ACCURACY OF 3D PRINTED IMPLANT SURGICAL GUIDES: A COMPARISON OF STEREOLITHOGRAPHIC AND DIGITAL LIGHT PROCESSING TECHNOLOGY

A Thesis

by

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ABSTRACT

Digital implant dentistry and dental applications of in-office 3D printing are rapidly becoming more prevalent in everyday practice. The way implant surgical guides are fabricated and fit in the mouth directly impact implant placement accuracy. There is a distinct lack of literature comparing these two printing methodologies with respect to guide accuracy and practical performance metrics. The primary aim of this work is to investigate two common 3D printing modalities currently in use for the fabrication of static implant surgical guides and quantitatively assess performance and if either modality has superior accuracy with respect to simulated implant placement. The secondary aims are to assess the real-world utility of each modality with respect to printing time, material cost analysis, printing success and guide fit.

A fully guided implant surgical plan was developed in CoDiagnostiX from DICOM and STL data. Sixty duplicated subject models were evenly allocated into two groups: SLA and DLP. Thirty surgical guides were fabricated for each group utilizing a Form 3B (SLA) and a Straumann P30 (DLP) 3D printer respectively. Guided implant placement was performed using 120 Straumann implant replicas and the implants were fixated with light cured Triad gel. Scan bodies were inserted into the implants and scanned with a Medit T710 benchtop scanner. This scan was evaluated in CoDiagnostix where the planned and actual implant positioning were compared. Printing metric data was recorded comparing printing time, material use and cost and print success throughout the study.

SLA printing had a statistically significant lower mean angular deviation (degrees) 0.77 ± 0.42 compared to DLP printing 1.02 ± 0.47 ($p = 0.002$). DLP printing had a statistically significant lower 3D offset at the implant neck (mm) 0.14 ± 0.07 compared to SLA printing 0.18 ± 0.11 ($p = 0.017$). No statistical difference was found between 3D offset at implant tip between printing

groups ($p = 0.768$). SLA Print success was 80% (8/10), DLP Print success was 100% (15/15). Cumulative SLA print time was 36 hours, 31 minutes, 25 seconds. Cumulative DLP print time was 5 hours, 39 minutes, 42 seconds. Both software calculated and actual print time/resin use, cost per guide, resin use per guide, print time per layer and print time per guide were statistically significant between printer type with DLP outperforming SLA in all printing performance metrics ($p < 0.001$).

While the present study does demonstrate statistical differences between SLA and DLP printing methodologies regarding implant placement accuracy, the clinical significance of this difference is questionable. The differences in printing metrics such as printing times, resin use and cost per guide does have real world ramifications and clinical relevance for the everyday use and utility of these two technologies in clinical practice.

PREFACE AND AIMS

The adoption and mainstream use of digital technologies including 3D printing in the practice of dentistry and oral rehabilitation continues to accelerate at a rapid pace. As the accuracy, ease of use and cost effectiveness of these technologies continues to improve, the routine use of in office 3D printing will become more commonplace throughout the practice of dentistry.

The existing literature surrounding 3D printing in implant dentistry unfortunately has great heterogeneity and is sometimes difficult to draw real-world conclusions. This field has been primarily advanced by the specialty of prosthodontics as 3D printing tends to fall into the realm of 'materials' research despite the periodontists emerging role as a leading implant specialist. The existing literature tends to focus primarily on unique case reports utilizing various technologies, comparisons of surgical outcomes or comparisons of products or workflows, many times without practical significance or considerations of everyday use.

3D printing in combination with pre-surgical implant planning software has special applications for the periodontist and other dental practitioners that place dental implants through providing cost effective, predictable, and relatively fast static surgical guides that assist in ideal implant placement and rehabilitation for patients.

For the practitioner interested in adopting and utilizing 3D printing technology in everyday practice – selecting the type of printing technology or the model of printer can be difficult due to the ever increasing variety of technologies, significant initial financial investment, unfamiliarity with the technology and the seemingly same claim of accuracy, precision and speed from all manufacturers. As technologies become more common in everyday practice, there is an increased need for scientific study of digital and printing workflows, outcomes, and utility so conclusions can be made based on evidence opposed to opinion.

The primary aim of this work is to compare two common 3D printing modalities currently in use for the fabrication of static implant surgical guides and quantitatively assess performance and if either modality has superior accuracy with respect to simulated implant placement. The secondary aims are to assess the real-world utility of each modality with respect to printing time, material cost analysis, printing success and guide fit.

DEDICATION

To my wife, Jennifer, for her never ending support, kindness, love, and patience throughout this entire venture. Also, to our children, Griffin and Viggo, and to all my family for their support, encouragement and love.

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In addition to the support of the dissertation committee, Dr. Pylant III aided in the laboratory process and as a consultant on digital implant workflows, digital design and 3D printing technologies. Additionally, Dr. Jennifer Pylant aided in the laboratory processes. The study inception, design, execution, and analysis for the study and all work for this thesis was performed independently by Dr. Pylant IV.

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NOMENCLATURE

3D	Three-dimensional
DLP	Digital Light Processing
SL / SLA	Stereolithography / (Stereolithographic Apparatus)
DICOM	Digital Imaging and Communications in Medicine
STL	Standard Tessellation Language
CT	Computed Tomography
CBCT	Cone Beam Computed Tomography
FOV	Field of view
CAD/CAM	Computer Assisted Design / Computer Assisted Manufacturing
CEREC	Chairside Economical Restoration of Esthetic Ceramic
UV	Ultraviolet
SLS	Selective Laser Sintering
FDM	Fused Deposition Modeling
FDA	Food and Drug Administration
VPS	Vinyl polysiloxane
CVS	Comma Separated Value

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

1.1: Dental Implants

Partial edentulism is a condition that mankind has attempted to prevent and correct throughout the ages. There is archeological evidence that indicates that as early as 2500 BC Egyptians used gold ligatures to attempt to stabilize mobile teeth. Rudimentary fixed bridges were fashioned out animal teeth, ivory and gold wire as early as 500 BC. The first evidence of a dental implant is attributed to the Mayan civilization where portions of shells were used as implants for mandibular incisors.[1] Implant innovations accelerated in the 1900s with the invention of the endosseous, periosteal, blade and transosseous implants – all made of varying alloys and materials including gold, irido-platinum, chromium-cobalt, stainless steel, aluminum, and vitreous carbon.[2–8] In 1965 *Dr. Brånemark* revolutionized implant dentistry with the placement of pure titanium endosseous implants in an edentulous patient which remained in place up to 40 years after their initial placement.[9,10] Titanium endosseous root form implants demonstrated superior longevity and success compared to other types of implants into the 1980s at which time *Albreksson* proposed a five part success criteria for the dental implant.[11] The criteria for success were modernized in 2008 by the International Congress of oral implantologists to include definitions of short, intermediate and long term success as well as a four part category to conditional implant success/failure.[12] This was consistent with a shift from a focus on pure survival of dental implants to one that focused on the functional health, longevity and restorative success of an implant. The definition of peri-implant health has most recently been updated by the American Academy of Periodontology in their 2017 joint world workshop with the European Federation of Periodontics.[13] Titanium and titanium alloy root form implants currently dominate the field of implant dentistry and their widespread adoption has led to an entire subspecialized field of biomechanical and biomaterials research.[14,15] Zirconia implants are currently under investigation and utilized in practice as an alternative to titanium based root form implants, however there are concerns about the long term longevity and fracture/crack resistance of the zirconia crystal lattice that makes up the implant despite short term clinical successes.[16,17] The long term success of dental implants in the treatment of partial or total edentulism is directly associated to accurate patient diagnosis, evaluation, restorative and surgical treatment planning.

1.2: Implant Planning

Initially, planning for implant placement primarily depended on the patient's available bone without many considerations for the final restorative outcome. Bone density, quantity and quality were classified and many oral implantologists focused on placing implants in the most ideal quality of bone that the patient had available.[18–20] Longitudinal studies investigated location of dental implants and bone quality/quantity with survival.[21] In the 1990s *Buser* demonstrated the predictable alveolar ridge augmentation technique of guided bone regeneration to assist a patient in developing the necessary quantity and quality of bone needed for dental implant placement and showed that implants placed in this regenerated bone were stable, functional and healthy.[22–24] Now alveolar ridge augmentation utilizing various techniques for vertical and horizontal bone gain are frequently used for site development for dental implants.[25] The focus has now shifted from a 'purely surgical' perspective to a restoratively driven perspective. A restoratively driven perspective facilitates both long term biologic health and restorative success.[26] This is in line with updated perception and views of dental implant success especially with respect to the final restorative result.

This shift was in part facilitated by improvements in diagnostic aids, specifically radiographic analysis, shifting from two dimensional images with superimposed structures to images without superimposition via the tomogram to eventually being able to visualize the bone in three dimensions.[27] Two dimensional radiography and panoramic radiography and use of calibrated rulers or clear templates were utilized as diagnostic aids for dental implant surgical planning. As early as the 1930's the first experimental tomography machines were developed that worked on the principle that with a moving X-ray source and moving receptor two dimensional images can be generated that do not have overlying structures superimposed.[27] The resultant two dimensional images were utilized in dentistry starting in the 1980s when dental specific tomographic units were developed that provided radiographic information in an orthogonal view which allow for increased information about a planned surgical site. Three dimensional imaging first began with the Medical CT which was first developed by *Hounsfield* in the late 1960s when he invented his prototype using salvaged parts from a lathe, and x-ray tube and cadaver specimens.[28] The first prototypes were developed in the early 1970s for human use but were limited in their adoptability because of limitations of computer power – requiring remote mainframe computers to process imaging. The concurrent development and improvements in computing power of the 1970s and 1980s that provided more compact and lower operational costs that made commercial medical CT imaging a reality.[28] In implant dentistry it was not until the introduction of cone beam computed tomography (CBCT) that three dimensional assessment became more readily available to dentists. In late 1990s to early 2000s the convergence of improved computing power, improved algorithms, resilient X-ray tubes and fast detectors allowed the prototyping, development, and production of commercial CBCT.[29,30] Since the first commercially produced CBCT in 2003 technological advancements in technology have made three dimensional imaging readily available to practitioners for diagnostic imaging in office. CBCT imaging allows for pre-surgical assessment of vital structures, bone morphology and quantity and quality in three dimensions in patients requiring dental implants. Benefits of CBCT imaging as an adjunct to 2D radiography include identification of incidental findings that can impact surgical procedures, being a means for facilitating pre-surgical anatomic measurement and implant placement, and as an integral part of generation of static surgical guides for implant placement.[31] CBCT utilizes a divergent cone shaped source of ionizing radiation that is directed through the area of interest onto the detector. The source of radiation and detector both rotate around a fixed area which is centered in the area of interest and acquires the entire field of view (FOV) in one rotation – minimizing exposure compared to traditional medical CT.[32] The resultant dataset is saved as a collection of images in either a single file or multi-file DICOM format.[33,34] The advent of accessible three dimensional imaging gave practitioners previously unknown insights into the surgical site and ushered in a new area of implant planning.

There have been major advances in implant treatment planning over time both in methodology and in technology – many of these advances through the advent of three-dimensional radiography. Patient assessment has and always is a necessary part of the treatment planning process as well as setting patient expectations for function, esthetics, and longevity.[35] Historically bone availability was the primary and sometimes sole methodology in determining an implants position, but this has shifted to a restorative methodology, utilizing diagnostic aids and laboratory methods to generate implant plans with a restorative focus.[36–38] Early restorative-based implant planning was an analog workflow and utilized combinations of clinical photography, articulated dental study casts, full contour wax ups of proposed restorations or denture setups with proper jaw relation.[39,40] Prior to assessable 3D imaging soft tissue thickness could be assessed via transgingival probing with a periodontal probe and transferring that information to a sectioned dental cast to outline the underlying bone structure.[40] Vaccu-form thermoplastic materials would be utilized with radio-opaque markers such as stainless steel balls or rods in areas where the proposed implant restoration was planned. The patient would wear these during imaging to aid in planning the implant position on radiographs.[40–42] Surgical guides for pilot drills could be fabricated with thermoplastic materials or with acrylic on dental models. Sophisticated prosthetic implant treatments such as customized healing abutments or temporary restorations all could be planned and fabricated prior to the advent of digitization and digital planning technology.[43,44]

However, with the development of accessible CBCTs and the concurrent improvements in optical and laser-based surface scanning – implant planning started to move into the digital realm. Computer assisted design / computer assisted manufacturing (CAD/CAM) in dentistry was first commercially available with the CEREC system in the mid 1980s, which was focused on milling ceramic inlays and onlays as replacements for traditional amalgam placement.[45,46] This was supplemented by the advent of intraoral confocal scanners and subsequently laboratory scanners that used either structured light or laser for digitization of a model or tooth.[47–49] These early scanners suffered from accuracy and utility issues due to large size and high cost. Highly accurate scanners typically were cost prohibitive industrial or laboratory scanners. Techniques that these scanners use include primarily structured light or laser. Structured light scanners use cameras set at fixed points relative to the subject being scanned and then a known optical pattern is projected across the subject.[50] The camera records this information and mathematical operations in software generate a surface map of the subject.[50] Laser based scanners utilized laser beams and mirrors that detect diffractions of the laser beam from the subject being scanned that is recorded and computed in software into a point cloud that generates a surface map of the subject.[51,52] This digitization generates a three dimensional map of the subject being scanned that commonly today is saved in the STL format. Early in digitization of dental models and scans there were issues with file formatting and sharing as many systems utilized proprietary algorithms or file types which forced a user to stay within a particular company's software ecosystem. Thankfully this is less often the case today as the open source STL format is more widely adopted and utilized. Digitization whether in the form of intraoral scanning or laboratory scanning is now in common use and has advanced to where digital scanning is relatively affordable, reliable and accurate for common use in the dental office, and there are a multitude of different options for clinicians to choose from. With the accessibility of STL and DICOM files in everyday practice, restorative planning can now take place in the digital realm in conjunction with implant planning. There are a vast multitude of case reports and series demonstrating a multitude of various digital techniques and digital implant planning software.[53–60]

1.3: 3D Printing

In three-dimensional manufacturing there are generally two overarching processes, subtractive manufacturing and additive manufacturing. The most common example of subtractive manufacturing is milling where a three-dimensional object is manufactured via removing structure from an existing object. Subtractive processes are greatly assisted today by advancements in computing power and CAD/CAM technologies – however an in-depth review of subtractive manufacturing is outside the scope of this review which will focus on additive manufacturing.

Additive manufacturing or 3D printing was first invented in the mid 1980s. In the following 15 years patents for most of the major types of additive manufacturing in use today would have been applied for and the first commercial versions produced. In the late 1970s early 1980s techniques for photo hardened layers that could be stacked to generate casting molds and creating three-dimensional plastic parts from UV exposure for rapid prototyping were introduced in Japan. In 1984 *Charles Hull* filed for a patent for the first 3D printing technology. This patent was issued in 1986 and the technology was coined the stereolithographic apparatus (where the term SLA is derived) by *Hull*, that utilized the stereolithographic (SL) process for manufacturing for which he founded the company 3D Systems to commercialize the process. A year later 3D systems introduced the SLA-1 which was the first commercial 3D Printer. Shortly after in 1989 selective laser sintering (SLS) was patented which uses a laser to fuse powder instead of a resin plastic. This machine was first produced by DTM in 1992.[61] Stratasys patented and developed the fused deposition modeling (FDM) printer in 1991. Interestingly DLP was first described in 1987 by *Larry Hornbeck* but for use in the cinema and projector industry and it was not until after the initial patent for SLA printing expired that it was utilized for additive manufacturing. By 2009 the patents for FDM and SLA printing expired which caused a rapid increase in the affordability and access to the technology transitioning 3D printing from purely a commercial or industrial setting to being widely available and affordable. It was not until 2012 that SLA and DLP based printers became more widely available due to lowered cost of the parts needed to fabricate printers. Today nearly all of the additive manufacturing technologies are utilized in dentistry and medicine. This ranges from SLS fabrication of titanium meshes, to SLA, DLP, and FDM printing for implant surgical guides, dentures, models, wax patterns, and temporary restorations.[62,63] This review will focus on two light cured 3D printing technologies SLA and DLP as they are utilized and compared in this investigation.

Stereolithography printing (SLA) utilizes a laser beam to cure a photosensitive resin layer by layer to manufacture objects. The printing requires a platform to build the object on, a reservoir or tank that uncured resin is held and a laser source of UV light to cure the resin. Printing occurs in cycles by layer. First the platform is submerged in the resin tank, then the laser cures the resin by moving across the uncured resin in the pattern of that layer and finally the build platform moves the specified distance of the layer thickness and then the process is repeated. Two main configurations of this technology exist, one where the build platform moves downward, and the laser is oriented above the resin pool and the second where the platform moves upward, and the laser is reflected by a mirror and it cures the layer from underneath. This is the method the SLA printer (Form 3B) in this investigation utilizes. Digital light processing (DLP) utilizes a similar method with respect to its platform and resin tank but differs in how it cures the resin. Instead of a laser moving across the pattern of a layer, a rectangular series of mirrors called digital micro reflector devices are used. Each mirror represents a pixel of the layer to be printed and are oriented whether or not a particular pixel is to be cured or not. Then the source light is emitted onto the series of mirrors curing the entire layer at once and the build platform is raised the set layer thickness. Curing entire layers at once irrespective of the number of pixels or layer shape significantly reduces construction time compared to SLA printing.

1.4: Surgical Guides and Treatment Evaluation

Currently there is a significant body of evidence demonstrating that implant surgical guides increase implant placement accuracy.[64–85] Compared to free-hand placement which utilizes only local landmarks for implant placement, guided implant placement can be divided into two primary categories: static and dynamic. Static navigation utilizes 3D printed or thermoplastic surgical templates that assist in implant placement whereas dynamic navigation utilizes either optical scanning or robotic assistance to guide the surgeon's implant motor during surgery with or without a template in the patients mouth.[86] This review will focus on static navigation which is further divided into two primary categories, partial guidance and full guidance. Partial guidance provides restriction of the implant drills for the pilot drills or subsequent drills but not the implant placement. *Younes et al*. demonstrated that partial guidance provided increased implant placement accuracy compared to freehand implant placement.[80] Full guidance allows for complete preparation of the osteotomy and implant placement through the surgical guide. Fully guided protocols also have demonstrated superior performance with respect to implant placement accuracy.[80]

Treatment evaluation historically was based upon assessment of two-dimensional radiography with a focus on biological and functional success. With the advent of CBCT imaging and implant planning software, treatment evaluation now is performed using pre-operative planning superimposed on a postoperative CBCT with a calibrated examiner making measurements of the spatial differences.[87–90] Assessments with this technology has demonstrated clinically favorable results with respect to implant placement accuracy but suffer from several inherent issues such as metal scatter, CT distortion around implants, and exposure concerns for the patient receiving additional radiation that may not be necessary for treatment. Newer technologies that utilize STL files to align data and generate an assessment of accuracy reduce patient exposure to ionizing radiation, reduce error from examiner bias or examiner measurement and eliminate the distortion of metal scattering around implants. This technology utilizes a digitized scan of an arch with scan bodies that is then aligned within the pre-operative surgical planning software and the deviations are calculated and displayed allowing comparisons of freehanded, partially guided and fully guided surgical implant placement.

CHAPTER II

RESEARCH METHODOLOGY

2.1 Ethical and Safety Statement

All research was conducted in accordance with the principles embodied in the Declaration of Helsinki and in accordance with local statutory requirements. No human subjects, animal subjects, or human derived medical information were utilized for this in-vitro study and as such is exempt from institutional review board on human and animal research. All technologies and materials utilized are currently FDA approved for use in humans in the United States and were utilized appropriately according to their FDA approval and manufacturers guidelines.

2.2 Research aims, Power analysis, Sample size

The primary aim of this work is to investigate two common 3D printing modalities currently in use for the fabrication of static implant surgical guides and quantitatively assess performance and if either modality has superior accuracy with respect to simulated implant placement. The secondary aims are to assess the real-world utility of each modality with respect to printing time, material cost analysis, printing success and guide fit.

An a-priori power analysis was performed prior to the initiation of the study to assist in determining adequate sample size for use yielding n=23 per group. The power analysis was adapted from Younes et al. 2018 to assist in this calculation, however due to the recently reported minor deviations in mean differences with positional variation utilizing similar analytic methods, the decision was made to increase the guide number per group from 23 to 30, yielding 60 placed implants per group.[80,88]

2.3 Master and Sample Cast Fabrication

A mandibular typodont (ModuPRO One, Acadental) was utilized to fabricate a master cast to serve as the subject for the study. Teeth #20,29 were removed from the typodont and slightly enlarged using a laboratory handpiece. A master negative of the modified typodont was then duplicated using an addition silicone VPS material (Elite Double 22, Zhermack S.p.A.) which was mixed according to manufacturer recommendations using a vacuum laboratory automatic mixer (Renfert Twister Evolution, Renfert GmbH) and duplicated in a model duplication flask. The master model was fabricated out of ISO Type 3 dental stone (Microstone, Whip Mix Corporation). The stone was mixed in a vacuum laboratory automatic mixer according to manufacturer recommendations using the master negative VPS mold. The master model was removed from the negative after initial curing and allowed to completely set for 24 hours. The master negative VPS mold was then used to fabricate 4 sample models from the same dental stone as the master model.

2.4 Master and Sample Cast Digitization – DICOM/STL

A cone beam CT radiograph of the master model was acquired using an inspected and calibrated commercially available in-office CBCT unit (Planmeca ProMax, Planmeca USA Corp.) at the following parameters: (401x401x401), 200µm, 90kV, 6.3mA, 12.062s, 699mGy*cm^2 and exported as a single frame DICOM file. The master model was digitized using a calibrated and commercially available laboratory structured light optical scanner (Medit T710, Medit Corp.) using the orthodontic model scanning setting and exported with no modifications to generate the master STL file. The original typodont with #s20,29 present was also digitized in the same method to generate a restorative proposal for digital implant planning. Sample models fabricated from the master negative VPS mold were digitized in the same manner.

2.5 Digital Implant Planning

The master DICOM file was imported to a digital implant surgical planning software (coDiagnostiX®, Dental Wings GmbH) and a new master surgical plan was generated for the mandible. The teeth were segmented from the DICOM data to separate them from the base of the master model. The coordinate system was then set parallel to the occlusal plane and centered in three dimensions within the arch and on the midline respectively. The panoramic curve was then set based upon the midline, canines, and 3rd molars. The coordinate system of the master STL file was then aligned within the DICOM data using 10-point repositioning and the segmented teeth by selecting common anatomic areas on both the teeth segmentation and the master STL file. Alignment was confirmed visually prior to proceeding. The restorative proposal STL was then aligned to the master STL file in the same manner. The #20 and #29 implants were selected as Straumann 4.1x10mm BLT dental implants and positioned within the extracted space of the master model consistent with an ideal restorative position in the site in all three dimensions. Both implants were then made parallel to each other within the software. The master surgical guide STL was then generated with tooth support on teeth #s 18,19,21-28,30,31 and rotation markers with a printing offset of 0.17 mm, width of 3mm, and large connectors with a sleeve offset of T7 (0 mm). Prior to printing guides all printers were calibrated and calibration matrices were fabricated to ensure the correct sleeve offset was utilized. The master surgical guide STL was then exported from the planning software.

2.6 3D Printing Preparation

The master surgical guide STL was imported into the SLA 3D printer manufacturers' proprietary 3D Printing software (PreForm, FormLabs Inc.). The printer, material and layer thickness were chosen (Form3B, Surgical Guide V1, and 100 μm respectively). The master guide was rotated into the recommended position of ~33˚ and printing supports were generated. Supports were visually inspected to confirm no supports interfered with the sleeve position in the surgical guide and no critical areas were left unsupported. The guides were aligned in the build space, print files generated and uploaded to the SLA Printer (Form 3B, FormLabs Inc.). The master surgical guide was imported into the DLP 3D printer manufacturers' recommended 3D Printing software (NetFabb, Autodesk Inc.). The printer, build platform, material and layer thickness were chosen (P30, Surgical Guide Platform, NextDent SG, and 100μm respectively). The guide was rotated into the recommended position within the build platform at 0˚ and printing supports were generated. Supports were visually inspected to confirm no supports interfered with the sleeve position in the surgical guide and no critical areas were left unsupported. The guides were aligned in the build space, print files generated and uploaded to the DLP Printer (P30, Straumann GmbH / Rapidshape GmbH).

2.7 SLA 3D Printing, Post Processing, Guide Finalization

3D printing was initialized on the calibrated SLA Printer (Form 3B, Formlabs Inc.) utilizing the appropriate resin tray, resin and build platform. Printing time was recorded from initiation of print to completion. The combined mass (g) of the platform carrier, build platform and completed print was measured using a digital scale. All SLA prints were post processed according to manufacturer's recommendations. After printing the build platform was transported to the post processing station where excess uncured resin was manually rinsed from the surgical guides and platform using 99% isopropyl alcohol. The guides and platform were then inserted into an automated 99% isopropyl alcohol bath (FormWash, Formlabs Inc.) for 20min. After the automated wash the guides and platform were then manually rinsed a final time with 99% isopropyl alcohol from a squirt bottle then gently dried using compressed air. After initial drying the guides were removed from the build platform manually with supports intact and placed into a light curing unit (FormCure, Formlabs Inc.) preheated to 60˚C for 30 minutes. After curing supports were removed using a separating disk in a laboratory handpiece. The guides were then placed in a distilled water bath in an ultrasonic cleaning machine (Pro-Sonic 2000, Sultan Healthcare) for 2 minutes. Guides were removed from the water bath and cleaned using a laboratory steam cleaner (HOT-SHOT Elite, Trident) and dried completely using compressed air. Stainless steel guide sleeves (T-sleeve-ø5mm-H 5mm-guided, Straumann GmbH) were manually coated with uncured resin (Surgical Guide V1, FormLabs) and fully inserted into the surgical guide and cured using a handheld curing unit (Valo, Kavo Dental) for 10 seconds. All sleeves were inspected for excess resin and excess resin was removed with a hand instrument and guide cleaned again using the laboratory steam cleaner and dried with compressed air. The surgical guide was then stored in a light-proof container until ready for implant placement.

2.8 DLP 3D Printing, Post Processing, Guide Finalization

3D printing was initialized on the calibrated DLP Printer (P30, Straumann GmbH / Rapidshape GmbH) utilizing the appropriate resin tray, resin and build platform. Printing time was recorded from initiation of print to completion. The combined mass (g) of the platform carrier, build platform and completed print was measured using a digital scale. All DLP prints were post processed according to manufacturer's recommendations. After printing the build platform was transported to the post processing station. The individual surgical guide platforms were removed from the main platform and then excess uncured resin was manually rinsed from the surgical guide and platform using 99% isopropyl alcohol in a squirt bottle. The guides and platform were then inserted into a manual pre-rinse 99% isopropyl alcohol bath in an ultrasonic cleaning machine (Pro-Sonic 2000, Sultan Healthcare) for 1 minute. The platform and guide were then transferred to a final rinse 99% isopropyl alcohol bath in the ultrasonic cleaning machine for 1 minute. After the manual washes the guides were then manually rinsed a final time with 99% isopropyl alcohol from a squirt bottle then gently dried using compressed air. After initial drying the guides while still attached to build platform were placed into a light curing unit (SHERAflash-light plus, SHERA Werkstoff-Technologie GmbH) for an initial cure of 5 minutes (3000 flashes) with 10 L/min of Nitrogen gas followed by a final cure at the same settings. After curing, guides were removed from platform and supports were removed using a separating disk in a laboratory handpiece. The guides were then placed in a distilled water bath in an ultrasonic cleaning machine for 2 minutes. Guides were removed from the water bath and cleaned using a laboratory steam cleaner (HOT-SHOT Elite, Trident) and dried completely using compressed air. Stainless steel guide sleeves (T-sleeve-ø5mm-H 5mm-guided, Straumann GmbH) were manually coated with uncured resin (NextDent SG, NextDent) and fully inserted into the surgical guide and cured using a handheld curing unit (Valo, Kavo Dental) for 10 seconds. All sleeves were inspected for excess resin and excess resin was removed with a hand instrument and guide cleaned again using the laboratory steam cleaner and dried with compressed air. The surgical guide was then stored in a light-proof container until ready for implant placement.

2.9 In-vitro Implant Placement

A sample model was placed on a custom clear platform on the benchtop and the surgical guide was placed onto the model. Surgical guide fit was qualitatively assessed for accurate fit through seating in inspection windows and the presence or absence of rocking was noted. A guided implant transfer piece was secured to an implant replica prior to implant placement using a hand ratchet. Prior to placement Triad was used to close the apical opening of the site and triad gel was added to the site to cure once the implant was in place. Care was taken to avoid filling the site completely which may cause hydrostatic forces on the implant positioning with the triad gel. Using a ratchet adapter the implant was placed into the site with the stop key at the correct depth and placed to depth and timing as accurately as possible. A light cure unit was used from underneath the model for 10 seconds to cure the Triad securing the implant in place. After initial curing the light curing was performed from the buccal and lingual for 10 seconds each. The hexagon of the implant transfer piece was stabilized with the holding key and the transfer part was loosened with the hand ratchet. The transfer screw and guided housing were removed from the implant, the guide was removed and the implant placement area cured again for 10 seconds. Implants were placed at the #20 position and then at the #29 position respectively for each sample model. Surgical guides were placed back into a light-proof container after use. Throughout the study implants were placed in an alternating fashion between DLP and SLA samples.

2.10 Scan body Placement and Model Digitization – STL

Scanbodies (RC Scan body, Straumann GmbH) were fully seated into both the #20 and 29 implant and hand tightened. The sample model with implants and scanbodies was digitized using a calibrated and commercially available laboratory structured light optical scanner (Medit T710, Medit Corp.) using the orthodontic model scanning setting and exported without modification to generate the placed implant STL file.

2.11 Treatment Evaluation Tool

In-vitro implant placement was then assessed using the treatment evaluation tool of the implant planning software (coDiagnostiX, Dental Wings GmbH). Implant placement STL files were aligned to the sample STL file using 5-point re-alignment and common anatomic areas between the sample STL file and the implant placement STL file. The top surface of the #20 scan body and #29 scan body was selected and validated by the software. The treatment evaluation tool then displayed the deviation from the implant placement to the original surgical plan by displaying angular deviation, 3D deviation at the implant neck and tip, as well as the linear deviations in all three dimensions used to calculate the 3D deviation at the neck/tip. CSV files of the collected data was exported for each sample implant placement.

2.12 Data Collection and Analysis

All data was collected and recorded in a spreadsheet (Excel, Microsoft Corp). The following data was recorded throughout the study: Model Group, Model Pour number, Guide fabrication number, Guide type, T-sleeve LOT, Implant placement number, Implant replica LOT, Scan body LOT, Scan body usage number. Deviations calculated from the treatment evaluation tool in CSV files were imported into the spreadsheet and angular deviation, 3D-offset (neck), and 3D-offset (tip) were recorded. Guide printing group, estimated printing time, printing time, estimated print volume, print volume, mass of printed guides with the build platform and carrier was measured. Actual print volumes were calculated by converting mass of resin into volume using a measured density of 2g/mL for each respective resin used. The difference in printing time, difference in volume, and the mass of the resin used in the print were calculated. Printing time per layer and guide, resin use per guide, cost per guide, and percent print success were calculated. A comparison of the scan body use was also performed within groups. Descriptive and comparative statistics were performed using statistical software (SPSS, IBM).

CHAPTER III

RESULTS

3.1 Implant Spatial Deviations

Primary statistical measures investigated centered around implant placement accuracy and included angular deviation, 3D offset of implant at the neck, 3D offset of the implant tip. Spatial deviations of 120 implant replicas (60 implants placed for each group) placed with 60 surgical guides (30 fabricated via SLA printing, 30 fabricated via DLP printing) were assessed and compared within and between groups. Independent t-tests were performed between groups to determine if the angular deviation or 3D offsets were statistically significant (Table 1).

Table 1. Spatial deviations (degrees and mm) between DLP and SLA fabricated surgical guides.

		3D Printer	
		P-30 (DLP) (n = 60)	Form 3B (SLA) (n = 60)
Angular Deviation (Degrees)* **(p = 0.002)**	Mean ± SD	1.02 ± 0.47	0.77 ± 0.42
	Median (IQR)	1.00 (0.68)	0.75 (0.48)
	Range (Min-Max)	2.10 (0.00 - 2.10)	2.00 (0.10 - 2.10)
3D Offset Neck (mm)* **(p = 0.017)**	Mean ± SD	0.14 ± 0.07	0.18 ± 0.11
	Median (IQR)	0.14 (0.11)	0.17 (0.13)
	Range (Min-Max)	0.30 (0.02 - 0.32)	0.67 (0.03 - 0.70)
3D Offset Tip (mm) (p = 0.768)	Mean ± SD	0.28 ± 0.14	0.27 ± 0.13
	Median (IQR)	0.26 (0.23)	0.25 (0.14)
	Range (Min-Max)	0.57 (0.02 - 0.59)	0.66 (0.07 - 0.73)

Independent Samples T-test, * indicates statistical significance between groups ($p < 0.05$)

Angular deviation was statistically significant between printing groups ($p = 0.002$), with implants placed with SLA printed guides having a mean deviation of 0.77 ± 0.42 degrees (range: 0.10 – 2.10) and implants placed with DLP printed guides having a mean deviation of 1.02 ± 0.47 degrees (range 0.00 – 2.10) respectively (Table 1, Figures 1,2).

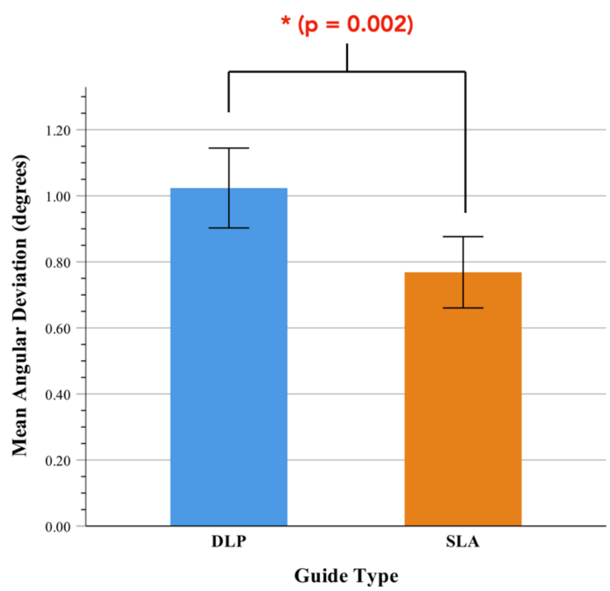

Figure 1. Mean angular deviation (degrees) by guide type.

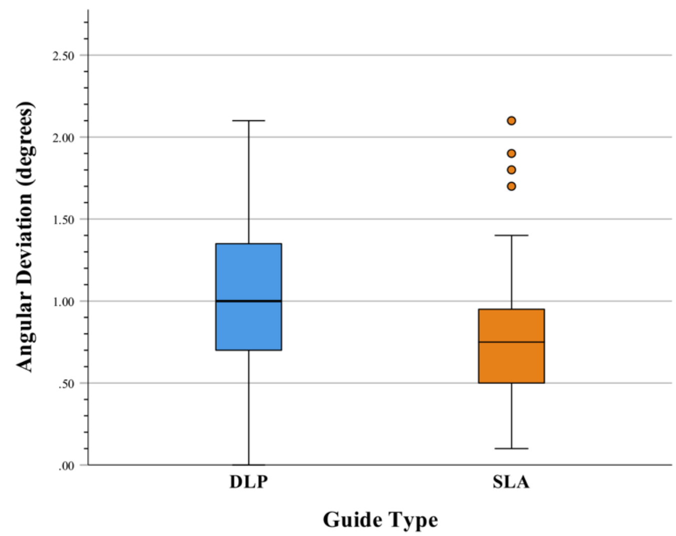

Figure 2. Box-plot of angular deviation (degrees) by guide type.

Guide Type
DLP
SLA

Independent Samples T-test, * indicates statistical significance between groups

3D offset at the implant neck was statistically significant between printing groups ($p = 0.017$), with implants placed with SLA printed guides having a mean deviation of 0.18 ± 0.11 mm (range: 0.03 – 0.70) and implants placed with DLP printed guides having a mean deviation of 0.14 ± 0.07 mm (range 0.02 – 0.32) respectively (Table 1, Figures 3,4). 3D offset at the implant tip was not statistically significant between printing groups ($p = 0.768$), with implants placed with SLA printed guides having a mean deviation of 0.27 ± 0.13 mm (range: 0.07 – 0.73) and implants placed with DLP printed guides having a mean deviation of 0.28 ± 0.14 mm (range 0.02 – 0.59) respectively (Table 1, Figures 3,4).

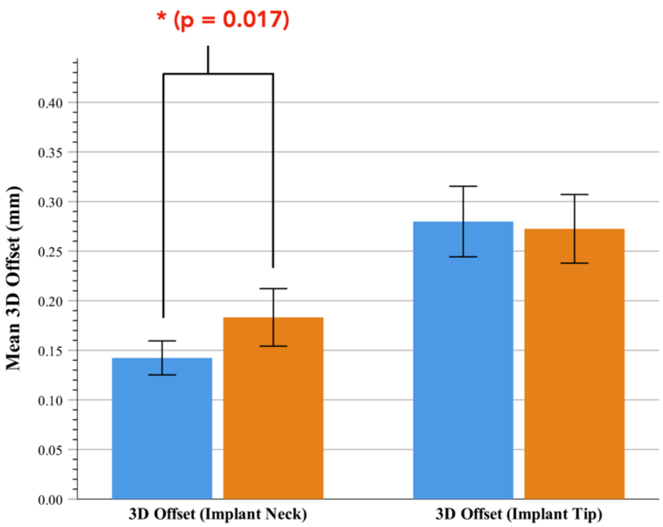

Figure 3. Mean 3D offset (mm) at implant neck and implant tip by guide type.

Guide Type
DLP
SLA

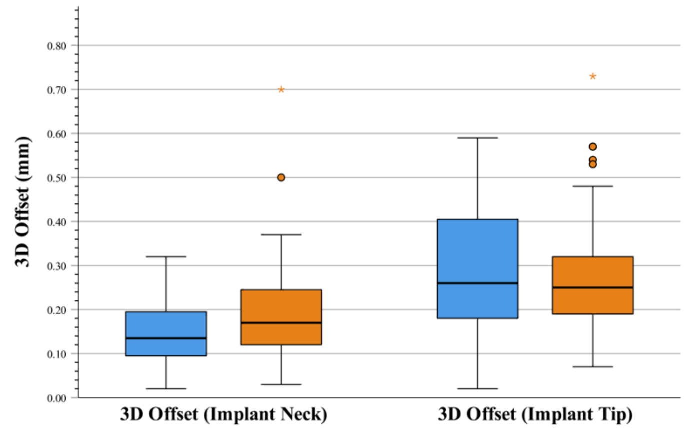

Figure 4. Box-plot of 3D offset (mm) at implant neck and implant tip by guide type.

Independent Samples T-test, * indicates statistical significance between groups

3.2 Printer Performance Metrics

Secondary statistical measures investigated centered around 3D printer performance metrics: including software estimated versus actual printing time and resin use, a material cost per surgical guide analysis, and print success percentage. Printer performance metrics were assessed for 25 prints (10 prints performed via SLA group, 15 prints performed via DLP group) and compared within and between groups. Independent t-tests were performed between groups to determine if any print time metrics or resin use metrics were statistically significant (Table 2).

Table 2. Printer Performance Metrics

		3D Printer	
		P30 (DLP), (n = 15)	Form 3B (SLA), (n = 8)
Time	Calculated Print Time*	0:23:12 ± 0:00:52	3:35:00 ± 0:01:31
	Actual Print Time*	0:22:35 ± 0:00:59	3:51:56 ± 0:16:24
	Δ Print Time*	0:00:38 ± 0:00:18	0:16:56 ± 0:15:43
	Print Time per Build Cycle*	0:00:08 ± 0:00:01	0:00:48 ± 0:00:03
	Print Time per Guide*	0:22.35 ± 0:00:59	0:57:59 ± 0:04:06
Resin Use	Calculated Resin Use (mL)*	15.68 ± 0.20	63.39 ± 0.49
	Actual Resin Use (mL)*	31.27 ± 1.49	84.13 ± 0.83
	Δ Resin (mL)*	15.58 ± 1.39	20.73 ± 0.56
	Resin Use per Guide (mL)**	19.72 ± 3.78	15.94 ± 0.86
Print Job Success	Percent Success	100% (15/15)	80% (8/10)
Cost Analysis	Cost per guide (USD)*	$4.13 ± $0.20	$5.26 ± $0.05
	Cost per liter resin (USD)	$264.00	$250.00
	Printer Cost (USD)	$25,379.00	$5,569.58

Independent Samples T-test, * indicates statistical significance between groups ($p < 0.001$), ** ($p = 0.012$)

Calculated print time was statistically significant between printing groups ($p < 0.001$), with SLA prints having a mean calculated print time of 3:19:06 ± 0:33:35 and DLP prints having a mean calculated print time of 0:23:12 ± 0:00:52 respectively (Table 2, Figure 5). Actual print time was statistically significant between printing groups ($p < 0.001$), with SLA prints having a mean print time of 3:39:09 ± 0:33:04 and DLP prints having a mean print time of 0:22:35 ± 0:00:59 respectively (Table 2, Figure 5).

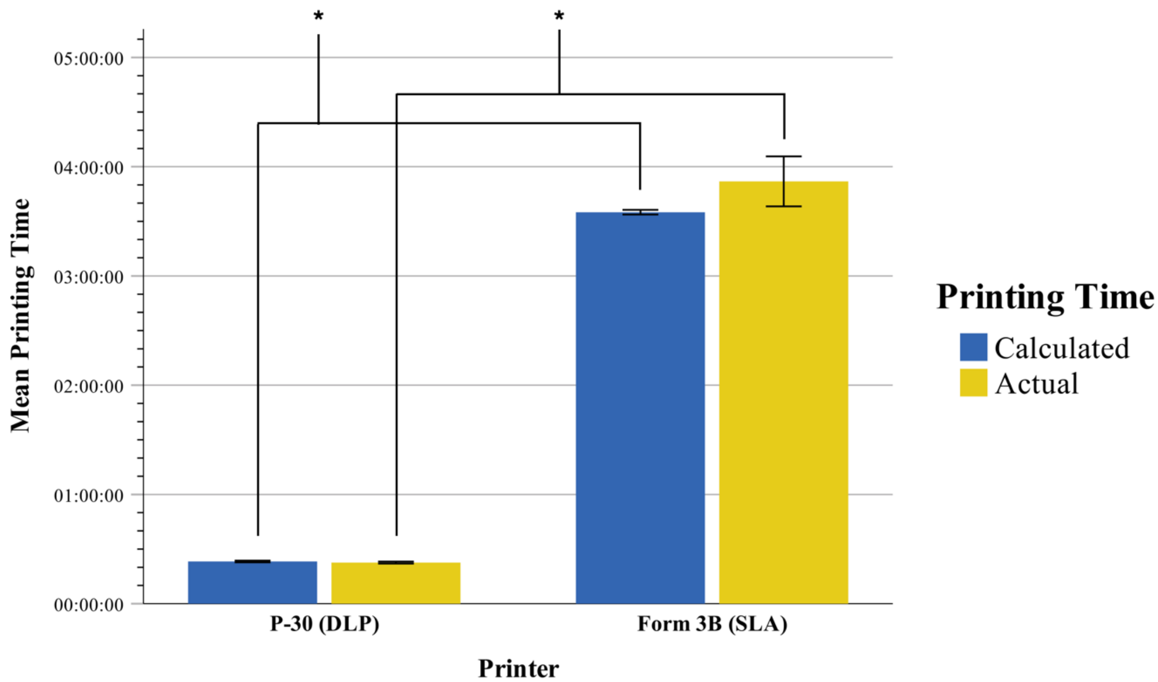

Figure 5. Mean calculated and actual print time per print job by printer type

Independent Samples T-test, * indicates statistical significance between groups, ($p < 0.001$)

Mean difference between estimated and actual print time was statistically significant between printing groups ($p < 0.001$), with SLA prints having a mean difference in print time of 0:20:03 ± 0:18:48 and DLP prints having a mean difference in print time of 0:00:38 ± 0:00:18 respectively (Table 2, Figure 6). Cumulative print time was calculated and significantly different between groups ($p < 0.001$) with SLA print time totaling 36:35:25 and cumulative DLP print time totaling 05:39:42. There was a print time difference of 30:55:43 between groups. Mean printing time per build cycle and per guide were calculated and were statistically significant ($p < 0.001$) between printing groups (Figure 7).

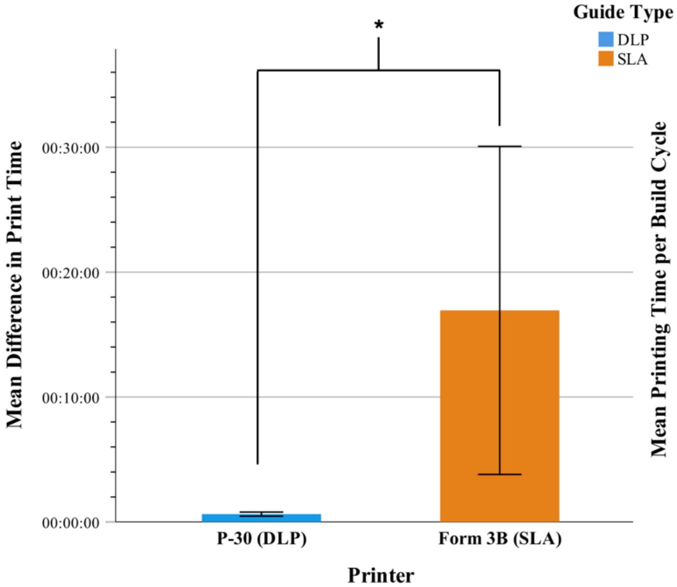

Figure 6. Mean difference between calculated and actual print time per print job by printer type

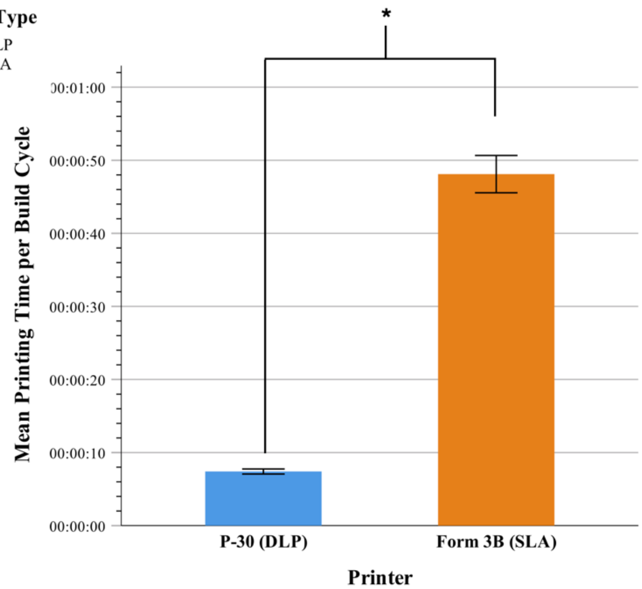

Figure 7. Mean print time per build cycle by printer type

Independent Samples T-test, * indicates statistical significance between groups, ($p < 0.001$)

Calculated resin use was statistically significant between printing groups ($p < 0.001$), with SLA prints having a mean calculated resin use of 57.01 ± 13.46 mL and DLP prints having a mean calculated resin use of 15.68 ± 0.20 respectively. Actual resin use was statistically significant between printing groups ($p < 0.001$), with SLA prints having a mean resin use of 77.70 ± 13.57 mL and DLP prints having a mean resin use of 31.27 ± 1.49 respectively (Table 2, Figure 8).

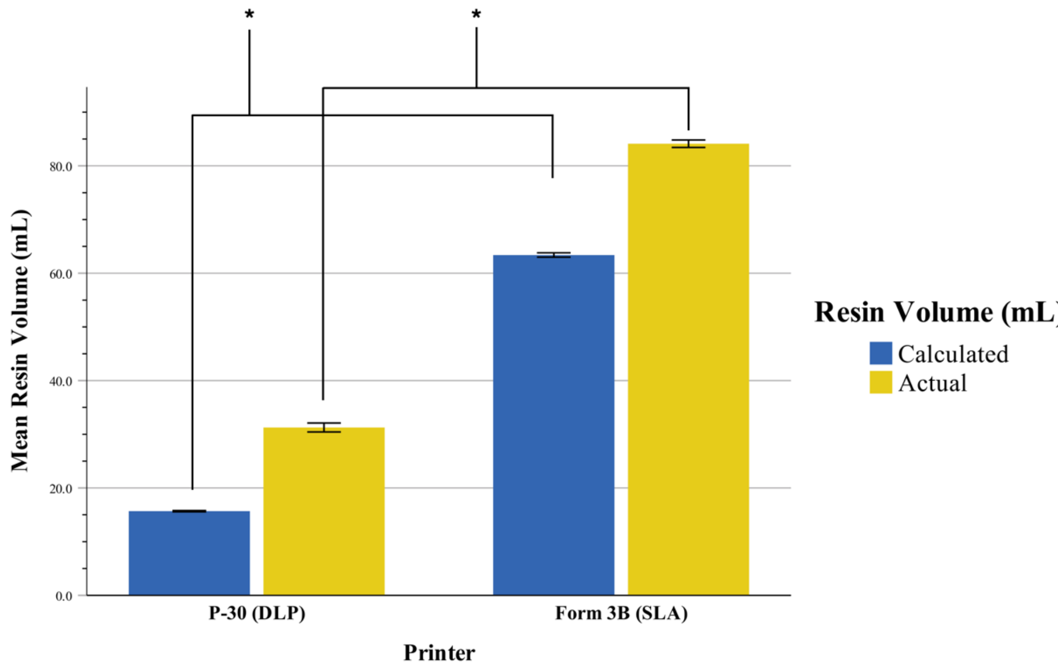

Figure 8. Mean calculated and actual resin use (mL) per print job by printer type

Independent Samples T-test, * indicates statistical significance between groups, ($p < 0.001$)

Mean difference between calculated and actual resin use was statistically significant between printing groups ($p = 0.005$), with SLA having a mean difference in resin use of 20.69 ± 0.52 mL and DLP having a mean difference in resin use of 15.58 ± 1.39 respectively (Table 2, Figure 9). Resin use per surgical guide was calculated and statistically significant between printing groups ($p < 0.001$), with SLA printed guides having a mean resin use of 15.90 ± 0.77 and DLP printed SLA printed guides having a mean resin use of 19.72 ± 3.78 (Table 2). Cost per surgical guide was calculated and also statistically significant between printing groups was $5.51 ± 0.53 USD for SLA guides and $4.13 ± 0.20 USD for DLP guides respectively (Table 2, Figure 10).

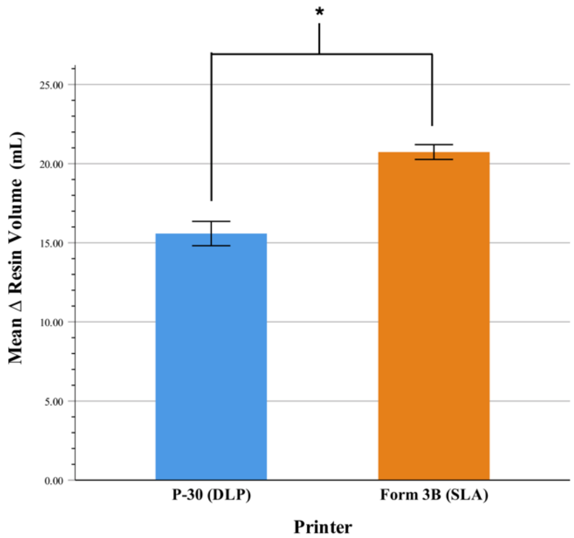

Figure 9. Mean difference between calculated and actual print time per print job by printer type

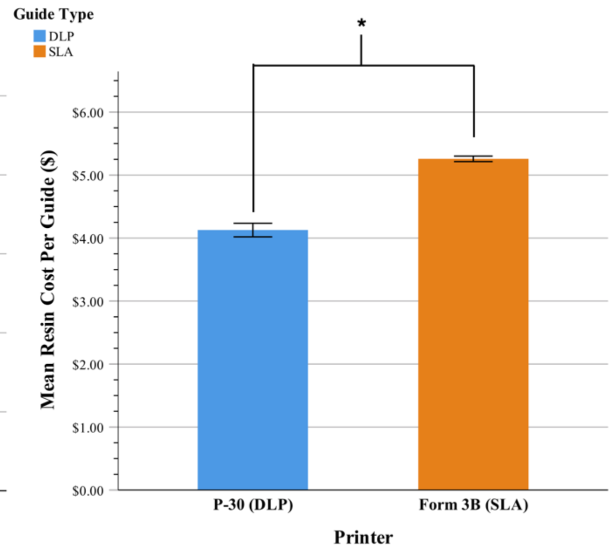

Figure 10. Mean resin cost (USD) per guide by printer type

Independent Samples T-test, * indicates statistical significance between groups, ($p < 0.001$)

Print success was compared between printers. The SLA printer required 10 prints to generate all 30 surgical guides, this includes 2 additional prints that were required due to print failure, the 8 remaining prints were successful yielding an 80% (8/10) print success rate. The DLP printer required 15 prints to generate all 30 surgical guides, this includes no additional prints as there were no print failures yielding a 100% (15/15) print success rate (Table 2).

An additional tertiary analysis was performed based upon the number of scan body uses with respect to primary outcome values angular deviation, 3D offset of implant at the neck, 3D offset of the implant tip within groups. Spatial deviations of 60 implant replicas in each printing group were divided into scan body use order (30 implants each) were assessed and compared within print groups. Independent t-tests were performed between scan body uses within print groups to determine if the angular deviation or 3D offsets were statistically significant (Table 3,4). Angular deviation was statistically significant within the SLA and DLP groups between first and second scan body use ($p = 0.013$, $p < 0.001$ respectively). Within the SLA group the first use had a mean angular deviation of 0.64 ± 0.30 degrees (range: 0.10 - 1.10) second use had a mean angular deviation of 0.90 ± 0.48 (range: 0.20 - 2.10). Within the DLP group the first use had a mean angular deviation of 0.83 ± 0.45 degrees (range: 0.00 - 2.10) second use had a mean angular deviation of 1.22 ± 0.41 (range: 0.60 - 2.00). 3D offset at the implant neck was not statistically significant in SLA but was in the DLP group between first and second scan body use ($p = 0.066$, $p = 0.021$ respectively). Within the SLA group the first use had a mean 3D offset of 0.21 ± 0.13 mm (range: 0.05 - 0.70) and second use had a mean 3D offset of 0.16 ± 0.09 mm (range: 0.03 - 0.37). Within the DLP group the first use had a mean 3D offset of 0.13 ± 0.06 mm (range: 0.02 - 0.23) and the second use had a mean 3D offset of 0.16 ± 0.07 mm (range: 0.03 - 0.32). 3D offset at the implant neck was not statistically significant in SLA but was in the DLP group between first and second scan body use ($p = 0.407$, $p < 0.001$ respectively). Within the SLA group the first use had a mean 3D offset of 0.26 ± 0.14 mm (range: 0.07 - 0.73) and second use had a mean 3D offset of 0.29 ± 0.13 mm (range: 0.10 - 0.57). Within the DLP group the first use had a mean 3D offset of 0.22 ± 0.11mm (range: 0.02 - 0.50) and the second use had a mean 3D offset of 0.34 ± 0.14 mm (range: 0.10 - 0.59).

SLA Printed Surgical Guides		Scanbody Use	
		First Use (n = 30)	Second Use (n = 30)
Angular Deviation (Degrees)* **p = 0.013**	Mean ± SD	0.64 ± 0.30	0.90 ± 0.48
	Median (IQR)	0.60 (0.50)	0.80 (0.53)
	Range (Min-Max)	1.00 (0.10 - 1.10)	1.90 (0.20 - 2.10)
3D Offset Neck (mm) p = 0.066	Mean ± SD	0.21 ± 0.13	0.16 ± 0.09
	Median (IQR)	0.18 (0.12)	0.15 (0.14)
	Range (Min-Max)	0.65 (0.05 - 0.70)	0.34 (0.03 - 0.37)
3D Offset Tip (mm) p = 0.407	Mean ± SD	0.26 ± 0.14	0.29 ± 0.13
	Median (IQR)	0.23 (0.016)	0.26 (0.12)
	Range (Min-Max)	0.66 (0.07 - 0.73)	0.47 (0.10 - 0.57)

Table 3: Scan body use in SLA printed guides

DLP Printed Surgical Guides		Scanbody Use	
		First Use (n = 30)	Second Use (n = 30)
Angular Deviation (Degrees)* **p < 0.001**	Mean ± SD	0.83 ± 0.45	1.22 ± 0.41
	Median (IQR)	0.75 (0.63)	1.20
	Range (Min-Max)	2.10 (0.00 - 2.10)	1.40 (0.60 - 2.00)
3D Offset Neck (mm)* **p = 0.021**	Mean ± SD	0.13 ± 0.06	0.16 ± 0.07
	Median (IQR)	0.12 (0.09)	0.15 (0.11)
	Range (Min-Max)	0.21 (0.02 - 0.23)	0.29 (0.03 - 0.32)
3D Offset Tip (mm)* **p < 0.001**	Mean ± SD	0.22 ± 0.11	0.34 ± 0.14
	Median (IQR)	0.22 (0.16)	0.39 (0.23)
	Range (Min-Max)	0.48 (0.02 - 0.50)	0.49 (0.10 - 0.59)

Table 4: Scan body use in DLP printed guides

CHAPTER IV

DISCUSSION AND CONCLUSIONS

The overall precision and accuracy of any process is determined by the each of the individual steps that make up the process. This is especially true in guided implant placement as the quality and accuracy of the final implant position depends on primarily the initial planning material (DICOM and STL files), the accuracy of the manufacturing technology (milled, thermoplastic, or 3D printed) and the surgical technique.

This *in vitro* study compared a SLA and DLP printer and focused on the accuracy of each manufacturing technology and found statistically significant differences between the accuracy of implant placement with respect to angular deviation and 3D offset at the implant neck between SLA and DLP technologies, but no difference at 3D offset at implant tip. SLA printed guides were statistically superior with respect to angular deviation with a mean deviation of 0.77 degrees compared to DLP with mean deviation of 1.02 degrees ($p = 0.002$) and DLP printed guides were statistically superior with respect to 3D offset at implant neck with a mean deviation of 0.14 mm compared to SLA with mean deviation 0.18 mm ($p = 0.017$). The results of the present study demonstrate several key differences from the existing body of evidence – specifically differences in angular deviation and 3D offset. *Anunmana et. al* compared DLP, SLA and PolyJet printing, and found no significant difference with respect to angular deviation with a mean deviation (degrees) of 2.3 ± 0.61, 2.54 ± 0.70, and 2.47 ± 0.72 for SLA, PolyJet and DLP printing respectively.[87] In the same study they found significant differences in 3D offset with a mean deviation at the neck (mm) of 1.66 ± 0.15, 1.48 ± 0.07, and 1.87 ± 0.25 for SLA, PolyJet and DLP respectively and for the tip (mm) 1.86 ± 0.22, 1.72 ± 0.12, and 2.03 ± 0.26 for SLA, PolyJet and DLP respectively.[87] *Herschdorfer et al*. in their investigation of SLA printed surgical guides compared to MultiJet and PolyJet printed surgical guides found no significant differences between printing groups in any parameters measured with a median (IQR) angular deviation (degrees) of 1.30 (0.62) for SLA; 1.15 (1.23) for PolyJet; and 1.10 (0.65) for MultiJet printers.[88] With respect to 3D offset the median and interquartile range for the entry offset and apex offset (mm) were 0.19 (0.16) and 0.36 (0.16) for SLA, respectively; 0.20 (0.13) and 0.34 (0.26) for Polyjet, respectively; and 0.23 (0.10) and 0.32 (0.08) for MultiJet, respectively.[88]

The present study compared to previous *in vitro* and *in vivo* studies demonstrates a significantly decreased mean angular and 3D deviation and an increased precision in experimental parameters.[80,87,89,90] The assessment method of the actual implant placement compared to the planned placement is one of the primary sources of error in studies that assess surgical guidance protocols or fabrication method on implant placement. There is a significant variation in the literature ranging from studies investigating treatment accuracy based upon post-operative CBCT measurement and analysis, but there is a general consensus on the accuracy of implant placement with computer generated static surgical guides.[64–67,91] There are limitations with current methods used to assess implant placement accuracy due to CBCT scatter, scatter halos around dental implants, CBCT scanning parameters and voxel resolution that can impact measurements by up to 1 mm.[92] This study and several other studies in the recent literature utilize a digital scan with scan bodies to asses implant placement accuracy which eliminate the need for a postoperative CBCT and eliminating the variance of examiner error in estimating implant placement on an overlaid CT, the distortion around dental implants and scatter.[87–90] The variation between these studies then may be related to differences in printing parameters such as layer thickness, print orientation in printers, post processing techniques, age of surgical guide, scan body placement, and digitization technique.[93–97] This study attempts to minimize the influence of these potential various factors through study design and utilizing a laboratory grade patterned light scanner with a resolution of 0.004 mm for digitalization of the post implant placement STLs instead of using an intraoral scanner which can induce error based upon scanning technique. The present study also utilizes an implant fixation scheme that prevents any material from acting on the implant placement which may impact the accurate assessment of 3D printer on implant placement. Although a statistically significant difference between 3D printers and spatial deviations were noted in this study, the clinical relevance of this difference is negligible as the error tolerance is well within the margin of safe implant placement around vital structures as well as much lower than previous *in vitro* and *in vivo* studies.

Despite the low clinical relevance of the present studies' results with spatial deviations, the significant differences found regarding printing performance and printer metrics are especially relevant for the clinician incorporating 3D printing into their everyday practice. There is a growing body of evidence that the utilization of 3D printed surgical templates significantly reduce chair-time, reduce recovery time, increase implant placement accuracy and reduce patient morbidity compared to traditional surgical techniques in both medicine and dentistry.[80,98–102] Currently there have been few reports discussing printing performance metrics that are of important consideration to the practitioner considering utilizing this technology in practice. Print success is often not mentioned or discussed in many investigations of 3D printing and failed prints are excluded or not reported in the assessment which gives an inaccurate representation of the printers being compared. The current study found a 100% success rate of the DLP printed guides (15/15) and an 80% success rate of SLA printed guides (8/10). Both printers performed adequately with respect to print success but varied significantly in printing time. SLA prints had a mean print time of 3:39:09 ± 0:33:04 and DLP prints had a mean print time of 0:22:35 ± 0:00:59 respectively. The large difference in printing time has major significance if there are any print failures. The two failed SLA prints created a loss on average of 3 hours 39 minutes each. This difference becomes of even greater importance when the two methodologies are shown to produce very similar results with respect to spatial deviations on implant placement. These results, and estimated printing time results are comparable to previous studies.[87] The printing time metrics as well as the resin use and cost analysis presented in Table 2 are important factors for the clinician utilizing these technologies in practice as they assist in determining cost-effectiveness and especially time-effectiveness of each technology. Incorporation of additive manufacturing technologies in everyday practice can be a significant initial investment especially for industrial or laboratory grade printers compared to more financially accessible printers. More studies are needed to investigate different tiers of 3D printers within the same type of printing technology. This is a limitation of this study as it compares a laboratory/industrial grade DLP printer to a consumer SLA printer. The estimated and actual time/resin use and print success were significantly lower in the consumer SLA printer which has reliability implications in everyday practice that reduce its cost-effectiveness over time.

Interestingly this study also found a difference in the number of scan body use on the primary outcomes of spatial deviations (Table 3,4). This result is consistent with a previous study comparing scan bodies reuse within a full arch scan of a bar restoration that showed that there were significant differences based on reuse but within clinical tolerances.[103] This adds to the current evidence that there are significant differences in scan body re-use, which has clinical implications as many practitioners re-use scan bodies similar to the routine re-use of healing abutments in implant dentistry. This may have implications in implant restorations as well as in future assessments that utilize a treatment assessment tool system to investigate implant placement accuracy.

In conclusion, the current study demonstrated statistically significant differences in spatial deviations with SLA printing superior in angular deviation and DLP printing superior 3D offset at implant neck. There were no statistically significant differences between SLA and DLP printing at the implant tip. The statistically significant differences in spatial deviations present between printers are of minimal clinical relevance. Additionally, clinically relevant and statistically significant differences were found in the printing performance metrics with the DLP printer superior to the SLA printer. The current study strongly suggests that despite similar performance in implant placement, DLP printing offers superior printing reliability, performance and utility compared to SLA printing for implant surgical guides. Additional investigations comparing different tiers of DLP technology printers compared to different tiers of SLA printers will provide a more accurate view of the cost effectiveness of the individual technologies in practice. As additive manufacturing continues to advance, become more affordable, cost effective, and likely to be found in the dental office, investigations such as the current study will be a great asset to practitioners to make informed decisions about their choice of 3Dvprinter.

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