Tufts UNIVERSITY | School of Dental Medicine

Three-Dimensional Accuracy of Printed Alveolar Casts

by

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ABSTRACT

Objective:

The purpose of this in-vitro study was to evaluate the accuracy of 3D printed alveolar casts fabricated with three different 3D printers from digital scans on a reference typodont in the scenario of a maxillary veneer, two crowns, fixed dental prostheses and onlay.

Material and Methods:

A reference cast, prepared using a Kilgore K-2 typodont with various tooth preparations, was scanned using a Trios4 intra-oral scanner. This created an STL file that served as a digital reference for superimposition and the design of a digital alveolar cast. The digital cast was designed using (Exocad Dental CAD® 3.1 Rijeka) software, including movable dies and a cast base. This design was then exported as an STL file for 3D printing. Three 3D printers (Carbon DLS, Straumann P30+, Formlabs Form3b+) were used to print the alveolar casts, and all were cleaned and post-cured as per the manufacturers' instructions. The printed casts were then digitized using the same intra-oral scanner, and the resultant digitized casts were exported as STL files. Finally, the 3D deviations of each printed cast were calculated by superimposing the cast STL files onto the original digital reference cast using Geomagic Control X software. The software then determined the root mean square error for each clinical scenario.

Results:

The study observed significant differences between specific pairs of dental restorations in each category except for the veneers. For onlays, Carbon showed significantly lower RMS error compared to Formlabs® Form3b+ (P<0.001). In post-hoc comparisons, between Formlabs® Form3b+ and Straumann® P30+ (P=0.044). Similarly, Carbon exhibited significantly lower RMS error in the gold crown category than Formlabs® Form3b+ (P<0.001). For ceramic

crowns, both Formlabs® Form3b+ and Carbon had significantly higher RMS error than Straumann® P30+ (*P*=0.004 and *P*=0.010, respectively). In fixed dental prostheses (FDP), Carbon had significantly less deviation than both Straumann® P30+ and Formlabs® Form3b+ (*P*<0.001). Notably, no significant differences were found among the veneers' RMS error values (*P*=0.055).

Conclusion

According to this study, the Continuous Liquid Interface Production (CLIP) printer exhibited higher accuracy compared to the Stereolithography (SLA) printer for onlays (*P*<0.001), gold crowns (*P*<0.001), and fixed dental prostheses (*P*<0.001). Also, the Continuous Liquid Interface Production (CLIP) printer exhibited higher accuracy compared to the Digital Light Processing (DLP) for fixed dental prostheses (*P*<0.001).

On the other hand, the Digital Light Processing (DLP) exhibited higher accuracy compared to Continuous Liquid Interface Production (CLIP) the Stereolithography (SLA) printer for ceramic crowns (*P*=0.010), (*P*=0.004) respectively.

DEDICATION

In the Name of Allah, the Most Gracious, the Most Merciful. I dedicate this thesis to the most Supreme and Compassionate, Allah, the Almighty, who has bestowed upon me the strength, knowledge, and guidance to undertake this academic journey. His endless blessings and grace have been the driving force behind my perseverance and success.

To my beloved wife, Banan, you have been my unwavering pillar of support, a source of love and encouragement. Your boundless patience and understanding during the countless hours I spent immersed in research are deeply appreciated. Your belief in me and constant motivation have been the foundation of my achievements.

To my precious daughters, Maria, and Jumanah, you are my pride and joy. Your innocent smiles and unconditional love have been a constant source of inspiration, reminding me of the significance of my endeavors. May this thesis serve as a testament to the boundless love and dedication I have for you both.

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I dedicate this thesis to my beloved homeland, the place where I was born and where my identity comes from. I am extremely proud and grateful for our rich culture, our supportive community, and the opportunities that my country has provided, including my scholarship, which has made my academic journey possible.

This thesis is a humble offering of gratitude to all those who have played a significant role in my life, both seen and unseen. May Allah, in His infinite mercy, bless each one of you abundantly and grant me the strength to continue serving my family, community, and country with dedication and sincerity. Allah is my witness, and unto Him, I submit my efforts.

"In Him I trust, and unto Him is my return." (Quran 11:88)

With Regards,

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Introduction

Dentistry is rapidly changing with the advances in digital technology and manufacturing. Digital technology offers standardization in the process of prostheses fabrication and improves efficiency and patient comfort by minimizing the number of steps required. It also reduces the cost of the production, eliminates variables associated with multiple laboratory stages, and standardizes the process of prosthesis fabrication.[1]

Digital dentistry was first introduced by Duret and colleges in 1971 as computer-aided design/computer-aided manufacturing (CAD/CAM) and has been implemented in many areas of health care since then.[2] With early studies being more experimental rather than clinical, Heitlinger and Rodder began to share this approach in 1980.[3] In 1987, Sirona Dental Systems LLC (CEREC®, Charlotte, NC) developed the design of the first optical intraoral scanner (IOS) for restorative dentistry and was launched by a dentist from Switzerland, Dr. Mörmann, and a colleague, Marco Brandestini. The first chair-side CAD/CAM dental reconstruction device for commercial use was this system.[4]

The CAD/CAM system consists of three elements. First, data acquisition tools include IOSs, laboratory scanners, face scanners, and cone-beam computed tomography (CBCT). These methods convert geometry into casts that the machine can interpret (digital data). The second element is planning and processing software. This component is known as computer-aided design (CAD) that processes the data and merges different digital data, designs, and plans for either implant or tooth restorations to be fabricated. Finally, the manufacturing technology known as computer-aided manufacturing (CAM) transforms the digital product into the desired physical product either by subtractive or additive methods. Depending on the location of these components, the production concepts can be chairside, laboratory, or centralized.[5]

Research and development sectors in several companies have advanced their technologies and developed faster and more user-friendly CAD/CAM system components. These technologies are capable of recording and reproducing three-dimensional (3D) virtual casts of tooth preparation, and dental prostheses can be manufactured by using the virtual casts in the form of Standard Tessellation Language (STL).[6] STL is used for breaking the geometry of a surface into a series of small triangles or polygons (tessellation).

Traditional dental impressions have several disadvantages, including the need for material preparation, ongoing expenses, significant technical investment, potential patient discomfort, and the requirement for high clinical skills. Regardless of the materials and techniques used, there is always a degree of error associated with conventional impressions due to the numerous steps involved and materials handling. For example, all impression materials are prone to dimensional distortion during the setting process. Furthermore, when removing the impression from the patient's mouth, unavoidable deformation occurs, especially in undercut areas. Moreover, pouring the impression with stone material can further contribute to distortion during the setting process. However, familiarity with the conventional impression technique and dental stone can help minimize potential accuracy issues.[7, 8]

IOSs are becoming the preferred choice for dentists and patients in prosthodontics. This technology provides significant advantages, such as eliminating tray selection and reducing cast distortions during fabrication. Additionally, it removes the need for disinfection and shipping traditional impressions to dental laboratories. Patients find it much more comfortable and preferable, as it eliminates the potential for gagging or suffocation often associated with conventional impression techniques.[1, 9-11]

In the field of dentistry, new scanning technologies have emerged. These include the triangulation technique used by Cerec from Dentsply Sirona, the active wavefront sampling technique used by True Definition from 3M ESPE, and the confocal scanning technique used by iTero from Align Technology and Trios from 3Shape. The confocal scanning technique is notable for its faster scanning capabilities among these technologies. It focuses on an optical light beam to capture high-resolution visual images with improved accuracy and reduced distortions.[12] According to a study by Renne et al., the 3Shape Trios provides the best combination of speed and accuracy for complete-arch scanning.[13] In a study conducted by Pokpong et al., the accuracy of ten IOS was evaluated. The study found that the accuracy of all scanners decreased with increased scan distance. The trueness of the scanners varied, but precision was consistently favorable across all models. Additionally, diagonal scanning resulted in less accuracy for all scanners. Therefore, dentists should exercise caution and use a good scan pattern when scanning the full arch. The Trios series demonstrated the best scan results compared to other scanners.[12]

3D printing is the most innovative dental technology in the automotive and aerospace industry because it shortens the lead time for manufacturing, decreases the costs involved, and enables complicated standardized materials to be printed.[14] 3D printers produce 3D structures based on a 3D design file (STL file), centered on a 3D modeling register, to fabricate an object instead of reductive manufacturing in which material is subtracted to produce the object.[14]

In recent years, 3D printing accuracy has improved with the increased speed of printing.[15] Essentially, the printer's program cuts an object's STL file into several two-dimensional (2D) layers in the X and Y planes in 3D printing. Then, the printer successively continues building up the layers on top of each other before the object is perfectly shaped.[16, 17] Thereafter, to finalize the work, post-printing processing is necessary. Using this technology enables reduced wasting of material and creates objects with geometries that are very precise.[17]

However, an STL file can be translated into a physical cast with the advancement of CAD/CAM technology. With additive or subtractive CAM technology, CAD systems may construct 2D or 3D graphical representations of any object transformed into a physical object. In dentistry, 3D printing has become widespread, especially with the appearance of low-cost 3D printers. It may be used to make definitive casts, guides for surgery, and even dental prostheses. The standard of 3D printed dental casts has been deemed clinically appropriate in recent studies and, in most cases, equal to those provided by traditional approaches.[18]

One of the most important parameters that 3D printers need to pose to be clinically acceptable is accuracy. According to metrics and engineering, accuracy is defined as the “closeness of agreement between a measured quantity value and a true quantity value of a measurand”.[19, 20] In other words, it is the combination of trueness and precision. Trueness is interpreted as the ability of a measurement to match the actual value of the quantity being measured. On the other hand, precision is defined as the ability of a measurement to be consistently repeated.[19] In order for the printer to be accurate, it should possess high trueness and precision to consistently represent the true value of the patient condition.

The methods of 3D printers are different: stereolithography (SLA), digital light processing (DLP), photopolymer jetting (PPJ) and continuous liquid interface production (CLIP) are the most widely used techniques for dental applications, for example. [16] In general, SLA and DLP printers employ a similar printing process but vary in how they transmit the curing light to the resin.[17, 21]

The oldest and most popular process used for 3D printing is stereolithography. In order to draw the specifics of each layer of an object, this approach entails projecting a quickly advancing ultraviolet (UV) laser beam through a tank filled with light-sensitive liquid resin. Instead of the resin tank, the curing sheet is fixed to the construction platform of the printer. After each layer is finished, the construction platform slightly elevates, and a fresh layer is added on top of the preceding one. This sequence persists and recurs until the desired object is completely formed. Digital light processing is an alternative approach used in 3D printers to produce light. Instead of using a laser beam to scan one layer at a time, DLP printers simultaneously project a silhouette of a whole layer and cure it with a single shot of curing light that enables printing to be significantly quicker.[17, 21]

Photopolymer jetting, also referred to as material jetting (MJP), is a form of 3D printing that uses a printing head with multiple nozzles to build up the layers. The printer jets light-sensitive polymer onto a building platform that ascends gradually and cures one layer at a time using UV light.[17]

The aforementioned CLIP technology is an advanced system in which UV light images are projected in a continuous rapid sequence. When photosensitive resin material is exposed to UV light, it hardens. In contrast, the remaining liquid "unpolymerized" resin preserves a constant liquid zone due to oxygen inhibition, ensuring a continuous, rapid curing process. The advantage of CLIP technology is its quick printing capability, as 3D objects can grow continuously without interruption by controlling the oxygen flux.[16, 22]

Until now, few studies in the dental literature have evaluated the accuracy of 3D printing. However, studies are emerging recently that have evaluated the accuracy of this approach since the various additive process patents in 3D printing have expired. [16]

Dental casts from STL files extracted from digital scans and built using 3D printing with IOSs are becoming popular for fixed and implant prosthodontics. While IOSs facilitate the full digital workflow without the need for a physical cast, physical casts can still be needed for certain complicated prosthodontic procedures, especially in the anterior maxilla.[22-25]

Studies have compared the degree to which 3D printed casts deviate from conventional stone casts. Cho et al.[26] assessed the accuracy and replicability of SLA casts printed from digital scans of the full arch with five teeth prepared for fixed dental prosthesis (FDP) and single crowns. In this study, five conventional stone casts were fabricated and used as a control group. No significant difference was found between the two groups. However, there was a significant difference in the casts' area overall. The authors concluded that the digital workflow provided much less precise casts than traditional approaches produced.[26]

A research study by Aly et al.[27] compared the accuracy of 3D-printed casts made from IOSs through the SLA technique with traditional stone casts and digital replicas. The results showed that the digital casts had more errors than other groups in inter-arch and linear measurements. However, the errors were still within the acceptable clinical range. Furthermore, the study proved that the 3D-printed casts were a viable substitute for stone casts since they possess clinically acceptable accuracy.[27]

Another study by Al-Imam et al.[28] evaluated the trueness and precision of two different SLA printers (Dreve and Scanbiz) and compared them to those of stone casts. The study used a master model with a scenario of a 5-unit FDP, maxillary 1st molar, and canine as abutments. For the digital group, Trios IOS was used to take digital scans to print the casts. Their results showed that the conventional stone casts had the least amount of 3D deviation. The authors concluded that stone casts were more accurate.[28]

Alveolar Cast

The alveolar cast is a dentogingival cast that allows interchangeability of multiple removable dies on a common type IV gypsum dentogingival cast. This is often referred to as the carrot or Geller cast, named by Mr. Willi Geller, the Austrian dental laboratory technician. This cast allows an unchanged dentogingival relationship during the manufacture of restorations and has advantages for rendering fixed restorations over other definitive casts. The dentogingival relationship is demonstrated by preserving of details about the soft tissue, bypassing the need to trim the gingival contour while manufacturing a die. The tooth-tissue relation during the fabrication of the prostheses is not altered in this approach.[29]

The prospect of making several restorations on the same cast from various restorative materials and techniques is a further benefit of this method. It can also be used in computer-aided design/computer-assisted development systems with scanners because it precisely replicates the positioning, size, edges of the prepared teeth, boundaries of the surrounding soft tissue, and neighboring teeth without requiring any trimming, which would otherwise result in the loss of essential details. This additional capability of the alveolar model can allow multiple restoration and restorative materials to be evaluated simultaneously regarding their ability to transmit light and to enhance the recording of clinical esthetic treatments.[29]

It is important to fabricate a working cast with dies that accurately duplicate the location, surface area, and margins of the prepared teeth, underlying soft tissues, and adjacent teeth when fabricating indirect dental restorations. Gingival contours and occlusal vector force distribution of full- and partial-coverage restorations are the two most important factors that influence and maintain periodontal health.[30, 31] In the lab process of dies fabrication, dies are trimmed to expose the margins of preparations; however, the soft tissues emergence profile that surrounds the prepared teeth are lost. Failing to preserve these gingival elements may result in an inappropriate contour and emergence profile of the final restoration. The alveolar model is an innovative technique inspired by nature that can be used during the laboratory fabrication of all traditional and contemporary fixed restorations. This includes but is not limited to the tooth- and implant-supported prosthesis.[32]

Nevertheless, the procedure has drawbacks. Especially for less skilled dental laboratory technicians, the analog workflow for the alveolar cast is labor-intensive, time-consuming, and complicated. [18]

To the authors' knowledge, no studies have evaluated the accuracy of 3D printed alveolar casts generated from digital scans using an IOS for FDP.

OBJECTIVE

The purpose of this in-vitro study was to evaluate the accuracy of 3D printed alveolar casts fabricated with three different 3D printers from digital scans on a reference typodont in the scenario of a maxillary veneer, two crowns, fixed dental prostheses and onlay.

NULL HYPOTHESIS

There is no difference in the accuracy of the alveolar casts fabricated with the three different 3D printers (Carbon, Straumann P30+, Formlabs 3b).

MATERIALS AND METHODS

A prepared typodont (K-2- crown and bridge model, Kilgore) was used as reference cast with tooth preparations for a veneer, two single crowns, a fixed dental prosthesis and an onlay to simulate different clinical scenarios of a prepared teeth on maxilla that would be restored with multiple restorations. The maxillary typodont included a preparation for a veneer on the left central incisor (tooth #9), two single crowns on the right first molar and the right central incisor (Tooth #3 and #8) and the finish line was subgingival is this scenario, a 3-unit tooth-supported FDP from the left canine to the left second premolar (#11-X-#13) and an onlay on the right second molar (tooth #2). All other teeth in the typodont were intact. The typodont was scanned with the intra-oral scanner (Trios4, 3Shape, Copenhagen, Denmark). The scanner was calibrated before each scanning based on the manufacturer's instructions. The operator was calibrated by scanning the master casts ten times before starting the scans for the study. The scanning technique followed the manufacturer's recommendations. After the scanning was completed, the study's digitized reference cast was exported as an STL file. The exported STL file was used as a reference during the superimposition and the fabrication of the digital alveolar cast.

Designing the Digital Alveolar Cast

The alveolar cast was designed from the digital reference cast STL file. The STL file was imported into a Computer Aided Design software (Exocad Dental CAD® 3.1 Rijeka). First, the margins of the teeth preparations were traced. Then the alveolar cast was designed, including removable dies and the cast base. Finally, the generated data for the digital alveolar cast were exported as an STL file to make the design printable.

Printing the Alveolar Cast

The designed STL file was printed with three 3D printers. Group A: Carbon (The Carbon Digital Light Synthesis™ "Carbon DLS™"), Group B: Straumann® P30+ (Straumann, Manufacturer), Group C: Formlabs® Form3b+ (Form 3B+ 3D printer, Formlabs). All printed casts were processed and cleaned after printing. Then, all printed casts were post-cured based on the manufacturer's recommendations for each printer. The printed dies were passively inserted in their sockets and then checked for adequate retention.

Digitalizing the casts for the groups

The same IOS (TRIOS4) was used to scan the 3D printed casts from the three groups to eliminate the scanner's effect. The scanner was calibrated before the scanning based on the manufacturer's instructions. The scanning technique followed the manufacturer's recommendations. Finally, the digitized casts were exported as STL files. One calibrated operator completed all scanning procedures in the study.

STL superimposition procedures

Each cast STL file from the test groups was superimposed onto the digital reference cast's STL file in the 3D inspection software (Geomagic Control X, v. 2020.0.1; 3D Systems) using the best-fit alignment algorithm. The software was used to calculate each cast's 3D deviation using the root mean square (RMS) error related to the clinical scenario. The RMS error was calculated individually for the veneer, crowns, three-unit FDP, and the onlay.

Sample size calculation

A sample size calculation was performed using the software nQuery Advisor v. 9.1.1.0 (Statistical Solutions Ltd., Cork, Ireland). Based on the results of a pilot study, the effect size was assumed to be Δ^2=1.0. The calculation determined that a sample size of n=10 per group was adequate to obtain power of 1-β=99% in conjunction with a Type I error rate of α=.05. A sensitivity analysis showed that even if the assumed within-group standard deviation were increased by 50%, the power of the study would still be >80%.

Statistical analysis

Descriptive statistics (means, medians, standard deviations, minima, and maxima) were calculated. When the assumptions of normality and homoscedasticity were satisfied, statistical significance was assessed using one-way ANOVA as the omnibus (global) test, with Tukey's HSD used in post-hoc comparisons. When the assumption of normality was satisfied but the assumption of homoscedasticity was not, the omnibus test was conducted using Welch's ANOVA, with the Games-Howell test used in post-hoc comparisons. When the assumption of normality was not satisfied, the omnibus test was conducted using the Kruskal-Wallis test, with Dunn's test and the Bonferroni correction used in post-hoc comparisons. The assumption of normality was assessed using the Shapiro-Wilk test; the assumption of homoscedasticity was assessed using Levene's test. The significance level was set at $\alpha=0.05$, with the exception of tests in which the Bonferroni correction was used, for which $\alpha=0.05/3\approx0.0167$. SPSS v. 28 (IBM Corp., Armonk, NY, USA) was used in the analysis.

Results

Regarding onlays, Carbon had the lowest mean RMS and Formlabs® Form3b+ had the highest. The omnibus test comparing the groups was statistically significant ($P<0.001$) (Welch's ANOVA, Table 1). In post-hoc comparisons, the difference between Carbon and Formlabs® Form3b+ was statistically significant ($P<0.001$), as was the difference between Formlabs® Form3b+ and Straumann® P30+ ($P=0.044$) (Games-Howell test, Table 2).

Regarding gold crowns, Carbon again had the lowest mean RMS and Formlabs® Form3b+ again had the highest. The omnibus test was significant ($P=0.001$) (one-way ANOVA, Table 1). In post-hoc comparisons, only the difference between Carbon and Formlabs® Form3b+ was significant ($P<0.001$) (Tukey's HSD, Table 2). For ceramic crowns Straumann® P30+

had the lowest mean RMS while Formlabs® Form3b+ again had the highest. The omnibus test was significant (*P*=0.006) (Kruskal-Wallis test, Table 1). In post-hoc comparisons, the difference between Straumann® P30+ and Formlabs® Form3b+ was significant (*P*=0.004) and the difference between Straumann® P30+ and Carbon was significant (*P*=0.010) (Dunn's test with Bonferroni correction, Table 2).

Regarding veneers, the omnibus test was not significant (*P*=0.055) (Kruskal-Wallis test, Table 1). Therefore, no post-hoc comparisons were performed.

Regarding fixed dental prostheses, Carbon had the lowest mean RMS and Formlabs® Form3b+ had the highest. The omnibus test comparing the groups was statistically significant (*P*<0.001) (one-way ANOVA, Table 1). In post-hoc comparisons, Carbon was significantly different from both Straumann® P30+ and Formlabs® Form3b+ (both *P*<0.001) (Tukey's HSD, Table 2).

Discussion

The aim of the present in vitro study was to evaluate the accuracy of 3D printed alveolar casts for veneer, crowns, fixed dental prostheses and onlay using three different 3D printers. To the authors' knowledge, this is the first study to assess the 3D deviations of 3D printed alveolar casts for veneer, crowns, fixed dental prostheses and onlay. The 3D printed casts were generated after digital scanning of a reference cast with TRIOS.

Some null hypotheses were rejected, as the Carbon printer exhibited higher accuracy compared to the Formlabs® Form3b+ printers for onlays (*P*<0.001), gold crowns (*P*<0.001), and fixed dental prostheses (*P*<0.001). Also, the Carbon printer exhibited higher accuracy compared to the Straumann® P30+ (*P*<0.001). However, the Straumann® P30+ printer resulted in casts that had better 3D accuracy for ceramic crowns. On the other hand, there was no significant difference in the scenario of veneers between the three printers.

Accurate and precise digital casts are crucial for creating successful prostheses in clinical settings, with less than 200 μm recommended trueness.[33] The marginal fit of fixed prostheses is crucial, as any misfit can result in various dental problems such as secondary caries, pulpitis, gingivitis, and bone loss, ultimately leading to the prosthesis' failure. To avoid such issues, prostheses made from STL files must thoroughly check with the working casts to minimize errors before being delivered to patients. The clinically acceptable marginal fit range for fixed prostheses is between 90 μm to 200 μm.[33-35]

The utilization of 3D printing technologies in dentistry has facilitated the fabrication of diverse objects possessing varying geometries through the implementation of appropriate materials. The tolerances inherent in the manufacturing processes are contingent upon the specific clinical applications involved.[36] The establishment of clinically acceptable limits for assessing the 3D precision of working casts used for dental treatment has significant implications. The precision of these casts has the potential to influence the degree of misfit observed in fixed prostheses, leading to more pronounced marginal or internal deviations prior to the delivery of the prosthesis.[36] Previous studies have produced contradictory results regarding the clinically acceptable degree of misfit. The reported clinically acceptable marginal gap for fixed dental prostheses is 120 μm.[37-39] In a systematic review conducted by Svanborg et al., data were presented for zirconia restorations. The findings indicated that the accuracy of the marginal fit was 59 μm, while the internal fit was 61 μm.[40, 41] Despite the statistically significant differences observed between the SLA unit and other systems, a deviation of 220 μm was deemed clinically acceptable. However, clinicians are aware of these variations when considering a particular clinical application. While the literature describes a broad range of tolerance levels, ranging from 100 to 500 μm, for additive manufacturing applications, further research may be necessary to guide clinicians.[42]

There is no consensus on definition of marginal gap values, with reported values ranging from 25 to 200 μm, nor on a common method of evaluation. The American Dental Association states that the proper fit of a fixed prosthesis ranges from 25 to 40 μm, but it is very difficult to reach such a goal using most of the current manufacturing technology.[43] The marginal gap level of 100 μm was defined as clinically acceptable and the 120 μm was considered the maximum tolerable marginal opening, but this was based in publications in the 1970s, 80s and 90s. The ideal gap should be small enough to prevent ingress of saliva and/or lactic acid, which is the byproduct of bacterial metabolism.

According to Wesemann et al., deviations below 300 μm were classified as excellent.[44] However, it is important to note the distinction between orthodontics and prosthodontics. A measurement difference of less than 300 μm between 3D printed and orthodontic casts is deemed clinically acceptable in orthodontics. On the other hand, prosthodontics requires higher levels of accuracy due to higher precision requirements.[45]

In the current investigation, all fabricated working casts demonstrated trueness values ranging from 98 µm to 250 µm, fulfilling the more recent predetermined criteria for clinical acceptability.

The present study encompassed the utilization of three distinct printing methodologies, namely SLA technology employed in the Formlabs® Form 3b+ printer, DLP implemented in the Straumann® P30+ printer, and CLIP technology employed by the M2 Carbon printer.

Rungrojwittayakul et al. assessed the precision of three-dimensional printed dental casts fabricated with CLIP technology and DLP technology printers. They employed the intraclass correlation coefficient (ICC) to determine the level of accuracy achieved by the 3D-printed casts. Their findings revealed that, compared to the DLP printer group (0.097 mm), the casts produced with CLIP technology (0.052 mm) exhibited significantly lower levels of variation when compared to the reference model which means that the deviation falls within the acceptable range, signifying that the 3D printed casts meet the clinically established criteria for acceptability.[22] A previous study by Kim et al. determined that the PolyJet and SLA techniques demonstrated superior trueness for tooth measurement 78 µm ,107 µm respectively, compared to the DLP and fused filament fabrication techniques 143 µm ,188 µm respectively.[14] Nevertheless, their results represent that the trueness of both PolyJet and SLA techniques within clinically acceptable range.

The IOSs are suitable for simple to moderate clinical applications. However, during the scanning process, errors can occur due to the superimposition of approximately 1200 images. These errors are most common in steep inclines and limited tooth surfaces in the anterior teeth. Additionally, filter algorithms and calibration can cause errors during computer processing.[12, 46, 47]

Several other factors can influence the accuracy of IOSs. Intraoral conditions like temperature, relative humidity, and illumination can impact the operator's scanning pattern and skill level. Also, the sensor fogging, the ambient light conditions and the jaw position (maxilla vs mandible) also play a role. The components of the scanner unit, including the capture box, receiver, and light source, can also affect accuracy. The speed of the computer software used for processing is also critical. When evaluating the accuracy of IOS, it is essential to consider the scanning area, its length, and the presence of surface irregularities.[48, 49]

The available literature discusses various factors associated with additive manufacturing (AM) that have the potential to impact the accuracy of printed objects. These factors encompass the build angle, resolution (layer thickness), type of resin used, speed of the printers, laser intensity, and post-curing procedures.[16, 17, 50]

The build angle, which refers to the angle at which the object is printed, plays a crucial role in determining the accuracy of the 3D printed object. The build angle impacts the arrangement and stacking of the material layers during the printing process. Consequently, it can influence the printed object's quality and mechanical properties.[51] In a laboratory study conducted by Osman et al., the influence of the build angle on the accuracy of 3D-printed dental restorations was evaluated. A complete coverage dental crown was designed and fabricated using a DLP 3D printer with nine different build angles. The results indicated that the build angle of 135° (45°) exhibited the lowest RMS error, indicating higher accuracy, followed by the 210° build angle.[52]

Choi et al. recommended specific strategies to minimize printing errors in their study. These strategies included aligning the occlusal plane of the 3D printed model, parallel to the platform and setting the build angle to 180 degrees to position the tooth cusp away from the platform. Furthermore, considering the layer thickness and printing time capabilities of the two 3D printers in their study, a layer thickness of 50 micrometers was optimal.[53] Similarly, Belén et al. proposed a suggestion for the 3D printing workflow of the printers employed in their study. They recommended horizontally nesting the full-arch cast, highlighting its advantages in terms of efficiency and effectiveness.[54] In the research conducted by Revilla-Leon et al., the intaglio surfaces of occlusal devices manufactured with a 3D printer displayed the highest trueness value when printed with a 0-degree print orientation.[55] Regardless, certain studies have proposed an oblique angle of 30-45 degrees for printing casts, emphasizing that the build angle and layer height interact significantly to influence the accuracy of the printed casts.[56, 57]

Regarding the building angle, the building angle for the 3D printers used in this study was established at 180 degrees as were recommended from previous studies.[50, 53-57] Furthermore, the manufacturer's recommendation "Formlabs®" suggested that the flat surfaces to an incline of 10-20 degrees significantly boosts the success rate in 3D printing. When the model is printed at an angle, it reduces the surface area of each layer and minimizes contact with the printing tank. As a result, the print experiences less force during the build platform's ascent with each layer. Nevertheless, there is a lack of consensus regarding the recommended building angles for dental casts in the existing literature. Additionally, it was crucial to apply appropriate supporting structures to stabilize the object and prevent distortions during the printing process. To ensure accurate printing, sufficient supporting bars were included during the nesting of the STL file prior to each printing session, following the instructions provided by the nesting software specific to each printer. However, these parameters were not explicitly tested in this study, highlighting the need for further research on these aspects concerning dental casts.

Additive manufacturing devices construct 3D objects using x-, y-, and z-dimensions. The z-dimension, also known as the print layer height, plays a crucial role in determining the smoothness and level of detail on the surface of the printed part. While the specific manufacturing system determines the x-y build directions, the operator often adjusts the print layer height. Previous research has shown that the print layer height directly impacts the print quality.[15, 42] However, opting for the most diminutive print height, which increases surface detail, does not guarantee improved accuracy. Reducing the layer height leads to increased layers during the manufacturing process. Consequently, a higher number of layers introduces more opportunities for potential errors, such as deviations from the intended print boundaries, artifacts, and print failures.[15, 58]

The resolution of each printing technique varies, with SLA printers' resolution in the x- and y-planes being determined by the diameter of the laser beam used. In contrast, DLP 3D printers have resolution determined by the size of the pixels relative to the build platform.[16, 21, 50] Moreover, Sherman et al. and Zhang et al. conducted studies to evaluate the accuracy of DLP printed models using varying layer thicknesses ranging from 20 µm to 100 µm. Both studies concluded that all printed casts achieved clinically acceptable levels of accuracy. Therefore, like SLA printers, it can be inferred that a layer thickness of 100 µm can produce DLP printed models with clinically acceptable accuracies.[59, 60] Therefore, Akyalcin et al. determined that DLP technology significantly reduced surface variation compared to SLA models.[42] These studies revealed that changing the filling pattern from solid to hollow resulted in reduced material wastage, shorter build time, and lower costs, with no statistically significant difference in mean error.[61]

In the current study, a resolution of 100µm was selected for all 3D printers, except for the Straumann P30+, which had a recommended resolution (layer thickness) of 50µm per the manufacturer's guidelines. However, the results of this laboratory-based study demonstrate that the M2 Carbon printer exhibited superior accuracy with a resolution of 100µm layer thickness. Although the Straumann® P30+ (DLP) group had a higher resolution, it exhibited lower accuracy than the Carbon printer in all scenarios except for ceramic crown production. However, no statistically significant difference was observed between these two groups, except in the case of fixed dental prostheses. However, in scenario of ceramic crowns the Straumann® P30+ (DLP) group had higher accuracy and statistically significant difference was observed between these two groups.

It should be noted that when evaluating the accuracy, the RMS error alone does not provide information about the direction or pattern of displacement. More precise methods, such as coordinate measuring machines (CMMs) or linear measurements, are recommended to identify displacement type, direction, and magnitude accurately. These techniques offer a more comprehensive assessment of the displacement characteristics.[24] Even more clinically meaningful, will be the fabrication of restorations on the 3D printed casts and retrofitting on the reference casts to assess the clinical fit. The clinical implications of these would be the most clinically impactful.

It is crucial to highlight that the superimposition technique can introduce more errors as the scanned area increases. Although there were variations in the resin type and post-print processes, all procedures followed the manufacturer's instructions to minimize printing errors.

Choi et al. conducted a study comparing the accuracy of dental models fabricated using conventional, milling, and three-dimensional (3D) printing methods.[53] They used a maxillary typodont cast and obtained digital impressions using an intraoral scanner. The digital impressions were then converted into physical casts using conventional stone casts, milled gypsum casts, and 3D printed casts using an SLA 3D printer and a DLP 3D printer. The accuracy of the casts was evaluated using the Geomagic Control X analytic program. The results showed that the trueness and precision of the conventional stone casts were significantly smaller than those of the other groups. There was no significant difference in the trueness value among the other groups, but the precision value was significantly smaller for the conventional stone casts s, followed by the milled casts. The SLA 3D printer and DLP 3D printer casts showed no statistically significant difference in the precision value.[53] It is worth noting that the evaluation in this study focused on the dies, unlike Choi et al., who evaluated the entire arch. Additionally, the two studies had differences in the layer thickness resolution and post-printing process, which can affect the overall accuracy.

Cho et al. conducted a study comparing the surface accuracy of conventional and 3D printed casts for prepared teeth, including single and 3-unit fixed dental prostheses preparations.[26] The outcomes indicated no significant difference in surface accuracy between the conventional and 3D printed casts for single and 3-unit fixed dental prostheses preparations. This suggests that digital fabrication methods are compatible with conventional methods in terms of surface accuracy for these types of preparations.[26] Nonetheless, our study did find significant differences among the three cast groups when comparing trueness for all types of preparations.

Furthermore, the printing speed is an additional factor that should be considered. Among the printers used in this study, the Formlabs® Form3b+ exhibited the slowest speed, requiring two printing cycles to produce two casts, while the Straumann® P30+ and M2 Carbon printers each produced one cast per cycle. Interestingly, the Straumann® P30+ group experienced three misprinted casts, whereas the other printers did not encounter any misprints. However, there is a lack of literature on the impact of the number of printed models per cycle on the accuracy of 3D printing.

This is the first study to report the printed alveolar cast technique demonstrated clinically acceptable accuracy for different clinical scenarios with three different printers. The results of this study represent a notable breakthrough in dental technology, providing a promising and dependable alternative to conventional methods. This advancement has the potential to revolutionize dental practice and elevate patient care. The research establishes a foundation for future investigations and improvements in the printed alveolar cast technique, shaping the future of dentistry and benefiting patients globally.

There were many limitations in the present in-vitro study. Designing the cast through the Computer Aided Design software (Exocad Dental CAD® 3.1 Rijeka) plays a significant role of the dies fitting in the hollow model base. We tried to equalize the parameter of the dies and the model base, generated the STL file, and then printed it with three different printers. However, after testing the fitting of the dies inside the model base, the dies were fitted only in the Formlabs® Form3b+ printer. The model base was too tight, and we could not insert the dies for Straumann® P30+. Also, the model base was too wide, and the dies were loose after the insertion of the Carbon printer. Multiple trials were made by changing the Horizontal Shaft Gap (HSG), which the software identifies as "the spacing between a die and the model base in horizontal (x and y) direction." The HSG for the Carbon, Formlabs®, and Straumann® P30+ printers were 0.06 mm, 0.08 mm, and 0.1 mm, respectively. To improve the accuracy of printing, it is essential to optimize the parameter settings. Additional research is required to minimize deviations and optimize parameters for different types of 3D printers.[53]

The finish line location can affect the scanning trueness of the crown finish line. A lab study was conducted by Hongseok et al. to evaluate the effect of subgingival finish line location and saliva contamination on the trueness of crown finish line scanning.[62, 63] They found that the intraoral scanners were unable to capture the subgingival finish lines accurately. In the scans with subgingival finish lines, there were both vertical and horizontal discrepancies with positive values, resulting in J-shaped prosthesis margins. This error pattern may have occurred because the gingiva surrounding the finish lines prevented the scanning light from reaching and reflecting from the deepest corners of the gingival sulcus. Consequently, the scanner generated misrepresented images of the deeper portion of the finish lines. Furthermore, they concluded that the accuracy of equigingival finish lines was found to be clinically acceptable during scanning. Although the presence of saliva on the finish lines caused slight increases in both vertical and horizontal discrepancies, they were still considered within an acceptable range. However, significant discrepancies were found when scanning 0.5- and 1.0-mm subgingival finish lines, resulting in open margins and under-contouring. Saliva-contaminated specimens showed even higher discrepancies, and the negative impact of saliva contamination was most pronounced when the finish line was subgingival.[62] Clinical implications include the importance of good retraction prior to taking a digital impression. Fundamental prosthodontic principles are incumbent whether an analog or digital workflow is used, and the clinician should be able to visualize the margins prior to scanning, to avoid unsuccessful margin location later in the digital workflow cascade. However, the author believes that the DLP exhibit higher trueness in scenario of ceramic crowns because the finish line was subgingival and the HSG for this printer was wider than the other printers which is 0.1 mm. So, it is expected that the IOS will capture the finish lines accurately.

Another limitation is the inherent nature of an in-vitro study. Although a digital impression of the reference cast was obtained through an intraoral scanner, certain factors, such as saliva, limited mouth opening space, and difficult accessibility to the posterior area were not considered. Further studies incorporating the actual clinical environment are needed to obtain more accurate results.[64] Taking a digital impression method has many advantages, such as saving time, reducing potential errors created from materials, and reducing patient discomfort. However, some limitations still prevent it from replacing the conventional stone casts entirely. Ongoing studies are being conducted to investigate the accuracy of digital impressions made by intraoral scanners, and it has been reported that the accuracy is sufficient for clinical use.[65] On the other hand, only a few studies have examined the accuracy of 3D printed casts. Most research on preparing teeth for prosthesis fabrication has concentrated on the single crown and 3-unit fixed dental prostheses preparations. As a result, additional studies are necessary to determine the accuracy of long-span prostheses, including half-arch or full-arch restorations. Additionally, the veneer preparations may be hard to capture with IOS and the margin detection may be challenging. The constant evolution of IOS and 3D printers seems in track with constant improvements.

Based on our investigation, the printed alveolar cast technique demonstrated clinically acceptable accuracy for veneers and onlay restorations. However, further investigation is required to determine the exact parameters for each printer in order to fabricate more accurate alveolar casts.

Conclusion

Based on the limitations of the present in-vitro study, the following conclusions may be drawn:

1. The Continuous Liquid Interface Production (CLIP) printer exhibited higher accuracy compared to the Stereolithography (SLA) printer for onlays ($P<0.001$), gold crowns ($P<0.001$), and fixed dental prostheses ($P<0.001$). Also, the Continuous Liquid Interface Production (CLIP) printer exhibited higher accuracy compared to the Digital Light Processing (DLP) for fixed dental prostheses ($P<0.001$).
2. The Digital Light Processing (DLP) exhibited higher accuracy compared to Continuous Liquid Interface Production (CLIP) the Stereolithography (SLA) printer for ceramic crowns ($P=0.010$), ($P=0.004$) respectively.
3. Despite the promising results, the 3D printed alveolar cast cannot completely replace conventional stone alveolar casts until further improvements are made. The technique showed clinically acceptable accuracy for veneers and onlay restorations, but more research is needed to determine precise parameters for each printer to achieve even more accurate alveolar casts.

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APPENDICES

Appendix A:

Table 1: Accuracy (based on RMS measured in millimeters) of each printer per prosthesis type (n=10 for each combination of prosthesis type and printer)

Prosthesis Type	Printer	Mean	Median	SD	Min	Max	*P*
Onlay	**Carbon**	0.121	0.117	0.028	0.072	0.180	<0.001 [a]
	Formlabs	0.254	0.254	0.010	0.233	0.270	
	P30	0.185	0.183	0.076	0.083	0.284	
Gold Crown	**Carbon**	0.136	0.119	0.053	0.077	0.246	0.001 [b]
	Formlabs	0.223	0.223	0.026	0.177	0.253	
	P30	0.180	0.166	0.057	0.120	0.276	
Ceramic Crown	**Carbon**	0.216	0.236	0.052	0.118	0.265	0.006 [c]
	Formlabs	0.226	0.228	0.033	0.170	0.266	
	P30	0.164	0.166	0.037	0.116	0.227	
Veneer	**Carbon**	0.098	0.092	0.024	0.073	0.134	0.055 [c]
	Formlabs	0.149	0.132	0.057	0.080	0.218	
	P30	0.109	0.095	0.046	0.066	0.218	
Fixed dental prostheses	**Carbon**	0.130	0.130	0.039	0.084	0.181	<0.001 [b]
	Formlabs	0.207	0.213	0.023	0.168	0.238	
	P30	0.199	0.203	0.038	0.122	0.244	

a. based on Welch’s ANOVA

b. based on one-way ANOVA

c. based on the Kruskal-Wallis test

Table 2: Post-hoc comparisons for prosthesis types with significant omnibus tests

Prosthesis Type	Printers	*P*
Onlay [a]	**Carbon - Formlabs**	<0.001
	Carbon - P30	0.066
	Formlabs - P30	0.044
Gold Crown [b]	**Carbon - Formlabs**	<0.001
	Carbon - P30	0.111
	Formlabs - P30	0.131
Ceramic Crown [c]	**Carbon - Formlabs**	0.761
	Carbon - P30	0.010
	Formlabs - P30	0.004
Fixed dental prostheses [b]	**Carbon - Formlabs**	<0.001
	Carbon - P30	<0.001
	Formlabs - P30	0.837

a. based on the Games-Howell test

b. based on Tukey's HSD test

c. based on Dunn's test with Bonferroni correction ($p<0.05/3 \approx 0.0167$ were considered statistically significant)

Appendix B:

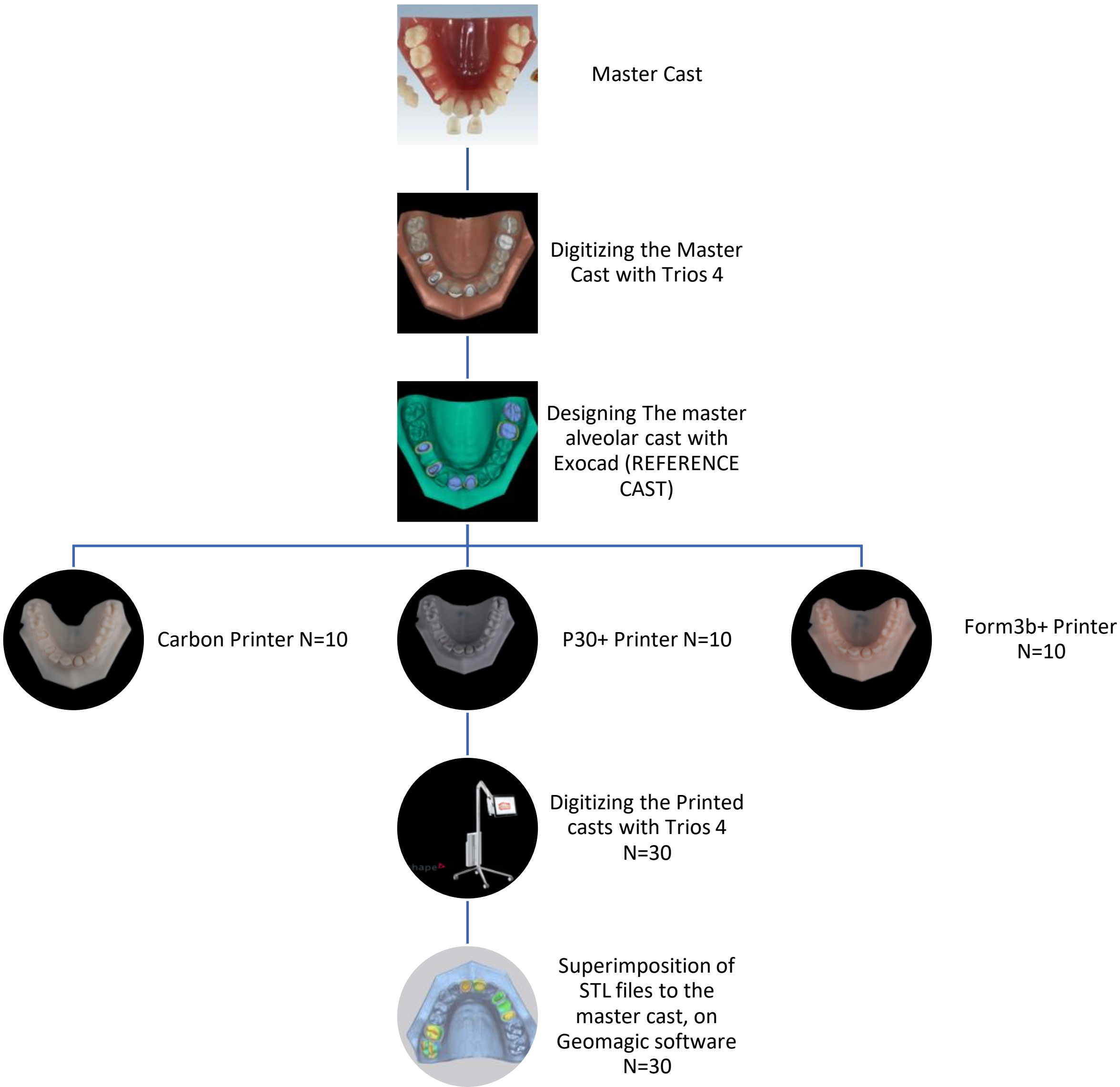


Figure 1. The Flowchart of This Study

Figure 2. Straumann® P30+ printer.

Figure 3. Formlabs® Form 3b printer.

Figure 4. M2 Carbon 3D printer.

Figure 5. Inra-oral scanner (Trios 4 , 3shape).

Figure 6. Reference Cast

Figure 7. Digitized Reference Cast

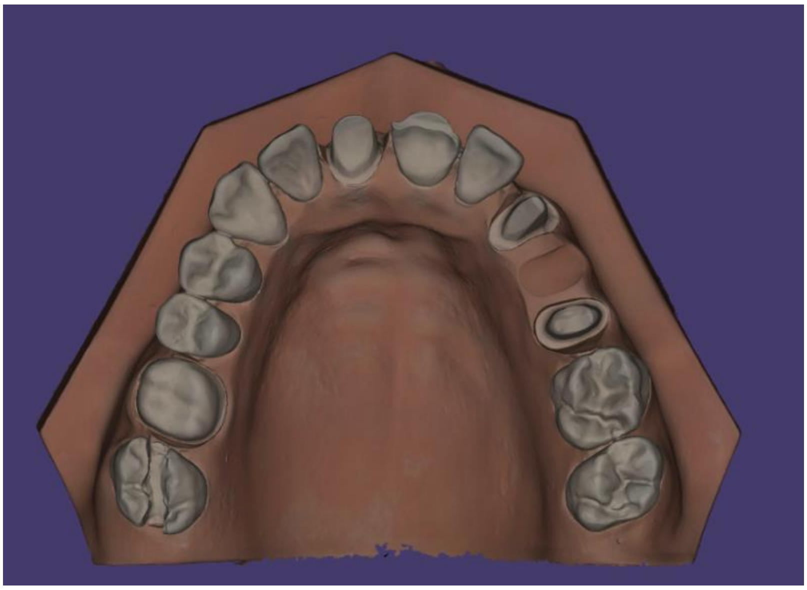
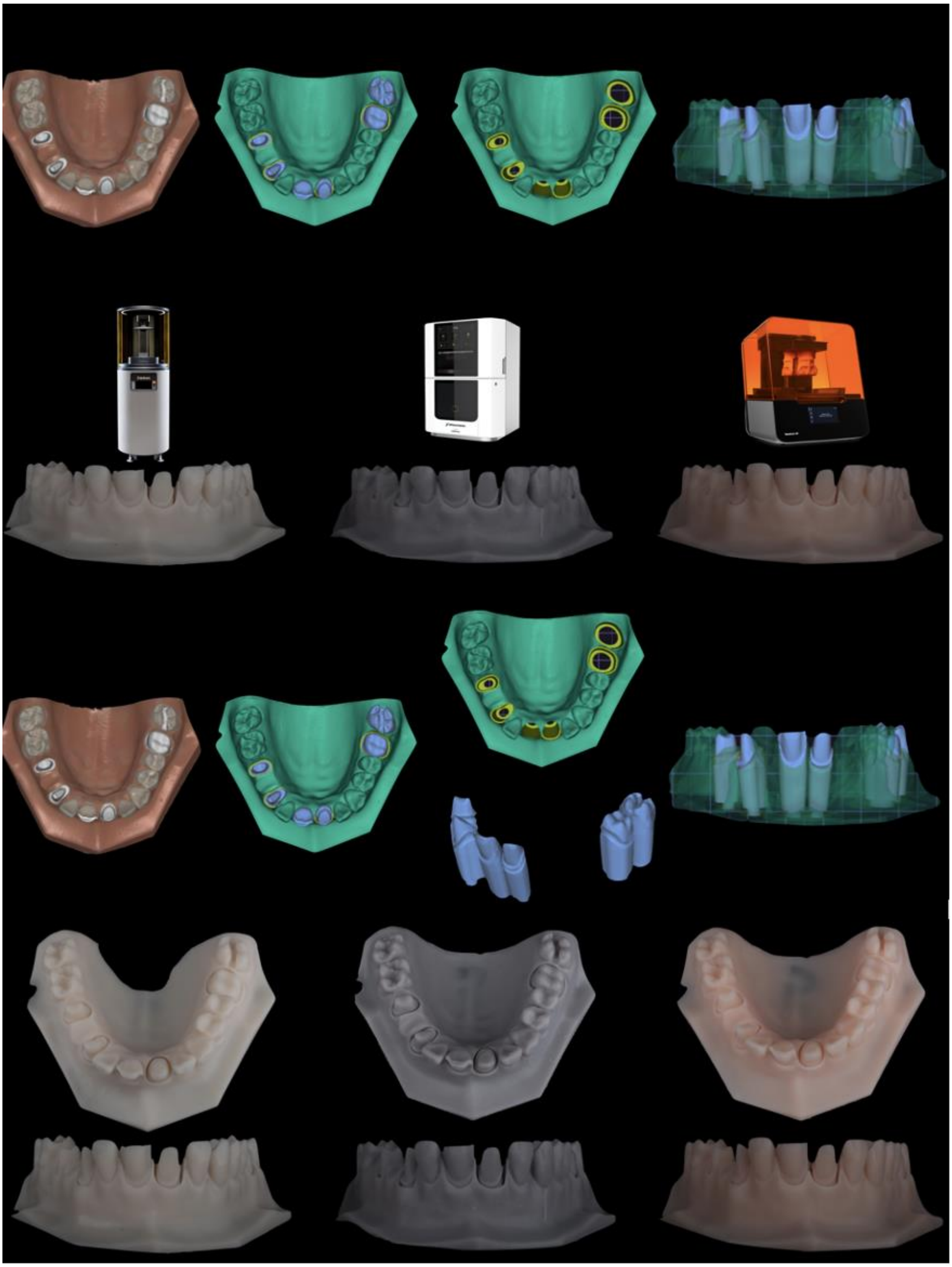


Figure 8. Exocad Designing of Alveolar Cast and Printing with Three Different Printers



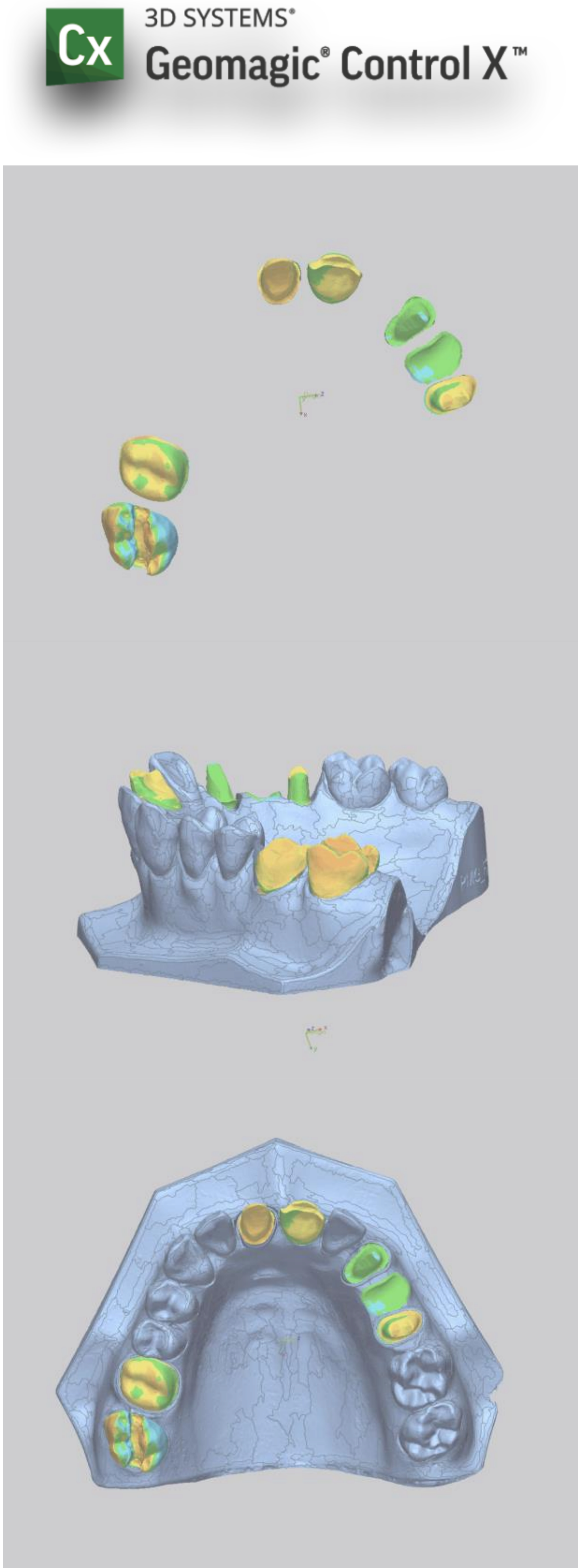


Figure 9. Superimposition of STL files to the master cast, on Geomagic software (Geomagic Control X, 2020.0.1-3D Systems, Rock Hill, SC, USA).

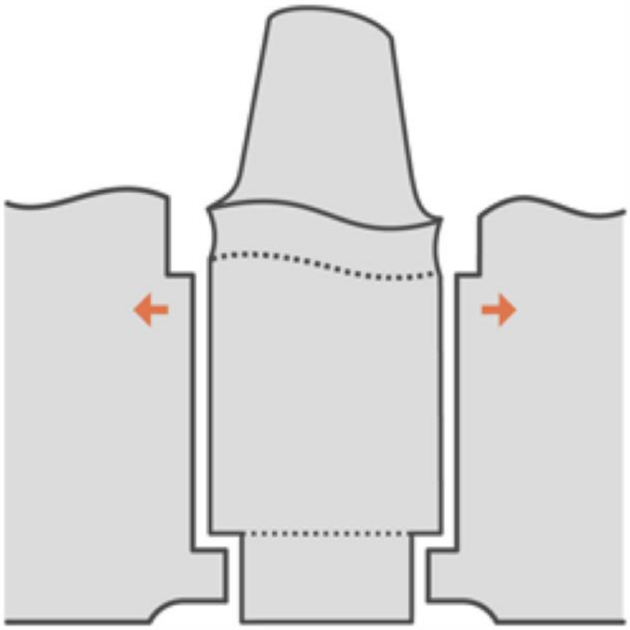


Figure 10. Horizontal Shaft Gap (HSG)