Tufts UNIVERSITY | School of Dental Medicine

In-vitro study of the Dimensional stability of full-arch implant printed model over time.

A Thesis

Presented to the Faculty of Tufts University School of Dental Medicine
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Dental Research

by
Abdulla Al-Ghfeli
August 2021

DEDICATION

I dedicate this thesis to my beautiful and amazing family. Who has been a constant source of support and encouragement during the challenges of my residency and my Master Research Program. I am truly thankful for having you as my family.

ACKNOWLEDGMENTS

I am greatly thankful for the help, support and advice of my principal investigator, Dr. Kang, and my committee members: Dr. Kim, Dr. El-Rafie, Dr. Morgan and Dr. Finkelman without whom this project would not be possible.

As well I would like to thank Mr. Kudara for his help and support in some of the laboratory steps.

TABLE OF CONTENTS

THESIS COMMITTEE

Thesis Advisor

Kiho Kang, D.M.D
Professor Advanced Education Program in Prosthodontics
Department of Prosthodontics and Operative Dentistry

Committee Members

Yong Jeong Kim, D.M.D
Associate Professor
Associate Director of the Advanced Education Program in Prosthodontics
Tufts University School of Dental Medicine

Khalid Elrafie, D.D.S
Assistant Professor
Department of Prosthodontics
Tufts University School of Dental Medicine

Sujey Morgan, D.D.S
Assistant Professor
Department of Prosthodontics
Tufts University School of Dental Medicine

Matthew Finkelman, Ph.D.,
Associate Professor
Department of Public Health and Community Service
Tufts University School of Dental Medicine

ABSTRACT:

Aim: To evaluate and compare the dimensional stability over time of the 3D printed models from 3 different printers (SLA, CLIP & DLP).

Hypothesis:

1- The printed models from a SLA printer are dimensionally more stable over time than the printed models from a DLP printer or CLIP printer for a completely edentulous arch.

2- The 3D printed models are more dimensionally stable at the later time points as compared to the earlier time points.

Materials & Methods: A completely edentulous mandibular cast with four abutment level implant analogs (RC, Straumann, Repositionable Analog for SR Abut. Ø4.6mm) with adequate antero-posterior (AP) spread were fabricated to simulate the routinely occurring clinical situation of a completely edentulous mandible restored with an implant supported prosthesis. The difference in angulation between the 4 implants was under 20° providing an acceptable clinical condition. The approximate locations of the implants were #19, 22, 27 and 29. Three notches were made on the master cast. The cast served as the master cast. The master cast was digitized using a lab scanner and scan bodies (CARES® Mono Scan body SRA Ø 4.6 mm) to have the master cast as an STL file. From this STL file of the master cast, three groups were prepared and evaluated: Bego printer group (n=12), Carbon printer group (n=12) and Formlab printer group (n=12).

All of the 3D printed models from the three groups were digitized for comparison using a high-resolution reference scanner (Activity 880 scanner; Smart Optics, Bochum, Germany) at 5 different time points. All 3D printed models were put in a box and stored in an air-conditioned laboratory.

The digitized STL files by a high resolution desktop scanner were super-imposed with the digitized STL file from the previous scan to compare the 3D dimensional changes in the inspection software (Geomagic, Control X). Data were analyzed via a mixed-effects model.

Results: The Formlab printer had the lowest mean value 9.85 µm (SD=2.27 µm), followed by the Carbon printer group with a mean of 12.73 µm (SD=1.97 µm). The Bego printer group had the highest mean value of 14.57 µm (SD=3.01 µm). When pooling the data from the different printers, the highest mean value was at 2 days, and the lowest mean value was at 18 days. The mean decreased from each time point to each subsequent time point. Regarding the results of the mixed-effects model, the global tests for the two factors showed that the difference between time points was not statistically significant ($p = 0.109$), but the difference between printers was statistically significant ($p < 0.001$). All three post-hoc tests were statistically significant: Bego vs. Carbon ($p = 0.002$), Bego vs. Formlab ($p < 0.001$), and Carbon vs. Formlab ($p < 0.001$).

Conclusion:

Within the limitations of this in-vitro study, the 3D printed models from the Bego 3D printer showed less dimensional stability than the Carbon printer, which showed less dimensional stability than the Formlab 3D printer. Although the time points showed decreased dimensional changes of the 3D printed models up to 18 days, there was no significant evidence of differences among time points.

LIST OF TABLES

LIST OF FIGURES

In-vitro study of the Dimensional stability of full-arch implant printed model over time.

INTRODUCTION:

Digital technology has expanded rapidly in the past decade, and gained popularity in dentistry, particularly among prosthodontists.[1] The digital revolution affected many dental aspects such as desktop, face & intraoral scanners, Cone Beam Computed Tomography (CBCT), CAD/CAM software & guided surgery, 3D printing and milling machines.[2] The idea of using optical scanning to develop an intraoral grid-surface mapping system was first introduced in the 1970's by Youg and Altschuler. Later, in 1984, the Duret system was developed by Duret which was the first CAD/CAM system to generate a single full coverage restoration. Mormann and Brandestini developed the CEREC system which was the first commercially available dental CAD/CAM system.[3] It has several advantages, as it saves time [1] and allows various procedures to be accomplished with less cost [4]. Digital dentistry allows us to take impressions, fabricate and deliver some prostheses in the same day, thereby reducing the chair time.[5] The use of digital dentistry can help produce restorations of such high strength materials as alumina and zirconia that can be fabricated only by CAD/CAM, which has a software program that allows us to design the restorations in 3D on the computer screen.[6]

Digital technology advancement has also become an essential aspect of dental implant surgery. Digital implant planning using CBCT, intraoral scanners and CAD/CAM technology have allowed us to fully complete the digital workflow and led to the fabrication of prosthetically driven surgical guides that are designed and 3D printed using digital dentistry and enhance the accuracy of implant placement [7].

Implant framework passive fit:

For long-term success, it is very important to achieve a passive fit of a fixed implant supported dental prosthesis. By having a passive fit of the prosthesis, it can avoid or reduce the risk of having biological or technical complications which include bone resorption, chipping or veneering material, screw loosening or framework fracture, which can lead to prosthesis or implant failure.[8] It has been reported that obtaining an absolute passive fit of the prosthetic framework of the implant fixed complete dental prosthesis (IFCDP) is impossible, but it is not yet established what degree of misfit will cause the previously mentioned technical and biologic complications. Even though obtaining a passive fit is impossible the clinician should always aim for the best fit of the implant framework.[9] Generally, the implant supported prosthesis could have clinically acceptable passive fit it is seated with intimate contact with the implant without having any static load or strain on the supporting implants and the surrounding bone.[10-12] Researchers have tried to measure and quantify the amount of misfit to develop an acceptable range for misfit. Some researchers have described this acceptable range of misfit between the prosthesis and implant platform to be between 59 µm to 150µm,[8, 13] while others have suggested 10 µm to 200 µm.[13-15]

Several testing methods have been described to test the fit of the implant supported prosthesis such as finger pressure, visual inspection which sometimes can be clinically difficult, single screw test (Sheffield test), screw resistance test and radiographs.[11, 16] Several factors affecting the accuracy of the implant prosthesis have been identified by researchers. These factors can be categorized into 3 categories: implant impression, master cast fabrication, and framework superstructure fabrication related factors.[16-19]

1. Implant impression factors:

The first and crucial part in the fabrication of the final prosthesis process is the implant impression. Any error encountered during this step, it would continue and add up to the subsequent steps. Thus, an accurate impression is an important step in the fabrication process of the definitive restoration with a passive fit.[20, 21] Errors can arise from many factors which can influence the accuracy of the implant impression. Some of the factors are as follows: impression material, impression technique, implant alignment and connection type.[17-19, 21, 22]

First, dimensional stability is one of the main properties that the impression material needs to have, so it can transfer the implant 3D position intra-orally to the master case accurately. Some considerations which could compromise the stability of the impression material are production of by-product, exposure to moisture, contraction, or shrinkage.[11, 23] Type of materials depends on various factors, including but not limited to, implant alignment, type of restoration and clinician's experience.[24]

Second, regarding the impression technique, many researchers have compared the accuracy of final impressions produced by custom trays versus stock trays. The results favored the custom trays due to the controlled uniform thickness of the impression materials with the custom trays.[25] Regarding the impression technique, many studies have discussed the effect of different impression techniques. Most of the studies favored the open tray implant impression technique in terms of accuracy.[17, 26-28] One study found no statistically significant difference between the two techniques.[29] One in-vitro study reported that open tray implant impression is less accurate than close tray.[30] Papaspyridakos et al reviewed the literature to compare the accuracy of digital and conventional impression techniques for partially and completely edentulous patients. Their systematic review found that the conventional open tray technique with splinted impression copings demonstrated more accurate impressions for these patients.[31]

The impression material had no effect on the accuracy, while the implant angulation did. With respect to the digital impression, the authors indicated that insufficient data were available, and further studies were necessary.

Implant angulation is the final factor which could affect the accuracy of the master cast. Several studies have identified that the implant parallelism has an effect on the accuracy of the final impression. They concluded that if implant angulation is more than 20 degrees it can reduce the accuracy of the 3D implant position transferred to the master cast.[24, 32] Some authors concluded that impression accuracy is inversely related to the number of implants.[11, 31]

2. Master cast fabrication

An accurate master cast is an essential part for the passive fit of the final prosthesis; inaccuracy can cause an adverse effect on the prognosis of the final prosthesis.[33] The accuracy of the master cast can be verified using a verification jig. It can be fabricated extra- or intra-orally and after joining the coping part with a rigid material. It can be transferred back to the master cast for evaluation.[19] Many studies and publications have favored the use of the verification jig to test the accuracy of the master cast. In a study by Papaspyridakos et al., the authors found that the use of different materials used for splinting showed similar results.[31] Sorrentino et al. concluded that if the angles between implants exceed 20 degrees, it will result in a pronounced 3D variation.[24]

3. Framework superstructure factors:

A framework misfit on an implant can occur in the fabrication process which is carried out in the lab. Conventional casting and fabrication of the framework using base or noble metal alloys can introduce errors and casting distortion which eventually cause a misfit. Who will then need to section and solder the framework to achieve a passive fit.[34] Studies have shown that framework misfit is associated with many mechanical and technical complications such as screw loosening or fracture, abutment, or implant fracture.[35, 36] The introduction of CAD/CAM technology has made it possible to have better fit and less distortion of the framework superstructure.[37, 38]

Digital impression

Advancement in digital dentistry has led to better and easier communication between the clinician and the technician. One of the important advantages of digital technology is that it allows digital impressions to be taken. Digital impression can be taken using an intra-oral scanner (IOS) instead of the conventional impression technique. It also reduces impression distortion and allows 3D previsualization of the preparation. Another advantage is the reduction in cost compared to the materials that are used to fabricate conventional stone models [4]. According to a previous study, patients find digital impression the most preferred and effective technique for taking impressions as they found it more comfortable. [1] The IOS transfers intraoral images into a digital format called standard tessellation language (STL) file. This format can be used to produce a virtual cast, or it can be used to fabricate a physical cast by means of additive or subtractive methods (3D printing and milling respectively). The STL can be stored electronically and thus eliminate the need for space for storage, allowing the record to be safe and easy to be accessed if needed in the future.[39-48]

Lee compared the digital implant impression versus conventional impression in an in-vitro study for a single tooth replacement. He concluded that the accuracy milled cast from digital scan was comparable to the stone cast and can be applied in clinical practice.[49] Seelbach, Brueckel, and Wostmann in an in vitro study compared digital vs. conventional impressions of a prepared tooth, and the results showed that a prosthesis fabricated from a digital impression had similar accuracy to a prosthesis fabricated using conventional impression techniques.[50] Joda and Bragger concluded that it was more time efficient to fabricate a single implant crown using the digital workflow.[6, 51-53] total treatment time for the patient was less, predictable clinical fit of the fabricated implant crown with little to no minor occlusal adjustments. Another study compared the accuracy of conventional impression versus digital impression in restoring 2 implants with a 3-unit FPD in the mandible where the implants diverged at different angles (0, 15, 30, 400) by creating 4 different casts. The authors concluded that milled casts from digital impressions were less accurate than stone casts from the conventional impressions when angulation between the implant was 0 or 15.[36] Another in-vitro study [54] compared the passivity of fit of a 3-unit implant-supported FPD in the mandible between conventional impressions and stone casts to digital impressions and printed casts. The results showed that digital impressions and printed casts had significantly lower levels of strain than the FPDs fabricated conventionally but were not as precise as the conventional FPDs. Regarding completely edentulous patients, Vandeweghe et al. [55] conducted an in-vitro study to compare the accuracy of conventional vs. digital impressions using 4 intra-oral scanners to take impressions of multiple implants of an edentulous jaw. The reference group was taken using a highly accurate lab scanner. The 4 groups' accuracy was measured with respect to trueness and precision using metrology software. The results demonstrated that 2 intra-oral scanners (3M True Definition and Trios) were the most accurate for full arch implant impressions.

Papaspyridakos et al. [56] conducted another in-vitro study to compare the accuracy of digital and conventional impressions for completely edentulous patients with 5 implants at 2 different levels (implant and abutment). The authors concluded that digital impressions were nearly as accurate as conventional impressions. Further, their accuracy could be improved by using the conventional technique to splint with an implant-level impression. However, there was no difference between splinted and non-splinted impressions at the abutment level. In 2017 Amin et al. [57] carried out an in-vitro study to compare the accuracy of conventional vs. digital impressions for a full arch, and concluded that impressions with the True Definition scanner and Omnicam were significantly more accurate than conventional impressions with the splinted open tray technique.

Desktop scanners, IOS from TRIOS and True Definition have been studied and demonstrated similar accuracy to conventional impressions in both completely and partially edentulous implant cases. By that it provides an alternative to the conventional approach.[58]

3D printing:

Prosthodontists today can take impressions conventionally to make a physical master cast or they can take them digitally using an intra-oral scanner to make an STL file that can be converted to a physical cast by milling or 3D printing. As previously mentioned, the introduction of CAD/CAM made it possible to create a framework superstructure with less distortion and better fit to the master cast. The master cast can be manufactured with subtractive or additive processes. CAD/CAM technology incorporates three steps. The first is data acquisition using a desktop scanner to scan the patient's physical cast or an IOS. The second step is to transfer the STL file to the CAD software to design the needed object virtually. The third and last step is to export the STL file of the designed object into the CAM element which will fabricate the final product either by subtractive or additive methods.[59, 60] It is crucial to understand the difference between the two methods of manufacturing as well as the limitations of each.

The subtractive method of manufacturing involves milling or cutting a block of material to achieve the desired geometry with aspects controlled by the computer program. This manufacturing method is associated with excessive waste because more material is removed compared to the final product. Another limitation which is the restricted quantity of restoration that be fabricated per a milling session.[60, 61]

Additive manufacturing, also called rapid prototyping or 3D printing, has gained a lot of popularity in the last 5-7 years. The first 3D printed object goes back to the 1983s when Charles W. Hull invented the stereolithography or 3D printing.[62] He defined it as making a solid object by successively printing thin layers of ultraviolet curable material on top of one another. The 3D structures designed with the support of CAD. The additive manufacturing method has the advantage of reducing waste material while having the ability to produce fine and accurate details.[63] These advantages make 3D printing very useful in implant prosthodontics because it facilitates a quick and simple method for printing surgical guides, casts, or restorations. [64, 65]

It should be clearly understood that the 3D printing methods vary in relation to the technology used for printing. Currently what is used for dental application are the stereolithography (SLA), Digital Light Processing (DLP), Fused deposition modeling (FDM), Selective electron beam melting (SEBM), and Inkjet printing or Photopolymer jetting (MJ or PPJ) [60]. Each technology and printer have its own manufacturer's recommendation for post processing steps.

The transmitted curing light to the resin in the SLA & DLP are different but both have the same printing technique.[63, 66] The SLA printer projects a selectively fast moving and powerful ultraviolet (UV) laser beam into a filled vat with photosensitive liquid resin to build each layer of the object. After light curing of each layer the building platform raises gradually to allow the formation of the following layers. In the DLP printers the light curing differs from the SLA by projecting a silhouette of complete layer across the entire platform and cure it with a single flash of light which result in fast printing.[63, 66] The Fused Deposition Modeling (FDM) is an extrusion type of 3D printer which is less popular, A thermoplastic material are drawn through nozzle. In this nozzle its exposed to heat and then it melts and deposited layer by layer on the building platform. The speed and accuracy of this method is low compared to the other techniques and the material nozzle thickness will determine the quality of the final model. [63]

Selective electron beam melting (SEBM), this technology works with manufacturing parts by melting metal powder layer on top of the layer by an electron beam. This electron beam is created by heating a tungsten filament and directing the beam using a magnetic field. As the use of electrons has high energy than the light. The final produced parts are dense, void free and very strong. This technology has become very popular among other specialties such as maxillofacial and orthopedic surgery for construction of customized implants.[60]

Polyjet Printing (PP) or Photopolymer Material Jetting Printing (MJ or MJP), this technology selects a liquid resin to be jetted out of hundred nozzles, then it polymerize it with a UV light. As to the selective nature of this technique different properties can be designed using a variation in color or building material.[63, 65]

In 2014 a new 3D printing technology was invented by Joseph DeSimone, it was called as Continuous Liquid Interface Production (CLIP), this CLIP technology works by generating a light with continuous UV images from a digital projector through an oxygen-permeable, UV-transparent window below a liquid resin bath. It has a dead zone created above the window which maintains a liquid interface below the part. Above the dead zone, the curing part is drawn out of the resin bath. Using the CLIP 3D printing technology makes printing very fast and the final product can have a smooth-sided solid object of a wide variety of shapes using resins.

The accuracy of 3D printed models has been compared to that of conventional models in several studies. George et al. performed an in-vitro study to investigate the accumulation of errors in the digital workflow beginning from scanning to finishing by fabricating the prosthetic restoration. They concluded that there was no variation attributable to the software and scanner, but milled models from the software and scanner differed significantly [67].

In an in-vitro study, Alshawaf et al.[68] compared the 3D accuracy of stone casts and printed casts from conventional and digital impressions, respectively, for a partially edentulous patient. The authors concluded from the results that printed casts from digital impressions were less accurate than the conventional stone casts. However, because of the lack of sufficient evidence, the authors suggested that the accuracy of full-arch implant printed models generated from digital impressions vs. conventional stone casts fabricated with conventional impression techniques requires further study. Patzelt et al. [69] compared the accuracy of full-arch physical casts obtained from 3 different types of intra-oral scanners and fabricated by milling or stereolithography (SLA). Their results showed that physical casts produced by SLA were more accurate than milled casts.

Regarding published studies about completely edentulous patients, the number of such studies is still small regarding the accuracy of printed models. In a recent study, Revilla-Leon et al.[70] compared the accuracy of implant analogs' position on conventional dental stone casts to 4 different types of 3D printed models (additive processing). A Coordinate Measuring Machine (CMM) was used to measure the distortion and correct position for each system in the x-, y- and z-planes. The authors concluded that the direct light processing-DLP and multijet printing-MJP systems showed similar results to conventional dental stone CDS. In 2020, Revilla-Leon et al.[65] published another study about the accuracy regarding the implant replica position on the additive manufactured casts for a completely edentulous arch. The study compared the accuracy of conventional casts to a material jetting additive manufacturing (AM) technology using CMM. The author concluded that the AM technology demonstrated an accurate duplication with no significant difference in precision and trueness values of the implant replica position when compared to the conventional cast.

To the author's knowledge, there are no comparative studies for the dimensional stability of printed casts over time. Particularly given that the printed models are set after light curing, which is part of the post-processing stage, we do not know whether there are any dimensional changes over time. Therefore, it would be very beneficial clinically to investigate the dimensional stability of printed casts over time for a completely edentulous arch with implants.

Aim and Hypotheses:

Aim:

The aim of this in-vitro study was to evaluate and compare the dimensional stability over time of the 3D printed models from 3 different printers (SLA, CLIP & DLP).

Hypothesis:

1- The printed models from a SLA printer are dimensionally more stable over time than the printed models from a DLP printer or CLIP printer for a completely edentulous arch.

2- The 3D printed models are more dimensionally stable at the later time points as compared to the earlier time points.

MATERIAL AND METHODS:

A completely edentulous mandibular cast with four abutment level implant analogs (RC, Straumann, Repositionable Analog for SR Abut. Ø4.6mm) with adequate antero-posterior (AP) spread was fabricated to simulate the routinely occurring clinical situation of a completely edentulous mandible restored with an implant supported prosthesis. The difference in angulation between the 4 implants was under 20° providing an acceptable clinical condition. The approximate locations of the implants were #19, 22, 27 and 29. Three notches were made on the master cast. The cast served as the master cast (Figure 1). The master cast was digitized using a lab scanner and scan bodies (CARES® Mono Scan body SRA Ø 4.6 mm) to have the master cast as an STL file (Figure 2). From this STL file of the master cast, three groups were prepared and evaluated: Bego printer group, Carbon printer group and Formlab printer group (Figure 3). A flowchart of the study is illustrated in Figure 4.

Group 1: 3D Printed casts using the Bego printer (DLP):

The STL file of master cast from the lab scanner was used to print 12 solid casts in polyurethane models using stereolithography (DLP) technology. The printed casts had a space to fit the 4 implant replicas (Repositionable Analog for SR Abut. Ø4.6mm).

Group 2: 3D Printed casts using the Carbon printer (CLIP):

The STL file of master cast from the lab scanner was used to print 12 solid casts in polyurethane models using stereolithography (CLIP) technology. The printed casts had a space to fit the 4 implant replicas (Repositionable Analog for SR Abut. Ø4.6mm).

Group 3: 3D Printed casts using the Formlab printer (SLA):

The STL file of master cast from the lab scanner was used to print 12 solid casts in polyurethane models using stereolithography (SLA) technology. The printed casts had a space to fit the 4 implant replicas (Repositionable Analog for SR Abut. Ø4.6mm).

The Varseo printer only allows for one model to be printed at a time, whereas the Carbon allows for three and the Formlab can allow up to four models to be printed at the same time given that the models are placed horizontally on the build platform. In this study, all models were placed horizontally on the build platform in the nesting software for each printer, and the models were printed one at time for Varseo, three at a time with the Carbon and four at a time for Formlab printers.

The post-printing process was completed according to each printer's manufacturer's recommendation. The process involved washing the printed casts in an ultrasonic highly concentrated (~99%) alcohol bath, followed by curing for a designated amount of time under a set temperature for each printer. Lastly, abutment-level repositionable implant analogues (RC, Straumann) were fitted into all of the printed models and fixed into place using cyanoacrylate adhesive allowing them to be used as working casts (Figure 5).

Digitizing the casts from the three groups:

All of the 3D printed models from the three groups were digitized for comparison using a high resolution reference scanner (Activity 880 scanner; Smart Optics, Bochum, Germany) (Figure 6). This reference scanner can capture pictures and transform them to a 3-D image using a white light camera.

Polyetheretherketone (PEEK) scan bodies (CARES® Mono Scan body SRA ∅ 4.6 mm) were connected to the implant replicas (Repositionable Analog for SR Abut. Ø4.6mm) on the first test model and hand-tightened, then scanned with the digital scanner. The scan bodies (CARES® Mono Scan body SRA ∅ 4.6 mm) were transferred from the 1st model to the 2nd model for scanning. This process was repeated for all 12 casts in each of the groups. To eliminate and minimize any error associated with the scan bodies (CARES® Mono Scan body SRA ∅ 4.6 mm), for every scan the scan body was transferred from their position in model 1 to the same implant replica (Repositionable Analog for SR Abut. Ø4.6mm) in the other models of each group in order. Models were labeled randomly before scanning. One operator performed all of the scanning to calibrate the procedure, and the STL digital files were saved.

Dimensional stability of the printed models:

The 3D printed models from the three groups were scanned and measured using the same lab scanner at different time points (2 days, 6 days, 10 days, 14 days & 18 days). All 3D printed models were put in a box and stored in an air-conditioned laboratory.

STL superimposition procedures:

Using the inspection software (Geomagic Control 2020, 3D systems), the STL datasets of each model of each group were superimposed to the STL file of the previous scan. The STL file which was taken at day 2 was superimposed to the STL file of day 0, the STL file which was taken at day 6 was superimposed to the STL file of day 2, and so on. The STL superimposition for each pair of STL's began with "initial alignment," then with the "best-fit alignment" and finalized with the "3D compare" function. The difference was expressed as the Root Mean Square (RMS) deviation, which was obtained by the Geomagic software (Figure 7-9).

Power calculation:

A power calculation was conducted using the software nQuery Advisor (v. 7.0). The effect size for this calculation was based on a pilot study with a sample size of n = 5 observations per printer, using the scan from the previous time point as the reference. Based on the effect size observed in the pilot study, the calculation determined that a sample size of n = 12 per printer was sufficient to obtain power greater than 99% to detect a difference between printers, as well as power greater than 99% to detect a difference between time points, alongside a Type I error rate of $\alpha = 0.05$.

Statistical analysis:

Descriptive statistics (mean and standard deviation of RMS deviation) were calculated for each combination of printer and time point, as well as for each printer (pooling the data from different time points), each time point (pooling the data from different printers), and over the entire sample (pooling the data from different time points and printers). A mixed-effects model was used in the analysis due to the presence of multiple observations for each model (i.e., the presence of measurements at 2, 6, 10, 14, and 18 days for each model). The analysis was carried out using the PROC MIXED procedure in SAS, with RMS deviation defined as the outcome variable and printer and time point as the two factors. Post-hoc comparisons were performed for factors exhibiting a statistically significant global test; the Bonferroni correction was used for such post-hoc comparisons. The significance level was set at $\alpha = 0.05$, with the exception of tests in which the Bonferroni correction was used. **SAS® 9.4** (SAS Institute Inc., Cary, NC, USA) was used in the analysis.

RESULTS:

Table 1 shows descriptive statistics (mean and standard deviation) of RMS deviation for each combination of printer and time point. When pooling the data from the different time points, the Formlab printer had the lowest mean value of 9.85 µm (SD=2.27 µm), followed by the Carbon printer group with a mean of 12.73 µm (SD=1.97 µm). The Bego printer group had the highest mean value of 14.57 µm (SD=3.01 µm) (Table 2). When pooling the data from the different printers, the highest mean value was at 2 days, and the lowest mean value was at 18 days. The mean decreased from each time point to each subsequent time point (Table 3).

With regard to the results of the mixed-effects model, the global tests for the two factors showed that the difference between time points was not statistically significant ($p = 0.109$), but the difference between printers was statistically significant ($p < 0.001$) (Tables 2-3). Therefore, post-hoc tests comparing the printers were conducted. The Bonferroni correction was applied for the post-hoc tests; hence, the significance level was set at $\alpha = 0.05 / 3 \approx 0.0167$. All three post-hoc tests were statistically significant: Bego vs. Carbon ($p = 0.002$), Bego vs. Formlab ($p < 0.001$), and Carbon vs. Formlab ($p < 0.001$).

DISCUSSION

In implant prosthodontics, digital technology has expanded and altered the treatment approach and workflow. Even so, there is a lack of literature investigating the dimensional stability of 3D printed models over time of a completely edentulous patient. Consequently, this study was designed with the objective of observing the dimensional stability of the 3D printed models generated from an STL file obtained by digitizing a master model using a desktop scanner (Activity) over time. In this study three printers were used to print a 3D model: Bego, Carbon and Formlab. The 3D printing technology in the Bego printer was DLP, in the Carbon printer was CLIP and in the Formlab printer SLA technology was used. The inspection software Geomagic was used to assess the dimensional stability of the printed models by scanning each model at a different time point and comparing each scan to the previous one to see if there had been any dimensional change. The selected surface matching software can calculate and give different parameters such as RMS deviation, which is used to quantify the magnitude of deviation between 2 different 3D data sets. The lower the RMS deviation, the higher the 3D concordance of the 2 superimposed files.

The Formlab printer had the lowest mean RMS deviation value of 9.85 µm (SD=2.27 µm), showing significantly better dimensional stability than both the Bego printer 14.57 µm (SD=3.01 µm) and the Carbon printer 12.73 µm (SD=1.97 µm). Additionally, the Carbon printer showed significantly better dimensional stability than the Bego printer. This result was in accordance with our first hypothesis, as it demonstrated that 3D printed models from the Formlab printer (SLA) were dimensionally more stable than the 3D printed models from the Carbon (CLIP) and Bego (DLP) printers.

Many factors should be considered when assessing the different printers in terms of dimensional stability. First, the speed of printing and the number of models each printer can print at one time. The Carbon was fastest in printing with 3 models, followed by the Formlab with 3 models and lastly the Bego with only one model as the slowest among the 3 printers. Second is the orientation of printing or building angle of the model. It has an important influence on the printing time and on the mechanical properties.

In 2016 a study was published regarding the effects of building orientation on mechanical properties.[71] The authors compared two groups; one group was printed in a horizontal orientation so that the layers were parallel to the load direction, and the other group was printed in a vertical orientation with the layers perpendicular to the load direction. In this in-vitro study the authors concluded that vertically 3D-printed specimens with layers oriented perpendicular to the load direction have improved mechanical properties.[71] If we have to compare that with our study, then by printing the models horizontally the layers orientation will be perpendicular to the load of direction which will give the model an improved mechanical property.

Another factor is the resolution of the 3D printer, mainly its ability to replicate the finest detail. [63] The resolution is defined by x, y, and z axis in µm. The layer thickness usually corresponds to the z axis usually preset by the printer's manufacturer. Therefore, the determining factor that influences the accuracy is the XY resolution, and it can be different from one printer and printing technology to another. In our study we included one DLP (Bego) printer, one CLIP (Carbon) printer and one SLA (Formlab) printer. The resolution of the printers was 50µm for the Bego, 25µm for the Formlab and 25 µm for the Carbon printer. Based on the manufacturer's information the resolution can be adjusted to 50 and 100 µm if needed.

The type of resin and the post-printing process steps are important factors that can affect the dimensional stability of the printed model. In a study published in 2019[72], the authors evaluated the dimensional stability, accuracy, and reproducibility of the surgical guides for a long span partially edentulous patient. The three groups included in the study used 3 different additive manufacturing technologies. They used 2 different time points, one being the first 36 hours from production and the other after 1 month. It was mentioned that the high printing resolution and small printing layer thickness might be the explanation for the higher accuracy and reproducibility of the Polyjet 3D printer which could influence the dimensional stability as well. Adding to that the post-printing processing to allow for complete polymerization for any residual resin initiator in the SLA printer. which was not needed based on the manufacturer's recommendation for the Polyjet 3D printer. Spraying the surgical guides with antiglare spray before scanning might have some influence on the total results because the thickness can be difficult to control. The results showed that the 3D printed surgical guides from the Polyjet 3D printer showed better accuracy and reproducibility than the SLA 3D printer. After one month the surgical guides showed reduced accuracy from both printers. The authors[72] did not mention any information in the conclusion about the dimensional stability results, but they suggested in their discussion a further investigation should be carried out in regard to the dimensional stability of the 3D printed model. In this in-vitro study, post print processing was done according to the manufacturer's instruction. And the same with the resin, we used the one which was following the manufacturer's recommendation to minimize error.

Many published studies have evaluated the accuracy of 3D scanners. Son et al.[73]evaluated the accuracy of 3D dental scanners. They used desktop scanners and intraoral scanners. They concluded that intraoral scanners tend to show decreased accuracy from the anterior to the posterior of the scanned arch. In this study we used a desktop scanner, the desktop scanner (Activity 880 scanner) had a precision of 10 μm after calibration. This precision was verified previously in 2017 by Amine et al.[57] More effort was spent to minimize errors and standardize the steps including the following:

- One desktop scanner (Activity 880 scanner) was used to digitize all the printed models in an effort to eliminate the scanner effect.
- All of the laboratory work, including preparation of the master cast, digitization of the 3D printed models, working on the inspection software and completing all the superimposition in the Geomagic program was completed by a single operator.
- Locating notches were placed on the master cast.
- The same sequence and technique when scanning the models was used.
- The same scan bodies were used for all models. They were transferred from one model to the next model, with the same position of the implant on each model.

Limitations:

Using a desktop scanner in a laboratory setting is different than when using an intraoral scanner, thus eliminating factors such as space issue, saliva, location of the implants and surrounding soft tissue, which can affect the quality and accuracy of digital impression. The clinical scenario was only representing a completely edentulous mandible with four abutment level implants with a divergence less than 20 degree.

Clinical implications:

The 3D printed models which were fabricated from STL files in the Formlab printer showed the least RMS deviation, followed by the Carbon printer and then the Bego printer. The study investigated the clinical scenario of an edentulous mandible with four implants at the abutment level. The results indicated that a 3D printed model can be used to fabricate an implant supported prosthesis. Previous studies has shown with numbers the clinically acceptable fit of the implant fixed supported prosthesis. Further studies and investigation are needed to assess the dimensional stability of the 3D printed models for a longer period of time.

Conclusion:

Within the limitations of this in-vitro study, the following conclusions can be drawn:

I. The 3D printed models from the Bego 3D printer showed less dimensional stability than the Carbon printer, which showed less dimensional stability than the Formlab 3D printer.

II. Although the time points showed an increase in the dimensional stability of the 3D printed models up to 18 days, there was no significant evidence of differences among time points. Further investigation is needed to evaluate these changes over a longer period of time.

REFERNCES:

1. Lee SJ, Gallucci GO. Digital vs. conventional implant impressions: efficiency outcomes. *Clin Oral Implants Res*. Jan 2013;24(1):111-5. doi:10.1111/j.1600-0501.2012.02430.x
2. Mangano Guest Editor F. Digital Dentistry: The Revolution has Begun. *Open Dent J*. 2018;12:59-60. doi:10.2174/1874210601812010059
3. Liu PR, Essig ME. Panorama of dental CAD/CAM restorative systems. *Compend Contin Educ Dent*. Oct 2008;29(8):482, 484, 486-8 passim.
4. Strub JR, Rekow ED, Witkowski S. Computer-aided design and fabrication of dental restorations: current systems and future possibilities. *J Am Dent Assoc*. Sep 2006;137(9):1289-96.
5. Schepke U, Meijer HJ, Kerdijk W, Cune MS. Digital versus analog complete-arch impressions for single-unit premolar implant crowns: Operating time and patient preference. *J Prosthet Dent*. Sep 2015;114(3):403-6 e1. doi:10.1016/j.prosdent.2015.04.003
6. Joda T, Bragger U. Time-Efficiency Analysis Comparing Digital and Conventional Workflows for Implant Crowns: A Prospective Clinical Crossover Trial. *Int J Oral Maxillofac Implants*. Sep-Oct 2015;30(5):1047-53. doi:10.11607/jomi.3963
7. Sarment DP, Sukovic P, Clinthorne N. Accuracy of implant placement with a stereolithographic surgical guide. *Int J Oral Maxillofac Implants*. Jul-Aug 2003;18(4):571-7.
8. Jemt T, Hjalmarsson L. In vitro measurements of precision of fit of implant-supported frameworks. A comparison between "virtual" and "physical" assessments of fit using two different techniques of measurements. *Clin Implant Dent Relat Res*. May 2012;14 Suppl 1:e175-82. doi:10.1111/j.1708-8208.2011.00416.x
9. Papaspyridakos P, Lal K. Computer-assisted design/computer-assisted manufacturing zirconia implant fixed complete prostheses: clinical results and technical complications up to 4 years of function. *Clin Oral Implants Res*. Jun 2013;24(6):659-65. doi:10.1111/j.1600-0501.2012.02447.x
10. Abduo J, Lyons K, Bennani V, Waddell N, Swain M. Fit of screw-retained fixed implant frameworks fabricated by different methods: a systematic review. *Int J Prosthodont*. May-Jun 2011;24(3):207-20.

11. Buzayan MM, Yunus NB. Passive Fit in Screw Retained Multi-unit Implant Prosthesis Understanding and Achieving: A Review of the Literature. *J Indian Prosthodont Soc*. Mar 2014;14(1):16-23. doi:10.1007/s13191-013-0343-x
12. Katsoulis J, Takeichi T, Sol Gaviria A, Peter L, Katsoulis K. Misfit of implant prostheses and its impact on clinical outcomes. Definition, assessment and a systematic review of the literature. *Eur J Oral Implantol*. 2017;10 Suppl 1:121-138.
13. Karl M, Taylor TD. Bone Adaptation Induced by Non-Passively Fitting Implant Superstructures: A Randomized Clinical Trial. *Int J Oral Maxillofac Implants*. Mar-Apr 2016;31(2):369-75. doi:10.11607/jomi.4331
14. Chen CJ, Papaspyridakos P, Guze K, Singh M, Weber HP, Gallucci GO. Effect of misfit of cement-retained implant single crowns on crestal bone changes. *Int J Prosthodont*. Mar-Apr 2013;26(2):135-7. doi:10.11607/ijp.3137
15. Jemt T, Book K. Prosthesis misfit and marginal bone loss in edentulous implant patients. *Int J Oral Maxillofac Implants*. Sep-Oct 1996;11(5):620-5.
16. Abduo J, Bennani V, Waddell N, Lyons K, Swain M. Assessing the fit of implant fixed prostheses: a critical review. *Int J Oral Maxillofac Implants*. May-Jun 2010;25(3):506-15.
17. Al Quran FA, Rashdan BA, Zomar AA, Weiner S. Passive fit and accuracy of three dental implant impression techniques. *Quintessence Int*. Feb 2012;43(2):119-25.
18. Sahin S, Cehreli MC. The significance of passive framework fit in implant prosthodontics: current status. *Implant Dent*. 2001;10(2):85-92. doi:10.1097/00008505-200104000-00003
19. Wee AG, Aquilino SA, Schneider RL. Strategies to achieve fit in implant prosthodontics: a review of the literature. *Int J Prosthodont*. Mar-Apr 1999;12(2):167-78.
20. Akalin ZF, Ozkan YK, Ekerim A. Effects of implant angulation, impression material, and variation in arch curvature width on implant transfer model accuracy. *Int J Oral Maxillofac Implants*. Jan-Feb 2013;28(1):149-57. doi:10.11607/jomi.2070
21. Gibbs SB, Versluis A, Tantbirojn D, Ahuja S. Comparison of polymerization shrinkage of pattern resins. *J Prosthet Dent*. Aug 2014;112(2):293-8. doi:10.1016/j.prosdent.2014.02.006
22. Hariharan R, Shankar C, Rajan M, Baig MR, Azhagarasan NS. Evaluation of accuracy of multiple dental implant impressions using various splinting materials. *Int J Oral Maxillofac Implants*. Jan-Feb 2010;25(1):38-44.
23. Rashidan N, Alikhasi M, Samadizadeh S, Beyabanaki E, Kharazifard MJ. Accuracy of implant impressions with different impression coping types and

shapes. *Clin Implant Dent Relat Res*. Apr 2012;14(2):218-25. doi:10.1111/j.1708-8208.2009.00241.x

24. Sorrentino R, Gherlone EF, Calesini G, Zarone F. Effect of implant angulation, connection length, and impression material on the dimensional accuracy of implant impressions: an in vitro comparative study. *Clin Implant Dent Relat Res*. May 2010;12 Suppl 1:e63-76. doi:10.1111/j.1708-8208.2009.00167.x
25. Burns J, Palmer R, Howe L, Wilson R. Accuracy of open tray implant impressions: an in vitro comparison of stock versus custom trays. *J Prosthet Dent*. Mar 2003;89(3):250-5. doi:10.1067/mpr.2003.38
26. Carr AB. Comparison of impression techniques for a five-implant mandibular model. *Int J Oral Maxillofac Implants*. Winter 1991;6(4):448-55.
27. Ongul D, Gokcen-Rohlig B, Sermet B, Keskin H. A comparative analysis of the accuracy of different direct impression techniques for multiple implants. *Aust Dent J*. Jun 2012;57(2):184-9. doi:10.1111/j.1834-7819.2012.01685.x
28. Mostafa TM, Elgendy MN, Kashef NA, Halim MM. Evaluation of the precision of three implant transfer impression techniques using two elastomeric impression materials. *Int J Prosthodont*. Nov-Dec 2010;23(6):525-8.
29. Ebadian B, Rismanchian M, Dastgheib B, Bajoghli F. Effect of different impression materials and techniques on the dimensional accuracy of implant definitive casts. *Dent Res J (Isfahan)*. Mar-Apr 2015;12(2):136-43.
30. Balouch F, Jalalian E, Nikkheslat M, et al. Comparison of Dimensional Accuracy between Open-Tray and Closed-Tray Implant Impression Technique in 15° Angled Implants. *J Dent (Shiraz)*. Sep 2013;14(3):96-102.
31. Papaspyridakos P, Chen CJ, Gallucci GO, Doukoudakis A, Weber HP, Chronopoulos V. Accuracy of implant impressions for partially and completely edentulous patients: a systematic review. *Int J Oral Maxillofac Implants*. Jul-Aug 2014;29(4):836-45. doi:10.11607/jomi.3625
32. Stimmelmayr M, Beuer F, Edelhoff D, Guth JF. Implant Impression Techniques for the Edentulous Jaw: A Summary of Three Studies. *J Prosthodont*. Feb 2016;25(2):146-50. doi:10.1111/jopr.12305
33. Thalji G, Bryington M, De Kok IJ, Cooper LF. Prosthodontic management of implant therapy. *Dent Clin North Am*. Jan 2014;58(1):207-25. doi:10.1016/j.cden.2013.09.007
34. Haselhuhn K, Marotti J, Tortamano P, Weiss C, Suleiman L, Wolfart S. Assessment of the stress transmitted to dental implants connected to screw-retained bars using different casting techniques. *J Oral Implantol*. Dec 2014;40(6):641-8. doi:10.1563/aaid-joi-d-12-00029
35. Vere J, Bhakta S, Patel R. Prosthodontic complications associated with implant retained crowns and bridgework: a review of the literature. *Br Dent J*. Mar 23 2012;212(6):267-72. doi:10.1038/sj.bdj.2012.225

36. Lin WS, Harris BT, Elathamna EN, Abdel-Azim T, Morton D. Effect of implant divergence on the accuracy of definitive casts created from traditional and digital implant-level impressions: an in vitro comparative study. *Int J Oral Maxillofac Implants*. Jan-Feb 2015;30(1):102-9. doi:10.11607/jomi.3592

37. de Franca DG, Morais MH, das Neves FD, Barbosa GA. Influence of CAD/CAM on the fit accuracy of implant-supported zirconia and cobalt-chromium fixed dental prostheses. *J Prosthet Dent*. Jan 2015;113(1):22-8. doi:10.1016/j.prosdent.2014.07.010

38. Drago C, Saldarriaga RL, Domagala D, Almasri R. Volumetric determination of the amount of misfit in CAD/CAM and cast implant frameworks: a multicenter laboratory study. *Int J Oral Maxillofac Implants*. Sep-Oct 2010;25(5):920-9.

39. Chew AA, Esguerra RJ, Teoh KH, Wong KM, Ng SD, Tan KB. Three-Dimensional Accuracy of Digital Implant Impressions: Effects of Different Scanners and Implant Level. *Int J Oral Maxillofac Implants*. Jan/Feb 2017;32(1):70-80. doi:10.11607/jomi.4942

40. Chochlidakis K, Papaspyridakos P, Tsigarida A, et al. Digital Versus Conventional Full-Arch Implant Impressions: A Prospective Study on 16 Edentulous Maxillae. *J Prosthodont*. Apr 2020;29(4):281-286. doi:10.1111/jopr.13162

41. Jiang X, Lin Y, Cui HY, Di P. Immediate loading of multiple splinted implants via complete digital workflow: A pilot clinical study with 1-year follow-up. *Clin Implant Dent Relat Res*. Jun 2019;21(3):446-453. doi:10.1111/cid.12781

42. Joda T, Ferrari M, Gallucci GO, Wittneben JG, Bragger U. Digital technology in fixed implant prosthodontics. *Periodontol 2000*. Feb 2017;73(1):178-192. doi:10.1111/prd.12164

43. Marghalani A, Weber HP, Finkelman M, Kudara Y, El Rafie K, Papaspyridakos P. Digital versus conventional implant impressions for partially edentulous arches: An evaluation of accuracy. *J Prosthet Dent*. Apr 2018;119(4):574-579. doi:10.1016/j.prosdent.2017.07.002

44. Joda T, Bragger U, Zitzmann NU. CAD/CAM implant crowns in a digital workflow: Five-year follow-up of a prospective clinical trial. *Clin Implant Dent Relat Res*. Feb 2019;21(1):169-174. doi:10.1111/cid.12681

45. Alsharbaty MHM, Alikhasi M, Zarrati S, Shamshiri AR. A Clinical Comparative Study of 3-Dimensional Accuracy between Digital and Conventional Implant Impression Techniques. *J Prosthodont*. Apr 2019;28(4):e902-e908. doi:10.1111/jopr.12764

46. Menini M, Setti P, Pera F, Pera P, Pesce P. Accuracy of multi-unit implant impression: traditional techniques versus a digital procedure. *Clin Oral Investig*. Apr 2018;22(3):1253-1262. doi:10.1007/s00784-017-2217-9

47. Papaspyridakos P, Hirayama H, Chen CJ, Ho CH, Chronopoulos V, Weber HP. Full-arch implant fixed prostheses: a comparative study on the effect of connection type and impression technique on accuracy of fit. *Clin Oral Implants Res*. Sep 2016;27(9):1099-105. doi:10.1111/clr.12695

48. Papaspyridakos P, Kang K, DeFuria C, Amin S, Kudara Y, Weber HP. Digital workflow in full-arch implant rehabilitation with segmented minimally veneered monolithic zirconia fixed dental prostheses: 2-year clinical follow-up. *J Esthet Restor Dent*. Jan 2018;30(1):5-13. doi:10.1111/jerd.12323

49. Lee SJ, Betensky RA, Gianneschi GE, Gallucci GO. Accuracy of digital versus conventional implant impressions. *Clin Oral Implants Res*. Jun 2015;26(6):715-9. doi:10.1111/clr.12375

50. Seelbach P, Brueckel C, Wostmann B. Accuracy of digital and conventional impression techniques and workflow. *Clin Oral Investig*. Sep 2013;17(7):1759-64. doi:10.1007/s00784-012-0864-4

51. Joda T, Bragger U. Patient-centered outcomes comparing digital and conventional implant impression procedures: a randomized crossover trial. *Clin Oral Implants Res*. Dec 2016;27(12):e185-e189. doi:10.1111/clr.12600

52. Joda T, Bragger U. Time-efficiency analysis of the treatment with monolithic implant crowns in a digital workflow: a randomized controlled trial. *Clin Oral Implants Res*. Nov 2016;27(11):1401-1406. doi:10.1111/clr.12753

53. Joda T, Katsoulis J, Bragger U. Clinical Fitting and Adjustment Time for Implant-Supported Crowns Comparing Digital and Conventional Workflows. *Clin Implant Dent Relat Res*. Oct 2016;18(5):946-954. doi:10.1111/cid.12377

54. Karl M, Graef F, Schubinski P, Taylor T. Effect of intraoral scanning on the passivity of fit of implant-supported fixed dental prostheses. *Quintessence Int*. Jul-Aug 2012;43(7):555-62.

55. Vandeweghe S, Vervack V, Dierens M, De Bruyn H. Accuracy of digital impressions of multiple dental implants: an in vitro study. *Clin Oral Implants Res*. Jun 2017;28(6):648-653. doi:10.1111/clr.12853

56. Papaspyridakos P, Gallucci GO, Chen CJ, Hanssen S, Naert I, Vandenberghe B. Digital versus conventional implant impressions for edentulous patients: accuracy outcomes. *Clin Oral Implants Res*. Apr 2016;27(4):465-72. doi:10.1111/clr.12567

57. Amin S, Weber HP, Finkelman M, El Rafie K, Kudara Y, Papaspyridakos P. Digital vs. conventional full-arch implant impressions: a comparative study. *Clin Oral Implants Res*. Nov 2017;28(11):1360-1367. doi:10.1111/clr.12994

58. Rutkunas V, Geciauskaite A, Jegelevicius D, Vaitiekunas M. Accuracy of digital implant impressions with intraoral scanners. A systematic review. *Eur J Oral Implantol*. 2017;10 Suppl 1:101-120.

59. Alghazzawi TF. Advancements in CAD/CAM technology: Options for practical implementation. *J Prosthodont Res*. Apr 2016;60(2):72-84. doi:10.1016/j.jpor.2016.01.003

60. van Noort R. The future of dental devices is digital. *Dent Mater*. Jan 2012;28(1):3-12. doi:10.1016/j.dental.2011.10.014

61. Kessler A, Hickel R, Reymus M. 3D Printing in Dentistry-State of the Art. *Oper Dent*. Jan/Feb 2020;45(1):30-40. doi:10.2341/18-229-l

62. Barazanchi A, Li KC, Al-Amleh B, Lyons K, Waddell JN. Additive Technology: Update on Current Materials and Applications in Dentistry. *J Prosthodont*. Feb 2017;26(2):156-163. doi:10.1111/jopr.12510

63. Revilla-León M, Özcan M. Additive Manufacturing Technologies Used for Processing Polymers: Current Status and Potential Application in Prosthetic Dentistry. *J Prosthodont*. Feb 2019;28(2):146-158. doi:10.1111/jopr.12801

64. Oberoi G, Nitsch S, Edelmayer M, Janjic K, Muller AS, Agis H. 3D Printing-Encompassing the Facets of Dentistry. *Front Bioeng Biotechnol*. 2018;6:172. doi:10.3389/fbioe.2018.00172

65. Revilla-León M, Sadeghpour M, Özcan M. An update on applications of 3D printing technologies used for processing polymers used in implant dentistry. *Odontology*. Jul 2020;108(3):331-338. doi:10.1007/s10266-019-00441-7

66. Quan H, Zhang T, Xu H, Luo S, Nie J, Zhu X. Photo-curing 3D printing technique and its challenges. *Bioact Mater*. Mar 2020;5(1):110-115. doi:10.1016/j.bioactmat.2019.12.003

67. Koch GK, Gallucci GO, Lee SJ. Accuracy in the digital workflow: From data acquisition to the digitally milled cast. *J Prosthet Dent*. Jun 2016;115(6):749-54. doi:10.1016/j.prosdent.2015.12.004

68. Alshawaf B, Weber HP, Finkelman M, El Rafie K, Kudara Y, Papaspyridakos P. Accuracy of printed casts generated from digital implant impressions versus stone casts from conventional implant impressions: A comparative in vitro study. *Clin Oral Implants Res*. Aug 2018;29(8):835-842. doi:10.1111/clr.13297

69. Patzelt SB, Bishti S, Stampf S, Att W. Accuracy of computer-aided design/computer-aided manufacturing-generated dental casts based on intraoral scanner data. *J Am Dent Assoc*. Nov 2014;145(11):1133-40. doi:10.14219/jada.2014.87

70. Revilla-León M, Gonzalez-Martín Ó, Pérez López J, Sánchez-Rubio JL, Özcan M. Position Accuracy of Implant Analogs on 3D Printed Polymer versus Conventional Dental Stone Casts Measured Using a Coordinate Measuring Machine. *J Prosthodont*. Jul 2018;27(6):560-567. doi:10.1111/jopr.12708

71. Alharbi N, Osman R, Wismeijer D. Effects of build direction on the mechanical properties of 3D-printed complete coverage interim dental restorations. *J Prosthet Dent*. Jun 2016;115(6):760-7. doi:10.1016/j.prosdent.2015.12.002

72. Chen L, Lin WS, Polido WD, Eckert GJ, Morton D. Accuracy, reproducibility, and dimensional stability of additively manufactured surgical templates. *J Prosthet Dent*. Sep 2019;122(3):309-314. doi:10.1016/j.prosdent.2019.02.007

73. Son K, Lee KB. Effect of Tooth Types on the Accuracy of Dental 3D Scanners: An In Vitro Study. *Materials (Basel)*. Apr 9 2020;13(7)doi:10.3390/ma13071744

APPENDICES

Appendix A: Tables

Table 1: Mean (standard deviation) of RMS deviation (µm) for each combination of printer and time point (n=12 per combination)

		Time Point (days)				
		2	6	10	14	18
Printer	Bego	15.49 (2.05)	14.94 (1.42)	14.62 (3.56)	14.44 (4.53)	13.35 (2.52)
	Carbon	13.45 (1.80)	13.26 (2.77)	13.01 (1.43)	12.70 (1.21)	11.23 (1.75)
	Formlab	10.20 (2.25)	9.43 (2.56)	9.49 (1.96)	9.57 (2.86)	10.56 (1.67)

Table 2: Mean (standard deviation) of RMS deviation (µm) for each printer, pooling data from the different time points (n=60 per printer) *

Printer	Bego	14.57 (3.01)
	Carbon	12.73 (1.97)
	Formlab	9.85 (2.27)

Total	12.38 (3.12)

* The global test comparing the printers was statistically significant ($p < 0.001$). In post-hoc tests comparing the printers, all tests were statistically significant ($p < 0.05 / 3 \approx 0.0167$).

Table 3: Mean (standard deviation) of RMS deviation (μm) for each time point, pooling data from the different printers (n=36 per time point)*

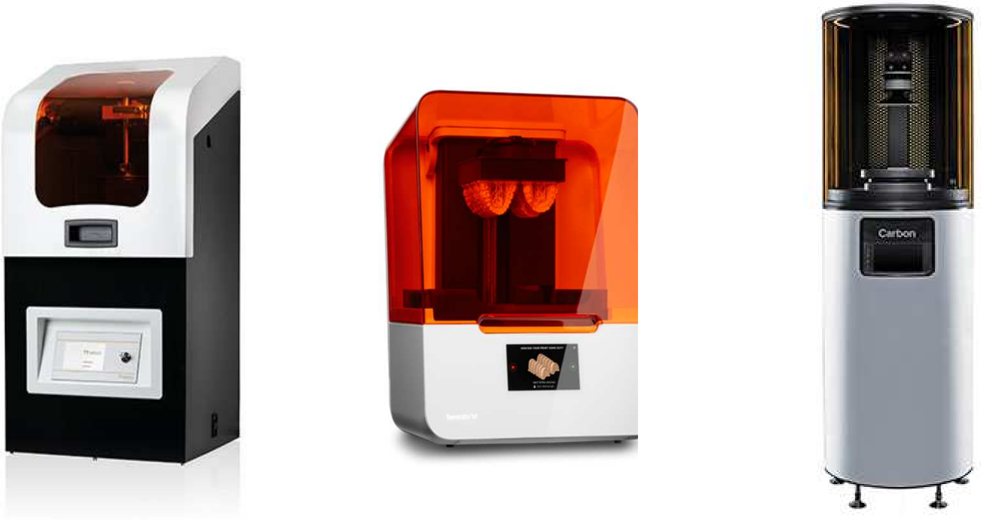
Time Point (days)	2	13.05 (2.97)
	6	12.54 (3.25)
	10	12.37 (3.25)
	14	12.24 (3.70)
	18	11.71 (2.30)
Total		12.38 (3.12)

* The global test comparing the time points was not statistically significant ($p = 0.109$).

Appendix B: Figures

Figure 1. Master cast of an edentulous mandible with four implants with screw-retained abutments (Straumann, SRAs).

Figure 2. Master cast with CARES Mono scan bodies attached to the SRAs prepared for scanning procedure



A B C

Figure 3. The 3D printers used in the study. A = BEGO. B = Formlab 3B by Formlabs, and C = Carbon

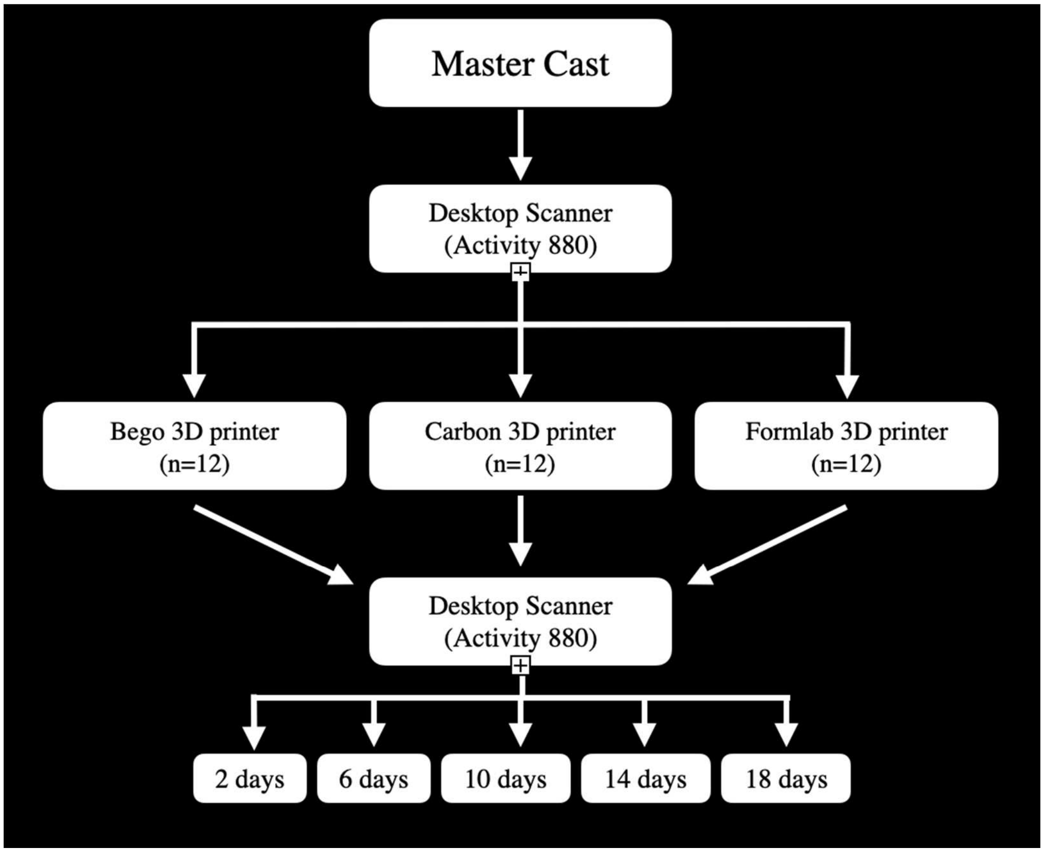


Figure 4. Flowchart of the study

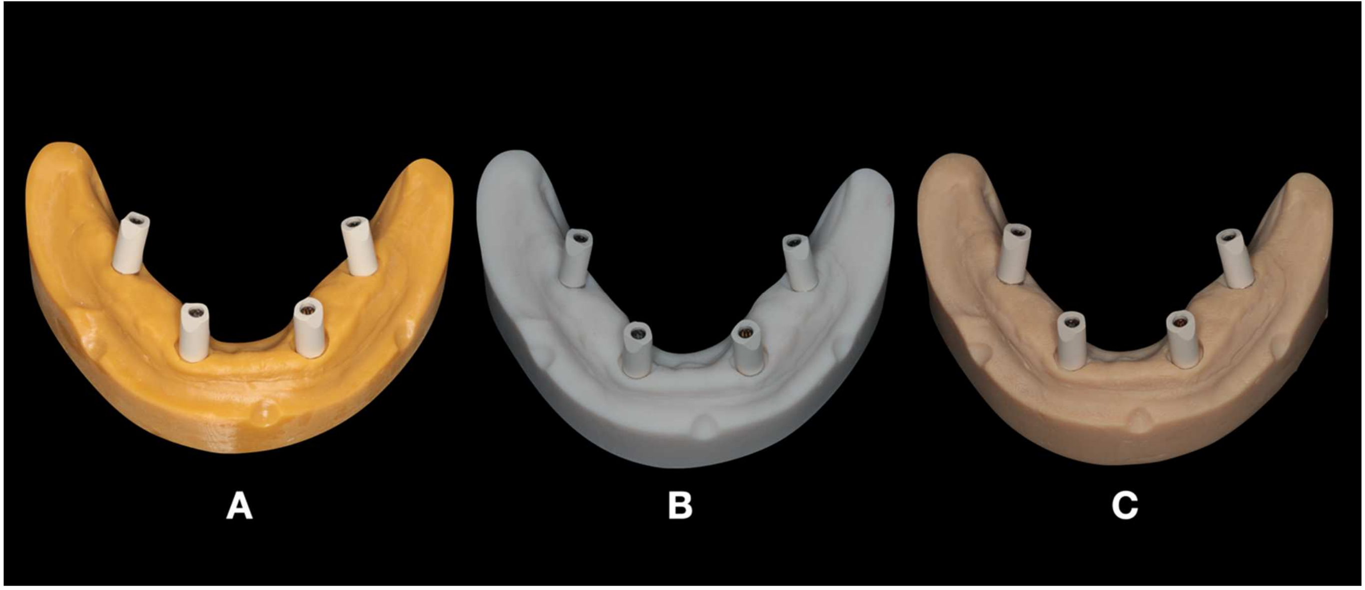


Figure 5. The 3D printed casts generated from the three printers representing the 3 test groups. The printed casts with CARES Mono scan bodies attached to the SRAs prepared for scanning procedure.

A = Bego printed cast, B = Carbon printed cast, C = Formlab printed cast

Figure 6. The Desktop scanner (Activity 880 scanner; Smart Optics, Bochum, Germany) used to digitize all the casts.

Figure 7. A superimposition of STL files of a 3D printed model from the Bego printer and a scan of the same model at a previous time point.

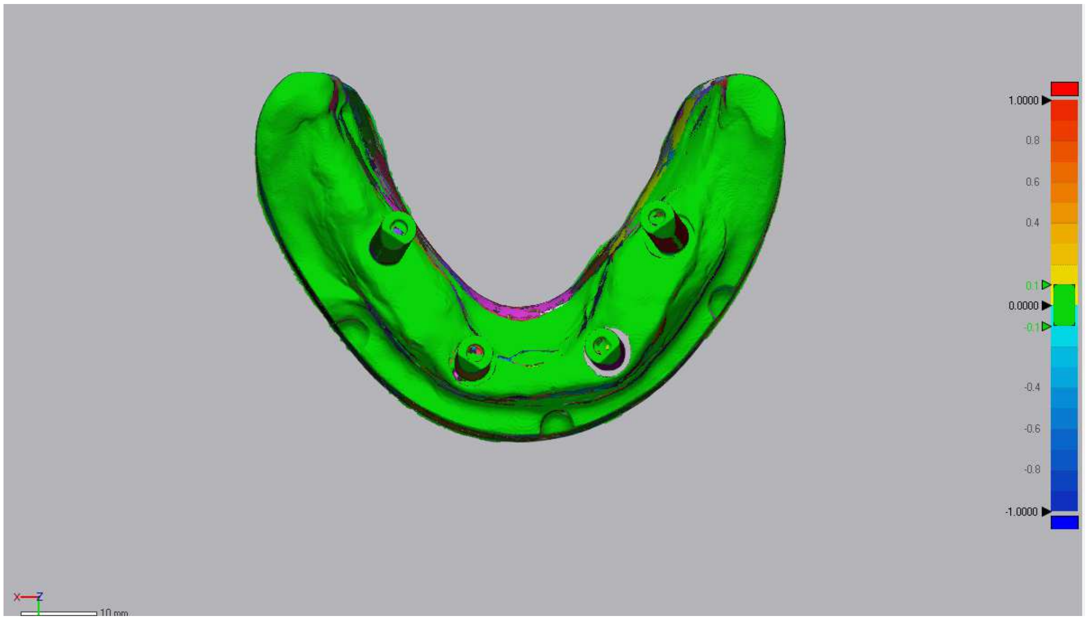


Figure 8. A superimposition of STL files of a 3D printed model from the Carbon printer and a scan of the same model at a previous time point.

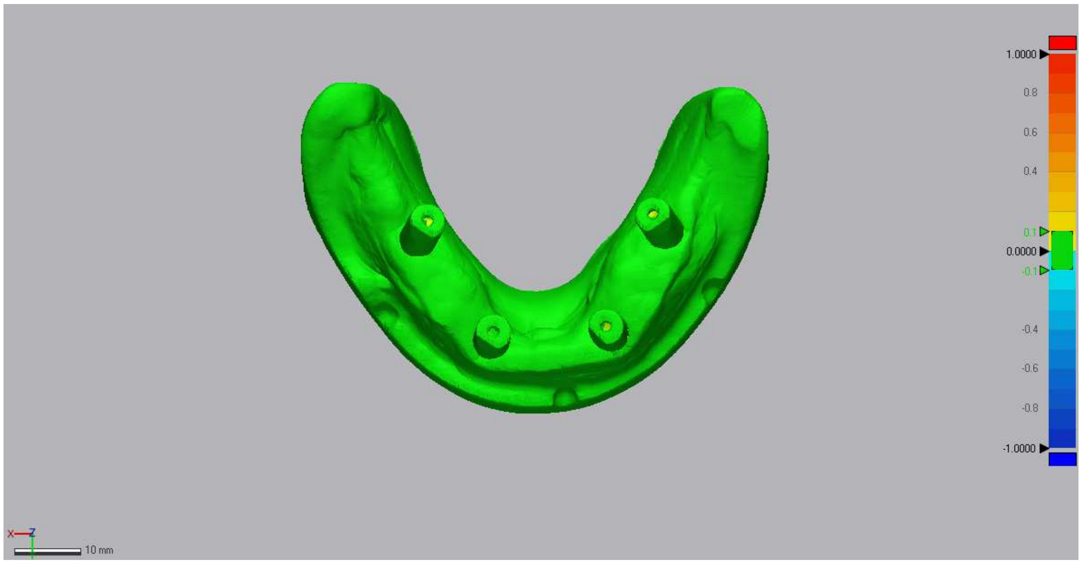


Figure 9. A superimposition of STL files of a 3D printed model from the Formlab printer and a scan of the same model at a previous time point.