of appointments for the patient.[66] Mouth guards and occlusal splints can also be fabricated via three-dimensional printing. Additionally, when temporary anchorage device templates are three-dimensionally printed, it can assist with the accuracy of TAD placement.

A nuance that is just recently receiving attention is the three-dimensionally printed bracket. Over the last 100 years, orthodontic brackets have truly evolved. Starting from bands welded to teeth and basic tooth attachments to exceedingly variable fixed appliances with pre-

adjusted prescriptions or customized prescriptions. Brackets can be tailored to specifically fit each patient's malocclusion. This reduces the time spent bending wire to make precise movements of teeth and decreases chair time. The first custom 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.[67] Orthodontic cases can now be finished with precision and with a reduced treatment time. Additionally, a company named Braces on Demand has created the ability for orthodontists to three-dimensionally design, print and process brackets in house. There are different types of resin available for the brackets to be printed from such as denture resin or biomedclear resin. This allows the orthdontist the ability to print brackets as needed in their office and is truly an innovation to the field of orthodontists.

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STATEMENT OF THESIS:

Objective:

- #1. Investigate the bond strength of 3D printed ceramic and resin bracket systems.
- #2. Compare the bond strength of 3D printed ceramic brackets to 3D printed resin brackets to ceramic and metal brackets.

MANUSCRIPT FOR PUBLICATION

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TESTING THE SHEAR BOND STRENGTH OF 3D PRINTED BRACKETS ON ENAMEL

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Abstract

Various types of malocclusions can benefit from orthodontic treatment, which nearly takes 2 years or more to complete. Thus, debonding of brackets during the treatment delays its completion and affects the quality of treatment outcome. During fixed-appliance orthodontic treatment, brackets are necessary in order to deliver the forces from the wires to the teeth. Bracket failure during treatment can cause unwanted biomechanical effects, prolong time in treatment and cause more harm than good to the patient. The aim of this in-vitro study was to test the shear bond strength of three-dimensional (3D) printed CAD/CAM ceramic and resin brackets and compare the bond strengths to traditional metal and ceramic bracket systems. This will allow us to evaluate how much shear stress they can withstand. The hypothesis is that there will be no difference in shear bond strength between the different bracket types. Fifty-five extracted and discarded premolars were divided into five groups with 11 teeth each. Group 1 was direct bonded with LightForce brackets (Polycrystalline Alumina); Group 2 was direct bonded with 3M Unitek Victory Metal brackets; Group 3 was direct bonded using 3M Unitek Victory Clarity brackets; Group 4 was direct bonded using Braces on Demand 3-D printed brackets in A1 denture resin (Formlabs); Group 5 was direct bonded using Braces on Demand 3-D printed brackets in BioMed Clear resin (Formlabs). All teeth were mounted in acrylic resin prior to being bonded with brackets. The debonding force was measured using the Instron Universal Testing Machine. The descriptive data analysis, the Shaphiro-Wilk test for normality, and the graphs suggested approximately normally distributed data in all groups. Multiple range testing shows that there are three distinct homogenous ranges or groups from the data collected. We can conclude from this that there is a statistical difference between the brackets.

Introduction

Three-dimensional (3D) printing technology is an emerging manufacturing process for many orthodontic appliances. 3D Printing has made advancements with the production of aligners, retainers, models, in-direct bonding trays and brackets. Customized bracket systems fabricated from three-dimensional scanning and computer aided designs and computer-aided manufacturing (CAD/CAM) techniques are being increasingly incorporated into orthodontic treatment. In orthodontics, these technological advances facilitate both diagnosis and treatment planning. The custom brackets enable treatment plans to be tailor made to each individual patient. The ability to 3D print brackets in office is an innovation and allows the orthodontist to fabricate brackets as they see fit.

In the early days of fixed appliances, the brackets were welded to gold or bands consisting of stainless-steel. Before starting treatment, the orthodontist had to create adequate space around each tooth to accommodate the bands. These spaces were then closed before the completion of treatment. Banded type appliances frequently caused trauma to the gingiva when being fitted and decalcifications under the bands were a risk[1].

Braces advanced from the metal bands wrapped around each tooth to adhesives that were being discovered to bond brackets onto teeth. The demand for increased esthetics led to the development of a variety of bracket systems to make braces less visible. This pressure for more esthetic options resulted in the development of labial appliance systems made of ceramic, plastic and even resin. Ceramic orthodontic brackets were introduced in 1987 as a more aesthetically pleasing alternative to the stainless-steel brackets. There are two types of ceramic brackets currently available in the market: polycrystalline alumina and monocrystalline alumina.

As time and technology has evolved we now have the option of using three-dimensional printing to fabricate brackets. Customized brackets for tooth movements have also been an innovation in the more recent years. Dynamic bracket customization allows for the function of the bracket to be enhanced as needed during the course of treatment. The customization allows for assessment of changes three-dimensionally (3D) via the use of intraoral scanning, cone-beam

computed tomography (CBCT), 3D photography and computer-aided design and computer-aided manufacturing (CAD/CAM) technologies[2].

Shear bond strength is the ability of a material to resist forces that cause the material's internal structure to slide against itself. In vitro bond strength between 6 MPa to 8 MPa is considered the gold standard according to Reynolds[3]. Shear bond strength is a measure of the resistance of a material to dislodge against a shearing mode of loading. Bond strength is defined as the load needed to break a bond divided by the cross-sectional area of the bonding interface. The shear bond strength test is a type of test used for evaluating bond strength. Shear bond strength tests the maximum stress that a material can withstand before failure in a shear mode of loading. In shear bond tests, two materials are bonded with an adhesive, and loaded in shear until it fractures. Shear bond strength testing is one of the most commonly used methods for measuring bond strength.The bond is fractured with the application of a force parallel to the adhesive interface.The test may be conducted with a metallic blade or a steel wire loop, as close as possible to the adhesive interface. Failure starts at the point where the blade applies a normal force. Although esthetics is a key characteristic for dental materials, specifically, care should be given to the mechanical properties and bonding longevity. Some variables that affect SBS testing are technique, storage medium, duration of polymerization of adhesive, the crosshead speed of shearing force. For an orthodontic bracket to work efficaciously it must be able to withstand normal masticatory forces without dislodgement. Bracket failure during treatment can cause an increase in the estimated treatment time as well as unwanted biomechanical effects. Broken brackets are common for a plethora of reasons such as moisture contamination while bonding, lack of clearance from opposing occlusal forces and patient compliance. The maximum occlusal force for children with normal facial height between the ages of 6-11 is approximately 5.01kg and adults with normal facial height is approximately 13.5 Kg[3]. A minimum range for the shear bond strength of brackets according to Reynolds is 5.9–7.9 MPa. This range has been widely accepted in the literature and is considered to be the gold standard. Values below this range could increase the risk of bracket failure during treatment and values above this range increases

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the risk of damage to surface enamel during debonding.[4]Shear bond strength of brackets depends on various factors such as bracket base design, bracket surface characteristics and bracket bonding area[5]. Studies regarding the influence of bracket base design on the strength of the bracket-cement interface by Knox *et al* evaluated different bracket base designs including 60-, 80-, and 100- gauge single mesh bases, a double mesh base and integrated metal base[6]. In this study, it was concluded that the bonding agent significantly affects the shear bond strength and that certain base designs may allow improved adhesive penetration or improved penetration of the curing light. An investigation by Pham *et al.* in 2016 researched the effect of bracket pad shape on shear bond strength on bovine teeth enamel[4]. The authors concluded that the bracket base shape has an effect on shear bond strength. Lastly, a study by Wang *et al.* examined the influence of retention base design on SBS. The retention base designs evaluated were retention groove, circular concave, single mesh and double mesh layers with varying size. This study concluded that retention base design of a bracket could affect SBS. The objective of bracket production is to obtain the flow of material in the irregularity of the base.[7]

During bracket removal, bond failure may occur in the bracket/adhesive interface (adhesive), in the adhesive/enamel interface (adhesive), in the adhesive layer (cohesive) both (adhesive and cohesive). Failures in the adhesive/enamel interface can lead to deleterious effects such as having enamel fragments removed along with the bracket base.[8]

Ceramic brackets bond to the tooth surface by forming both mechanical and chemical bonds. Silanisation of the bracket due to the silane coupling agent is responsible for the chemical bond and it improves the bond strength. Because of a significant increase in the bond strength, the stress of debonding can also be shifted from the bracket – adhesive interface to the adhesive-enamel interface, which is likely to damage the enamel surface during the debonding procedure. Metal brackets bond to the surface via mechanical bonds. They do not fracture under stress and are available at relatively low costs as compared to the ceramic brackets. The bonding

strength of ceramic brackets has been shown to be significantly higher than that of metal brackets.

Various articles and papers have discussed the shear bond strength of traditional metal brackets and ceramic brackets however it has not been investigated for 3D printed ceramic and resin brackets. This study was developed to test the shear bond strength of 3D printed CAD/CAM ceramic and resin brackets and compare them to traditional metal and ceramic bracket systems. This will allow us to evaluate how much shear stress they can withstand. A robust bonding ability of these 3D bracket systems is necessary to ensure their long-term clinical performance.

Materials and Methods

Collection of teeth specimens

For this in vitro study, a total of 55 extracted and discarded premolars were collected from patients whose teeth were being extracted according to their treatment plans. The protocol for this study was approved by the Institutional Review Board (IRB) of Case Western Reserve University School of Dental Medicine (STUDY20221520). The collected teeth were cleaned, and soft tissue was removed as needed with the use of a periodontal curette. Teeth were stored within a physiologic saline solution before testing. The inclusion criteria were as follows: (1) teeth with sound enamel, (2) teeth with crown size within normal limits, as confirmed by crown height and with measurement, (3) teeth that had never been bonded to brackets on the labial surface, (4) teeth which did not exhibit any large defects, carious lesions, restorations or crack lines on the labial surface.

A sample size calculation was performed using the G-Power analysis software. A total of 35 brackets (7brackets/group) were needed to ensure a study power of 80%, a level of significance of 0.05, and a minimum clinical difference of 0.63 MPa (Sha et al). A final sample of 55 was used in this study to take an attrition rate of 36% into account.

The teeth were separated into five groups of 11 teeth. Of the five groups, Group 1 was direct bonded with LightForce brackets (Polycrystalline Alumina); Group 2 was direct bonded with 3M Unitek Victory Metal brackets; Group 3 was direct bonded using 3M Unitek Victory

Clarity brackets; Group 4 was direct bonded using Braces on Demand 3-D printed brackets in A1 denture resin (Formlabs); Group 5 was direct bonded using Braces on Demand 3-D printed brackets in BioMed Clear resin (Formlabs).

Each bracket was weighed and area was calculated:

- Lightforce: 16.88mm2
- 3M Unitek Victory Metal: 12.53mm2
- 3M Unitek Victory Clarity: 19.77mm2
- Braces on Demand, A1: 20.48mm2
- Braces on Demand, BioMed Clear: 18.48mm2

Bracket:	**Area:**
Lightforce	16.88mm2
3M Unitek Victory Metal	12.53mm2
3M Unitek Clarity	19.77mm2
Braces On Demand, A1 Denture Resin	20.48mm2
Braces on Demand, BioMed Clear	18.48nn2

Table 1. Shows the bracket type and associated area.

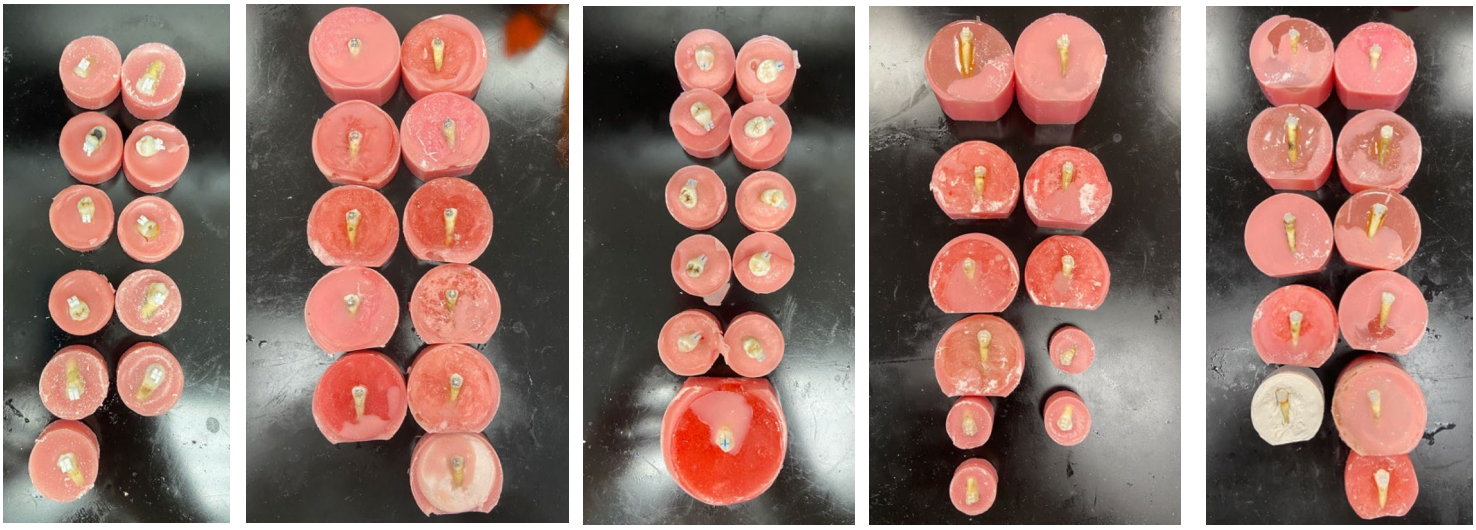


Figure 1. Brackets tested in study. From left to right: Lightforce Brackets, 3M Unitek Victory Metal, 3M Unitek Clarity, Braces on Demand A1 Denture Resin, Braces on Demand Biomed Clear

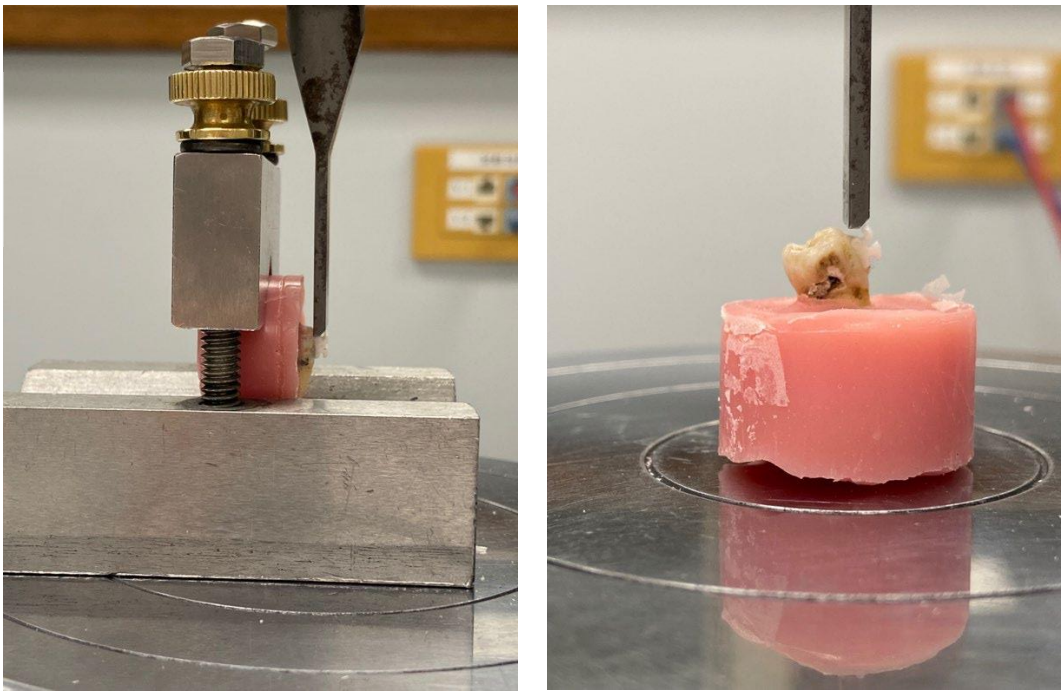


Figure 2. (Left) Ideal vertical bracket position during shear bond strength testing. (Right) Non-ideal vertical bracket positioning. This will lead to loss of crosshead force into the tooth rather than directed towards shearing the bracket. Hanson Et AL.

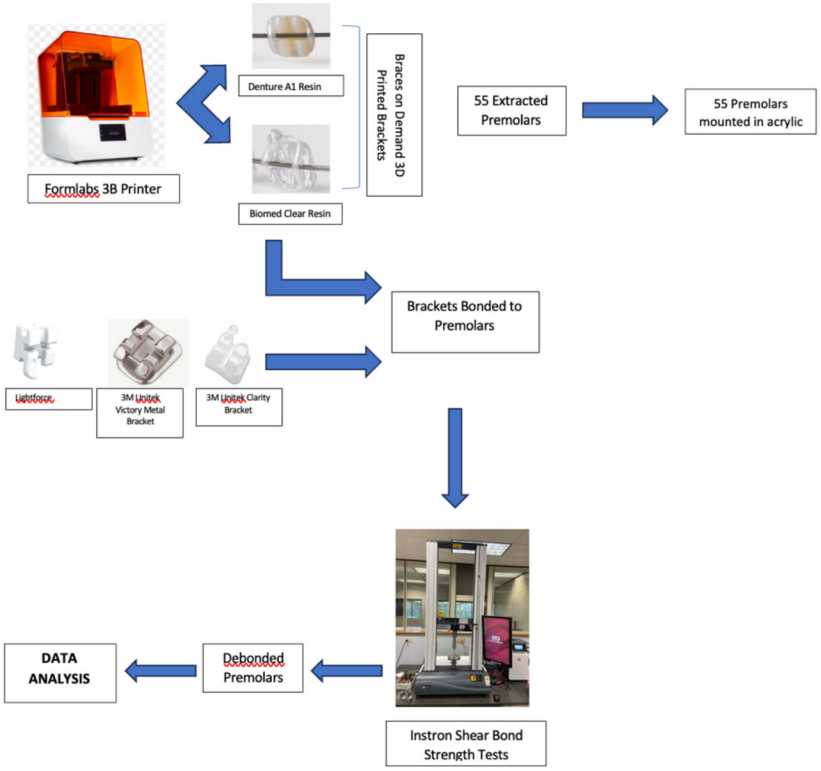


Figure 3. Schematic overview of the study workflow and design.

3-D Printed Brackets

The 3-D printed brackets used in this study were printed in an in-house lab using the FormLabs 3B printer. The software used to fabricate the brackets was Braces on Demand. The bracket prescription and slot size were selected, along with the specific resin for the brackets to be printed from. The printer was primed and the print jobs were successfully completed. The post-processing steps outlined by Braces on Demand was completed as follows: build plate was removed and excess resin was removed using a spray bottle containing 99% IPA, the bracket rafts were removed from the build plate and washed using the Form Wash system (15 minutes for BioMed Clear resin; 10 minutes for Denture tooth resin A1) and allowed to dry for 30 minutes, the rafts were then submerged in a glass bowl filled with vegetable glycerin and placed in the Form Cure system to cure (60 minutes for BioMed Clear resin; 30 minutes for denture tooth resin A1), upon completion of cure cycle the parts were removed from the glycerin bath and rinsed thoroughly with warm water to ensure all glycerin was removed, parts were then blow dried with compressed air, when dried completely they were removed from their supports.

Bonding

Prior to being bonded, all teeth were mounted in denture resin acrylic. All teeth were cleaned and pumiced. The labial surface of each tooth underwent 37% phosphoric acid (Reliance Blue Gel Etchant) treatment for 15 seconds. The surface was then rinsed completely and air dried until a chalky-white appearance was visible. The teeth were then primed (Reliance Assure Plus) and air was dispersed on the surface. The teeth were cured for another 10 seconds prior to the bracket being placed.

Bonding Resin (Reliance LightBond Blue Push Paste with Fluoride Blue Viscosity) was used to coat the entire surface of the bracket base with the use of a microbrush. Excess cement was removed as needed, allowing for an even and thin layer to remain on the bracket base. LightForce brackets were bonded in accordance to their specifics. The 3M Unitek Victory Ceramic and Metal brackets presented with a pre-packaged coating of bond (3M APC II Flash Free adhesive). The brackets were then seated in the ideal position on the teeth and firm pressure was applied. Light curing was completed by curing for 5 seconds on all four sides of the bracket using the VALO cordless LED curing light. Any excess cured cement was removed with a handpiece and bur.

All specimens were stored overnight (15 hours) at ambient temperature, pressure and humidity.

Shear Bond Strength Test and Failure Analysis

The debonding force of each of the 5 groups of brackets (in N) was measured by using the Instron Universal Testing Machine (3366 Single Column Testing System, Bisco Dental Labs, Schaumburg, Il). The samples were aligned with the bonding surface parallel to the blade and the force point was set at the middle of the bracket base and tie wings. A debonding force was applied to the specimen by moving the shear blade in an occluso-gingival direction. The crosshead speed was 1mm/min. The shear bond strength (N/mmsquared) was calculated by dividing the debond force by the surface area of the bonding base. After debonding of the bracket, the surfaces of the teeth and brackets were examined to confirm the bonding failure interface.

Statistical analysis

The statistical software StatAdvisor for all statistical calculations. The descriptive data analysis, the Shapiro-Wilk test for normality, and the graphs suggested approximately normally distributed data in all groups.

The intergroup variances were found unequal by Levene's test and therefore, the Welch one-way ANOVA was used. Finally, the Games-Howell post-hoc test was used to perform pairwise comparisons of the 5 bracket groups regarding their shear bond strength on the mounted premolars. The significance level was set at 0.05.

A sample size calculation was performed using the G-Power analysis software. A total of 35 brackets (7brackets/group) were needed to ensure a study power of 80%, a level of significance of 0.05, and a minimum clinical difference of 0.63 MPa (Sha et al). A final sample of 55 was used in this study to take an attrition rate of 36% into account.

The average shear bond strength of the different bracket groups is summarized in Table 2. The Welch one-way ANOVA ($P < 0.001$) indicated there is at least one bracket group with an average shear bond strength different from the others. Finally, the Games-Howell post-hoc test

that was used to perform the pairwise comparisons of the 5 bracket groups and is summarized in Table 3 showed the following:

A) The 3M Unitek Metal brackets (mean ± SD: 5.95 ± 4.11 MPa) had 4.8 MPa less shear bond strength than the 3M Unitek Clarity brackets (mean ± SD: 10.78 ± 4.02 MPa) ($p<0.001$)

B) No significant differences were found between 3M metal and Braces on Demand A1 brackets, 3M metal and Braces on Demand Biomed Clear, 3M Clarity and Braces on Demand Biomed Clear, Braces on Demand A1 and Braces on Demand Biomed Clear.
-3M Clarity brackets (mean ± SD: 10.78 ± 4.02 MPa)
-3M Metal brackets (mean ± SD: 5.95 ± 4.11 MPa)
-Lightforce: (mean ± SD: 20.76 ± 12.69 MPa)
-Braces on Demand, A1 (mean ± SD: 6.15 ± 1.66 MPa)
-Braces on Demand, Biomed Clear (mean ± SD: 6.29 ± 2.95 MPa)

Group 1	Group 2	Average Shear Bond Strength difference (MPa)	95% CI	p-value	significance
3M clarity	3M metal	-4.95	(-10, 0.12)	0.058	ns
3M clarity	BOD A1	-5.77	(-10, -1.52)	0.006	**
3M clarity	BOD BMC	-5.56	(-10.2, -0.89)	0.015	*
3M clarity	Lightforce	9.07	(-5.62, 23.8)	0.322	ns
3M metal	BOD A1	-0.819	(-4.98, 3.34)	0.972	ns

3M metal	BOD BMC	-0.611	(-5.21, 3.99)	0.994	ns
3M metal	Lightforce	14	(-0.66, 28.7)	0.063	ns
BOD A1	BOD BMC	0.208	(-3.35, 3.76)	1	ns
BOD A1	Lightforce	14.8	(0.25, 29.4)	0.046	*
BOD BMC	Lightforce	14.6	(-0.004, 29.3)	0.05	ns

Table 2.

Contrast	*Sig.*	*Difference*	*+/- Limits*	*P-Value*	
3M Metal - 3M Clarity	*	-4.83	4.58	0.9363	
3M Metal - LightForce	*	-14.81	5.12	0.0025	
3M Metal - BOD A1		-0.20	5.36	0.0393	
3M Metal - BOD BMC		-0.33	13.68	0.3923	
3M Clarity - LightForce	*	-9.97	3.93	0.0013	
3M Clarity - BOD A1	*	4.62	4.25	0.0427	
3M Clarity - BOD BMC		4.49	13.51	0.4232	
LightForce - BOD A1	*	14.60	4.87	0.0001	
LightForce - BOD BMC	*	14.47	13.60	0.0009	
BOD A1 - BOD BMC		-0.13	13.64	0.1852	

Table 3.

RESULTS

Multiple range testing shows that there are three distinct homogenous ranges or groups from the data collected (Table 4). We can conclude from this that there is a statistical difference between the brackets. The ANOVA table (Table 5) decomposes the variance of the data into two components: a between-group component and a within-group component. Since the P-value for that test is less than 0.05, there is a statistically significant difference between the means at the 5% significance level. We reject the null hypothesis and accept the alternative hypothesis. Each data set returned a standard skewness and standard kurtosis within the range expected for a normal distribution. We conclude that each data set can be modeled using a normal distribution (Table 6).

	Count	*Mean*	*Homogeneous Groups*
BOD A1	7	6.15	X
3M Metal	10	5.95	XX
BOD BMC	8	6.29	XX
3M Clarity	11	10.78	XX
LightForce	10	20.76	X

Table 4.

Source	*Sum of Squares*	*Df*	*Mean Square*	*F-Ratio*	*P-Value*
Between groups	1534.49	4	383.622	8.54	0.0000
Within groups	1842.2	41	44.9318		
Total (Corr.)	3376.69	45			

Table 5.

	Stnd. skewness	*Stnd. kurtosis*
3M Metal	0.17	-0.60
3M Clarity	0.60	0.043
LightForce	1.16	-0.61
BOD A1	0.54	-0.80
BOD BMC	-0.79	-0.19
Total	6.40	8.32

Table 6.

DISCUSSION

There have been many different studies completed on testing the shear bond strength of different dental adhesives, bracket base designs, and comparing different materials and designs of brackets. The literature is still developing regarding testing the shear bond strength of 3D printed resin and ceramic brackets in comparison to their counterparts.

In a study by Reddy et al 2 groups of 20 brackets each (Group A Ceramic, Group B Stainless-Steel) were tested. The mean shear bond strength of the ceramic bracket group was found to be superior as compared to that of the metal bracket group.[9] This is consistent with the data we collected in our project as the 3M metal brackets had a lower shear bond strength.

In an article by Hanson et al, the effect of printing material and air abrasion (AA) of bracket pads on the shear bond strength of 3D-printed plastic orthodontic brackets was discussed. Forty brackets 3D printed with resin were compared to forty brackets commercially manufactured. The 3D-printed orthodontic brackets presented clinically sufficient shear bond strengths both with and without AA prior to bonding. This is consistent with our data stating that 3D Printed Resin brackets are clinically acceptable for bonding.[10]

In a study by Papageorgiou et al, the aim was to evaluate the mechanical properties of resin-based materials as alternatives for the in-house preparation of orthodontic brackets. Comparing temporary and permanent crown resins. The 3D printed resins tested exhibited mechanical properties superior to contemporary plastic brackets while also offering the unique feature of total bracket customization to treat specific malocclusion[11]. This is consistent with our data stating that 3D Printed Resin brackets are clinically acceptable for bonding.

Comparison with other adhesives in a study by Shalini et al the strength of the bonding between orthodontic brackets and different orthodontic adhesives was studied. 120 premolars were bonded with stainless-steel brackets. The data shows the differences in shear bond strength averages based on the adhesive although the same bracket was used[12]. This data is consistent with ours regarding the lower shear bond strength range of the metal bracket.

3M Ceramic and Lightforce 3D printed brackets provide both high esthetics for treatment options. Both bracket types are also consistent with having bond strengths in the higher end of the ideal shear bond strength range. This is advantageous for ensuring brackets remain bonded to the patient's teeth however this can present problems for the enamel once debonding is necessary. The 3D printed resin brackets and 3M metal brackets had shear bond strength in similar ranges. The metal being on the lower end of the spectrum is consistent with previous literature. The 3D printed resin brackets provide both the clinically sufficient shear bond strength for clinical use as well as the option for customized brackets.

CONCLUSION

The objective of our study was to investigate the shear bond strength of 3D printed ceramic and 3D printed resin bracket systems and compare the bond strengths of 3D printed ceramic brackets vs. 3D printed resin brackets vs. ceramic and metal brackets.

- Within the limitations of our study, we can conclude that there is a statistical difference between the shear bond strength of 3D printed ceramic brackets, 3D printed resin brackets, ceramic brackets and metal brackets.

- Metal brackets have the lowest shear bond strength in comparison to brackets made of different materials such as ceramic and resin.
- 3D printed ceramic brackets have the highest shear bond strength, even exceeding that of the ideal SBS range.
- The 3D printed resin brackets shear bond strength falls in the ideal range for clinical application.

It should be noted that in vivo conditions are significantly more complex and uncertain than experiments done in vitro. Subsequently, these results should be applied carefully in clinical settings. Further clinical trials are warranted to clarify the findings of our study.

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APPENDICES

APPENDIX A: IRB APPROVAL

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

INITIAL APPROVAL

Principal Investigator:	Tarek ElShebiny
Title:	Testing the Shear Bond Strength of 3D Printed Brackets on Enamel
Submission Number:	STUDY20221520
IRB Office:	CWRU IRB
Approval Date:	4/26/2023
Effective Date:	4/26/2023
Approval End Date	N/A
Type of Submission:	Initial Study
Type of Review:	Expedited
Documents Reviewed:	• IRBCooperationLetter.pdf, Category: Letter of Cooperation; • Updated IRB Protocol 4/26/23, Category: IRB Protocol; • Complete Clarifications., Category: Other;

The IRB has reviewed this submission.

- Per Federal regulation, changes MAY NOT be made to any element of the current research without prior IRB approval, except to eliminate an immediate and apparent hazard to subjects enrolled in the study.
- Per Federal regulation, the research may not continue beyond the Approval End date. You must submit a continuing review form 6-8 weeks before this Approval End date in order to maintain IRB approval. Failure to maintain IRB approval is human subjects non-compliance. Please note that even if your study falls into a category that does not require an Approval End date, the institution may require a yearly "check-in" to confirm the status of the study.

***Approval by the IRB does NOT mean that you have permission to start your study. Prior to starting your study, you may be required to obtain (1) a coverage analysis for studies that involve patient care, regardless of source of funding, and/or (2) a contract with the Sponsor of your study or an agreement with any third-party collaborator that may receive UH or CWRU patient information in any format. Please ensure that all required approvals are obtained before initiation of research activity. ***

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.