



**DIMENSIONAL ACCURACY EVALUATION OF IMPLANT-SUPPORTED
PROVISIONAL PROSTHESES FABRICATED USING THREE DIFFERENT
3D PRINTING TECHNOLOGIES**

NUTCHANART LEEWATCHARARUNGCHAROEN

**A Thesis Submitted to the Graduate School of Naresuan University
in Partial Fulfillment of the Requirements
for the Master of Science Program in Dentistry**

2026

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protheses fabricated using three different 3D printing technologies "

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has been approved by the Graduate School as partial fulfillment of the requirements

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ABSTRACT

This study evaluated the dimensional accuracy of implant-supported provisional prostheses fabricated using three 3D printing technologies—stereolithography (SLA), digital light processing (DLP), and liquid crystal display (LCD)—across four span lengths (3-, 4-, 6-, and 12-unit). Sixty prostheses were digitally designed from a standardized edentulous maxillary model, fabricated, scanned, and analyzed by superimposing the printed specimens onto the original design. Dimensional accuracy was assessed using 3D color mapping and quantified by root mean square error (RMSE).

Two-way ANOVA with Tukey's post hoc test ($\alpha = 0.05$) revealed a significant interaction between span length and printing technology ($P < 0.05$). SLA consistently achieved the lowest RMSE values across short- and medium-span prostheses, with significantly lower deviations in the 3-unit group compared with DLP and LCD. For full-arch prostheses, SLA and LCD demonstrated comparable accuracy, both outperforming DLP.

Within-group comparisons showed stable RMSE values in DLP, slight reductions in LCD, and gradual increases in SLA as span length increased. Color

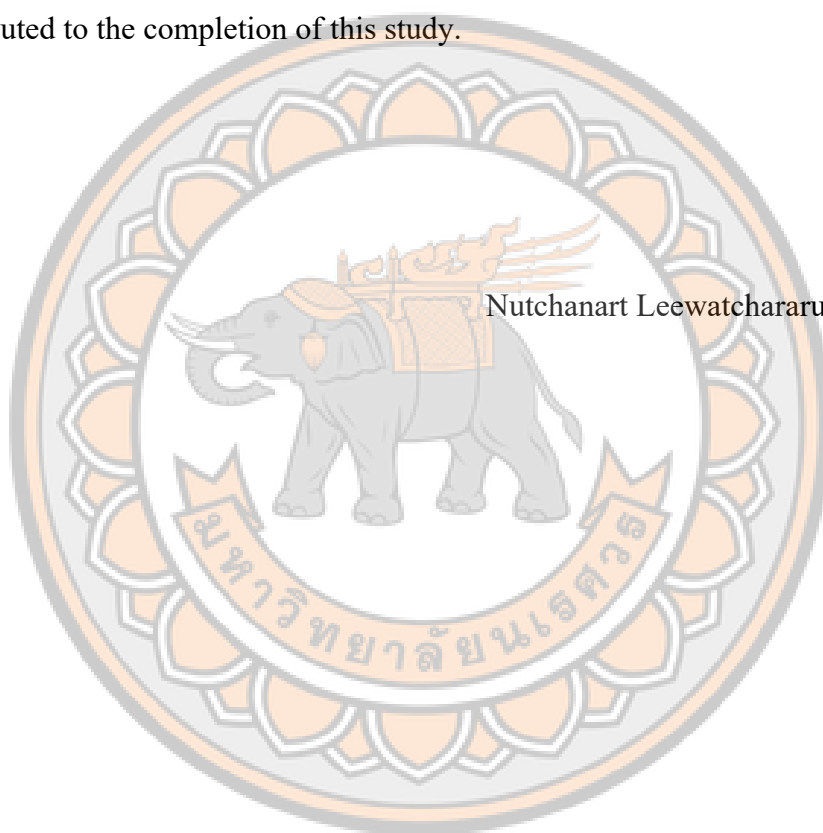
mapping confirmed these findings, with SLA specimens showing more uniform adaptation, whereas DLP and LCD exhibited greater deviations in longer spans.

Overall, prosthetic accuracy was influenced by both printing technology and span length. SLA provided the highest accuracy, while DLP and LCD produced clinically acceptable and cost-effective outcomes.



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Nutchanart Leewatchararungcharoen

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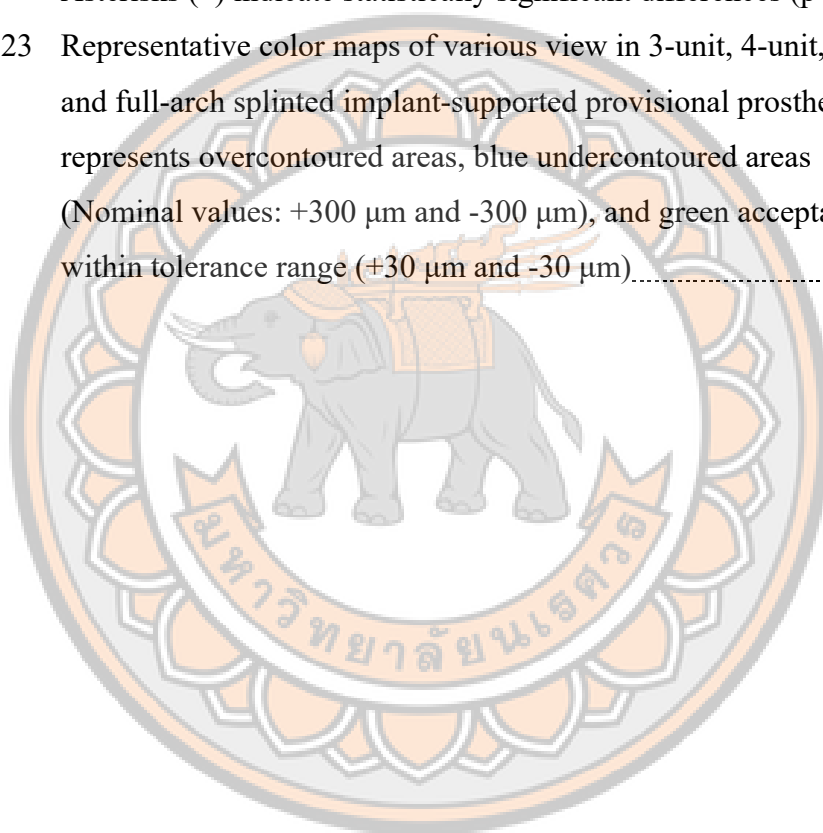
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CHAPTER I

INTRODUCTION

Background and rational of study

Implant-supported provisional prostheses play a crucial role in verifying prosthodontic considerations before the fabrication of definitive restorations. These considerations include soft tissue shaping for an optimal emergence profile, the occlusal scheme, and esthetics.^[1] Splinted implant-supported provisional prosthesis was used to minimize stress by load distribution and reduce the number of temporary implant abutment.^[2] Nowadays, computer-aided design and computer-aided manufacturing (CAD/CAM) technologies has been used to fabricate various types of prosthodontic restorations including Implant-supported provisional prostheses. The advantages of CAD-CAM over the conventional process for example the reduction of errors attributable to human labor, reduced laboratory processing time, reduction of clinical and laboratory procedures, and material costs.^[3]

In digital workflow, provisional prostheses can be fabricated with either subtractive manufacturing techniques (SM; milling) and additive manufacturing techniques (AM; 3D printing).^[4-9] SM involves milling a pre-polymerized polymethylmethacrylate disc fabricated under high-temperature and high-pressure conditions. Therefore, the advantage of definitive prostheses using polymethylmethacrylate discs is non-shrinkage owing to the absence of a polymerization process. However, the disadvantage of SM is the large amount of waste required for milling unnecessary portions and the difficulty of accessing undercut areas owing to bur size and machining axes.^[4] In contrast, AM is the process of joining materials to make parts from three-dimensional (3D) model data, usually in layers; the advantages include less generation of waste material and no limitations in the fabrication of prostheses with undercuts.^[4]

AM can be classified into seven methods.^[5] Among these seven methods, vat photopolymerization is the most popular, including traditional stereolithography (SLA), digital light processing (DLP), and liquid crystal display (LCD); the SLA, DLP, and

LCD techniques use photopolymerization to build 3D structures from a photopolymerizable liquid monomer. Fabrication using a DLP or LCD involves a short processing time. LCD has a high resolution but weak light exposure; therefore, the precision of LCD printing technology is inferior to that of DLP.^[5]

The dimensional accuracy and adaptation of provisional prostheses are fundamental requirements for the final success of the prosthesis. Adaptation is defined as the degree of fit between the prosthesis and supporting structures. Accuracy is classified into trueness and precision; “trueness” is the closeness of agreement between a test result and the accepted reference value, and precision is the closeness between test results defined by ISO 5725-1.^[10]

Previous studies has found that greater accuracy, with less deviation and shrinkage, was observed in the DLP printer compared to the LCD printer, especially in short-unit restorations.^[11] It is generally expected that higher accuracy would be provided by the SLA method compared to the DLP method, as the resin is polymerized point by point in SLA, while it is polymerized surface by surface in DLP. However, According to studies by Lee J et al. found that higher accuracy is achieved by DLP method than by SLA method when the same resin material is used.^[12]

Considering the essentiality of implant-supported provisional prostheses and the convenience of 3D printing technologies, the enhancement of 3D printing conditions may be provided with great advantages in the clinical environment. The accuracy analysis of 3D-printed provisional prostheses is considered one of the crucial steps to expand the clinical use of 3D printers in the field of dentistry. However, the dimensional accuracy of implant-supported multiple-unit provisional prostheses has not been extensively researched. There is still a lack of information regarding 3D-printed implant-supported provisional prostheses fabricated using different printing techniques, and there is a need for further study. Therefore, the purpose of this study is to analyze the dimensional accuracy of 3D-printed implant-supported multiple-unit provisional prostheses fabricated by SLA, DLP, and LCD 3D printers.

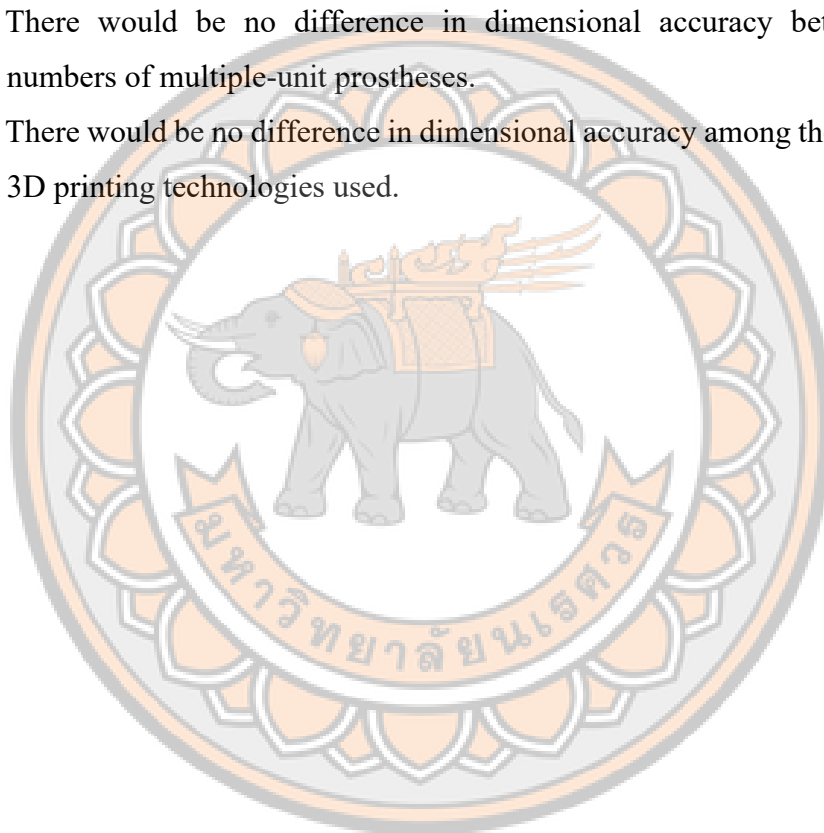
Research Purpose

To evaluate the dimensional accuracy of implant-supported provisional prostheses with different numbers of multiple units, fabricated using three different 3D printing technologies

Research hypothesis

The null hypothesis stated that:

- There would be no difference in dimensional accuracy between different numbers of multiple-unit prostheses.
- There would be no difference in dimensional accuracy among the three different 3D printing technologies used.



CHAPTER II

REVIEW LITERATURE

1. Digital fabrication technologies

1.1 Subtractive manufacturing

Subtractive manufacturing is a process of fabricating objects by grinding material from a solid block, using Computer-Aided Design (CAD) data and STL files to define the desired geometry.^[13] Subtractive manufacturing is less precise for dental prostheses with undercuts or complex internal geometries, and it also requires more extensive post-processing steps, which can lead to increased production time and labor costs. Additionally, cutting tools used in subtractive manufacturing tend to wear out over time and may need to be changed, leading to higher costs. However, subtractive manufacturing is less prone to shrinkage than additive manufacturing because it does not involve the printing process. Cheng et al. found that provisional crowns fabricated using milled technology had a significantly better fit than those fabricated using the conventional workflow.^[13] In contrast, Wu et al. found that conventional provisional prostheses had significantly better internal fit and smaller marginal discrepancy than milled and 3D-printed provisional prostheses.^[14]

1.2 Additive manufacturing

additive manufacturing, also known as 3D printing, is a layer-by-layer process for fabricating three-dimensional (3D) objects.^[15-17] They offer advantages in terms of reduced material waste and the ability to produce complex geometries without the need for extensive post-processing.^[7, 9, 18] Additive manufacturing (AM) processes, as outlined in the international standard ISO/ASTM 52900:2021, are divided into seven main types: Binder Jetting, Directed Energy Deposition, Material Extrusion, Material Jetting, Powder Bed Fusion, Sheet Lamination, and Vat Photopolymerization (VP).

1.2.1 Vat photopolymerization

Vat photopolymerization includes processes that utilize UV light to cure liquid photopolymer resin in a vat, building the object layer by layer.^[19] Vat photopolymerization is one of the most popular printing techniques in dentistry and is used to create a variety of dental restorations. Three common vat photopolymerization printing technologies are stereolithography (SLA), digital light projection (DLP), and liquid crystal display (LCD).^[20]

1.2.1.1 Stereolithography (SLA)

Stereolithography (SLA) is the most common type of vat photopolymerization printer. It represents an alternative vat polymerization method that relies on the processing of photosensitive liquid polymers activated by ultraviolet (UV) light.^[21] SLA printers are typically very accurate, but they can be slow and expensive. Patzelt et al. reported that SLA-produced models were more accurate than the milled model.^[22] (Figure 1)

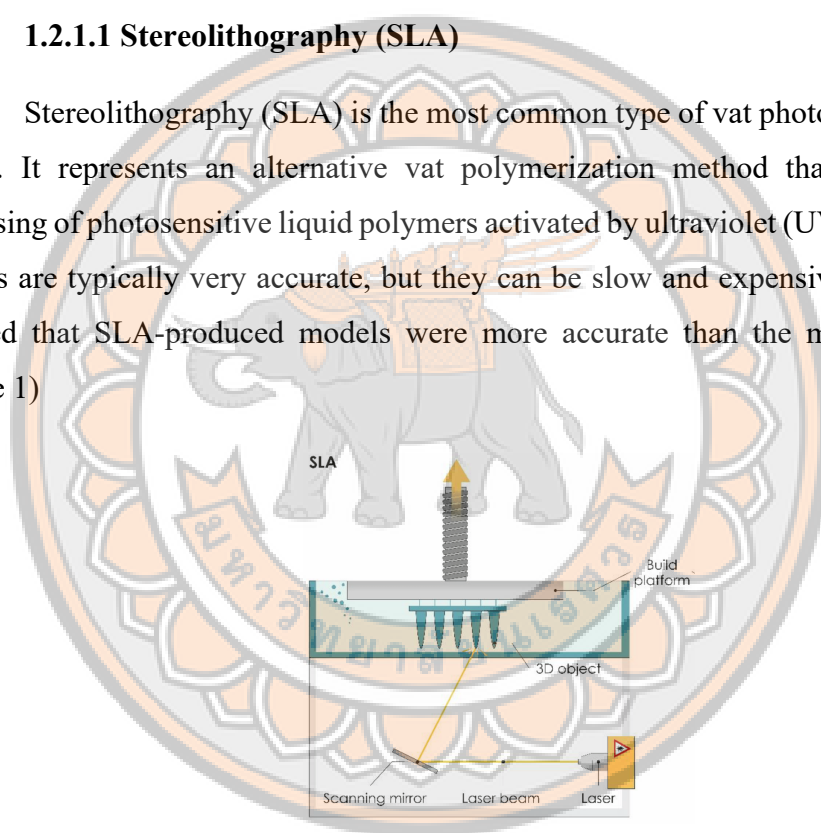


Figure 1: Schematic drawing of Stereolithography (SLA) printer

1.2.1.2 Digital light projection (DLP)

Digital light projection (DLP) involves crafting a prosthesis via photopolymerization, achieved by exposing a tank filled with acrylic or epoxy-based light-curing resin to ultraviolet (UV) light, and it stands out for its rapid printing speed and high precision.^[23] DLP printers are faster than SLA printers, but they may not be as accurate as SLA. (Figure 2)

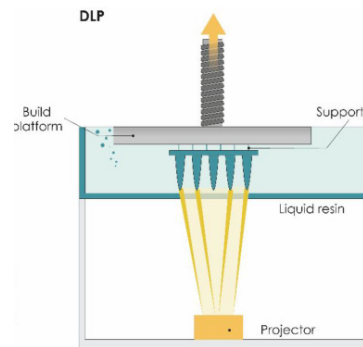


Figure 2: Schematic drawing of Digital light projection (DLP) printer

1.2.1.3 Liquid crystal displays (LCDs)

Liquid crystal displays (LCDs) function as dynamic mask generators, using liquid crystals to generate images at a low cost. However, they have some optical efficiency limitations, such as larger pixel sizes, lower filling ratios, slower switching speeds, and reduced optical contrast.^[24, 25]

The LCD method utilizes light to cure resin layer by layer, preventing hardening in unwanted areas of the LCD screen by masking them. This method is less prone to pixel distortion compared to the DLP method, where UV light is emitted across the entire surface. However, the LCD method has a slower curing speed, as the light intensity is weaker in comparison.^[12] (Figure 3)

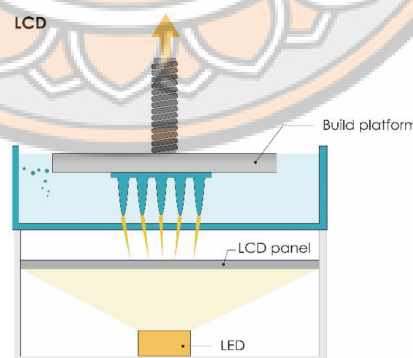


Figure 3: Schematic drawing of Liquid crystal displays (LCDs) printer

2. Vat photopolymerization resin

In 3D resin printing, the resin composition is crucial for determining the quality, strength, and functionality of the printed object. These resins are typically composed of monomers, oligomers that form the resin matrix, photo initiators that trigger polymerization when exposed to specific wavelengths of UV light, and various additives that enhance mechanical and electrical properties, as well as provide additional functionalities.

Monomers are the building blocks of the resin, typically liquid molecules that can polymerize when exposed to UV light, forming a solid structure. The most commonly used photocurable resins are acrylate-based^[26], Such as methacrylate or urethane acrylates, known for their rapid curing properties and versatility, enabling the production of both rigid and flexible parts.^[27] Epoxy-based resins are also used for parts requiring strong mechanical properties.

Oligomers, short polymer chains with lower molecular weights, influence the viscosity and mechanical properties of resins. They are generally a blend of monomers but with a lower molecular weight. They act as cross-linkers, providing the necessary structure for the final print. Common types include urethane oligomers and acrylic oligomers.

photoinitiators in the resin absorb energy and generate free radicals, which initiate a chain reaction that bonds the monomers and oligomers together, transforming the resin from a liquid or semi-liquid state into a solid polymer.^[19] Common photoinitiators include Benzoin derivatives and Camphorquinone (often used in dental resins)

Additives are incorporated into resin formulations to optimize the properties of 3D printed objects. Common additives include stabilizers to prevent premature curing, plasticizers to increase flexibility, filler materials like glass or carbon fiber for enhanced strength and durability, and pigments for color customization.

3. Dimensional accuracy analysis

The precise fit of provisional implant prostheses is considered crucial for improving the quality and efficiency of patient care. Provisional implant prostheses with high accuracy are shown to reduce chair time for adjustments, enhance the ease of insertion, improve adaptability and occlusion, and help prevent potential issues during use. Dimensional inaccuracies can lead to mechanical complications, biological issues such as peri-implantitis, and patient dissatisfaction due to poor aesthetics or discomfort.^[28] Therefore, measuring the dimensional accuracy of provisional implant prostheses is crucial for quality control in both clinical and laboratory settings. Several methods have been developed to measure the dimensional accuracy of provisional implant prostheses.

3.1 Dimensional accuracy assessment methods

3.1.1 Digital comparison using CAD software

The provisional implant prosthesis is scanned using either intraoral or laboratory scanners to create a three-dimensional (3D) file. This file is then aligned with the original CAD design using specialized software, which calculates any discrepancies between the models, often visualized with color-coded deviation maps.^[29, 30]

Color-coded deviation maps are visual representations that display the differences between two superimposed three-dimensional (3D) file in this case, the original CAD file and the provisional implant prosthesis scan file. The deviation map assigns different colors to various ranges of deviation, allowing for an intuitive understanding of where and how much the provisional implant prosthesis differs from the original design.^[31, 32]

The process of creating color-coded deviation maps.^[33]

- Scanning: The provisional implant prosthesis is scanned using a high-resolution 3D scanner.
- Superimposition: The provisional implant prosthesis scanned file is imported into CAD software and aligned with the original CAD design. This

alignment is crucial and is typically performed using best-fit algorithms to minimize discrepancies due to positioning.

- **Deviation Analysis:** The software calculates the distance between corresponding points. This involves computing the differences along the x, y, and z axes for each point.
- **Color Mapping:** The calculated deviations are mapped onto the surface using a color scale. Typically, a color spectrum from blue to red is used:
 - **Blue Shades:** Indicate negative deviations, where the provisional implant prosthesis is smaller than the design (material deficiency).
 - **Green Shades:** Represent areas within an acceptable range of deviation (often set close to zero deviation).
 - **Red Shades:** Indicate positive deviations, where the provisional implant prosthesis is larger than the design (material excess).
- **Interpretation:** The color-coded map allows clinicians and technicians to quickly identify areas where the crown may not fit properly and determine whether adjustments are necessary.

Color-coded deviation maps offer several benefits in evaluating the accuracy of the provisional implant prosthesis. These maps provide visual clarity, enabling immediate assessment of deviations and making it easier to identify problem areas. They offer quantitative data, with the software providing exact numerical values for deviations at specific points, allowing for precise adjustments.^[34] Efficiency is enhanced as inaccuracies can be detected without physical measurement tools, saving time in the evaluation process. Additionally, these maps facilitate documentation, creating a record of the assessment that can be used for quality control and communication between the dental laboratory and the clinician.^[35]

However, there are considerations to keep in mind when using color-coded deviation maps. Threshold settings must be appropriately set within the software to reflect clinical requirements. Moreover, users must be proficient in using the CAD software to ensure accurate alignment and interpretation of results.

Color-coded deviation maps are used extensively in both research studies evaluating the accuracy of different fabrication methods and in clinical practice for quality control.

Advantages of this method include being non-destructive and providing both qualitative and quantitative data on the dimensional accuracy of the provisional implant prosthesis. It allows for precise measurements at any point on the crown's surface. However, the accuracy depends on the resolution of the scanners and the algorithms used in the software. Technical expertise is required to operate the software and interpret the results accurately.

3.1.2 Replica technique

The replica technique involves creating a physical replica of the internal space between the provisional implant prosthesis and the abutment using a low-viscosity silicone material. The crown is filled with the material and seated on the abutment. After setting, the provisional implant prosthesis is removed, leaving a replica that represents the internal fit. This replica is sectioned and examined under a microscope to measure the thickness at various points ^[36, 37]

This method is cost-effective and relatively simple. It provides direct measurements of the internal fit and marginal gaps. However, it is destructive to the replica, and there's potential for distortion during sectioning. The accuracy may also be influenced by the properties of the replica material.

3.1.3 Micro-computed tomography (Micro-CT) scanning

Micro-CT scanning produces high-resolution 3D images of an object's internal and external structures. In measuring provisional implant prosthesis, micro-CT allows for non-destructive examination of internal fit and marginal gaps. Software tools analyze the scanned images to measure discrepancies between the provisional implant prosthesis and the abutment ^[38]

This method provides detailed visualization of internal features not accessible by other non-destructive methods. It is particularly useful for evaluating internal fit without sectioning the provisional implant prosthesis. However, micro-CT scanning is

costly, requires specialized equipment and expertise, and is not widely available in all dental laboratories.

3.1.4 Optical microscopy

Optical microscopy involves examining the provisional implant prosthesis seated on the abutment under a microscope to assess marginal fit. Gaps between the provisional implant prosthesis margin and the abutment are observed and measured using calibrated eyepieces or digital imaging software. [39]

While accessible and straightforward, this method is limited to assessing external surfaces and marginal areas. It does not provide information about the internal fit of the provisional implant prosthesis. Measurements can be subjective and are subject to human error.

3.1.5 Laser scanning and interferometry

Laser scanning captures the surface topography of the provisional implant prosthesis using laser technology. The scanned data is compared to the original CAD file to identify deviations. Interferometry uses the interference patterns of laser light to measure surface irregularities with high precision [40,41]

These methods offer high accuracy and are non-contact, making them suitable for delicate surfaces. They are effective for measuring complex geometries and fine surface details. However, they are sensitive to surface properties such as reflectivity and may require surface treatment to obtain accurate results. Specialized equipment and expertise are necessary.

3.2 Evaluation parameters

3.2.1 Root mean square error

The Root mean square error (RMSE) is an important metric for evaluating the accuracy of estimators by comparing predicted values with observed values. It is calculated by taking the square root of the average of the squared differences between the predicted and observed values.[42] RMSE is recognized as a valuable tool for assessing accuracy in digital dentistry. Digital impressions are compared with reference

or actual dental dimensions, and the alignment between predictions and reality is quantified using RMSE. RMSE lacks standardization as a measurement, and its interpretation depends on the range and variance of the data. Therefore, RMSE should be interpreted cautiously and used in conjunction with other metrics, such as trueness, precision, mean absolute error (MAE), or coefficient of determination (R-squared), for a more comprehensive assessment.^[42, 43]

4. Digital scanning technologies

4.1 Intraoral scanner

The intraoral scanner (IOS) is a device employing optical technology to capture digital impressions of teeth and soft tissues. Within dentistry, the IOS serves diverse purposes including diagnosis, treatment planning, creating restorations, placing implants, and facilitating orthodontic treatments.^[44] While the IOS offers various advantages over conventional impressions like enhanced patient comfort, reduced chair time, cost savings on materials, simplified storage and communication, and heightened accuracy,^[44, 45] it also presents certain limitations. These include the necessity for proper training, calibration, and maintenance, sensitivity to environmental factors such as moisture and blood, dependency on software and hardware compatibility, and a notable initial investment.^[44]

Moreover, the IOS finds utility in diagnostic applications, such as identifying caries, dental wear, periodontal diseases, and oral cancer. Through capabilities like high-resolution imaging, quantitative measurements, color mapping, and fluorescence analysis, the IOS assists dentists in recognizing and monitoring oral lesions and diseases.^[46] Nonetheless, it's crucial to underscore that while the IOS provides valuable insights, it cannot replace the significance of clinical examinations and histopathological confirmation. Further research is essential to firmly establish its diagnostic accuracy and reliability.^[46]

In summary, the IOS emerges as a promising technological advancement with the potential to enhance the quality of dental care and elevate the patient experience. Nevertheless, dentists should possess a comprehensive understanding of its pros and

cons and make informed decisions regarding the most suitable IOS based on available evidence.^[44-46]

4.2 Extraoral dental lab scanner

As the initial step in dental CAD/CAM (computer-aided design/computer-aided manufacturing) techniques, there are two ways to create a digital impression: direct intraoral scanning or indirect extraoral scanning of gypsum casts.^[47]

Extraoral scanners are generally recognized for their slightly better or comparable accuracy to intraoral scanners, primarily because a controlled scanning environment is provided. External interferences are minimized by this controlled setup, ensuring that consistent and reliable results are achieved. In contrast, intraoral scanners are directly influenced by intraoral conditions such as patient movement, oral humidity, and the presence of saliva. These factors can significantly impact the precision of intraoral scanners, particularly when complex anatomical regions are being scanned.

For full-arch scans, higher accuracy is consistently demonstrated by extraoral scanners. This superior performance is attributed to advanced features, including multi-axis motion plates and multiple sensors, which allow scanning angles and directions to be optimized. These capabilities enable complex cases to be handled more effectively by extraoral scanners. On the other hand, image-stitching techniques are heavily relied upon by intraoral scanners to create virtual models. Although this method is effective in many cases, deviations can be caused, especially in regions with less defined geometric structures, such as the anterior teeth and canine areas, where the transition from anterior to posterior arches presents additional challenges.^[48]

While the convenience of direct patient interaction and chairside use is provided by intraoral scanners, extraoral scanners are considered more suitable for laboratory-based workflows where precision and accuracy are critical.

CHAPTER III

RESEARCH METHODOLOGY

A total of 60 implant-supported provisional prostheses were fabricated using three different 3D printing technologies—stereolithography (SLA), digital light processing (DLP), and liquid crystal display (LCD)—across four span lengths: 3-unit, 4-unit, 6-unit, and full-arch (Fig 4). The design files were exported in STL format and processed using proprietary slicing software corresponding to each 3D printer (Table 1). Fabrication and post-processing were carried out according to the manufacturer's recommendations.

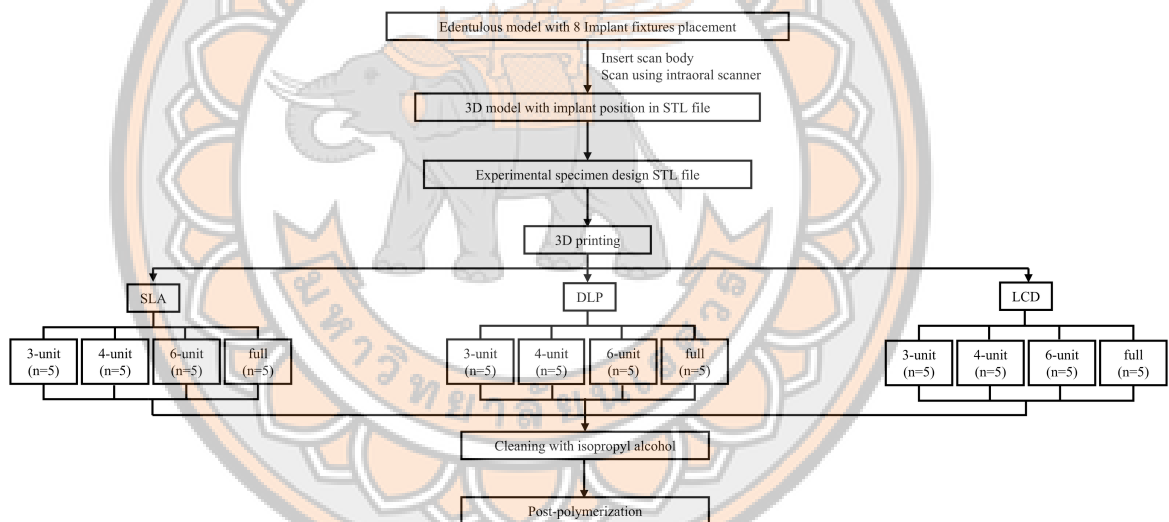


Figure 4. Flowchart of experimental specimen's preparation process fabricated by three printing -technologies (SLA, DLP, and LCD)

1. Population and Sample

The sample size was recalculated using G*Power 3.1 (Kiel University, Kiel, Germany). The alpha value (probability of a type I error) and statistical power ($1-\beta$, probability of not making a type II error) were set at 0.05 and 0.95, respectively. The effect size for this study was calculated based on the results of a pilot study. The calculation indicated a required sample size of 24 specimens across the three groups, corresponding to 8 specimens per group and 2 specimens per subgroup. However, to

ensure consistency with previous methodologies and to enhance the robustness of subgroup analyses, 5 specimens per subgroup were used in this study.

2 Specimens preparation

2.1 Design of implant-supported provisional prostheses

maxillary edentulous model (Osstem Co., Seoul, Korea) was used for the placement of eight implant fixtures by a prosthodontist. To transition to a fully digital workflow, the process began by scanning the upper and lower edentulous models using a laboratory scanner (E4, 3Shape, Copenhagen, Denmark) to design the baseplate. The baseplate was then printed with a DLP printer (P20+; Straumann, Basel, Switzerland) (Figure 5), followed by the fabrication of a bite block. A laboratory scanner was subsequently used to capture the bite block relationship (Figure 6), which was processed and utilized to design a digital complete denture with CAD software (3Shape Dental System 2021; 3Shape, Copenhagen, Denmark) (Figure 7).



Figure 5. 3D-printed base plate



Figure 6. Biteblock in CAD software (3Shape Dental System 2021)

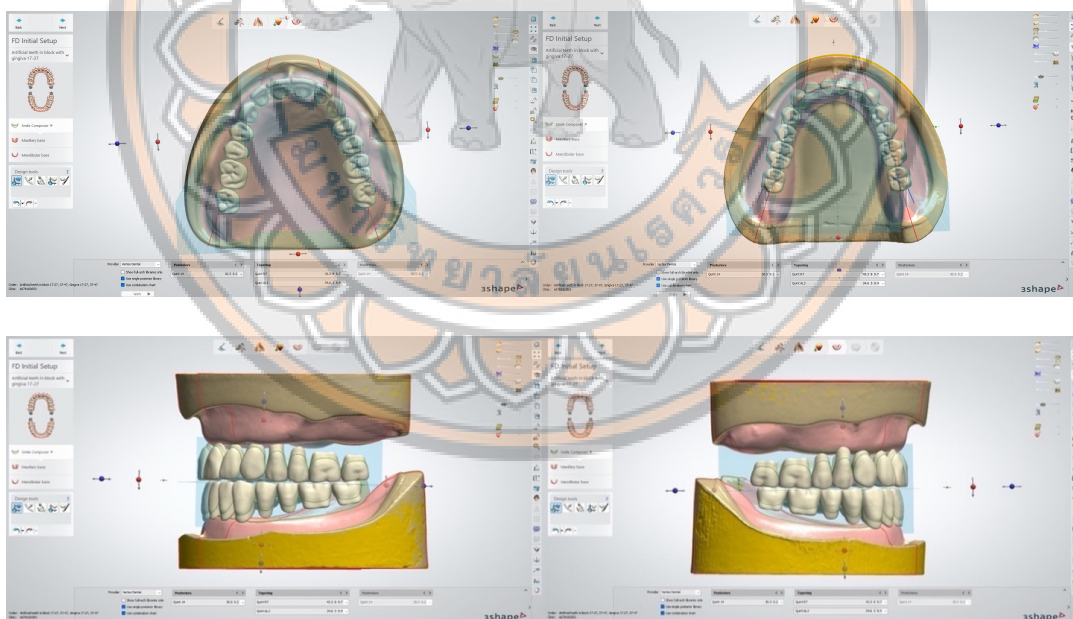


Figure 7. Digital complete denture design

After the digitally completed denture is obtained with a DLP printer (P20+; Straumann, Basel, Switzerland), the dual scan process is carried out (PaX-i3D Green, Vatech, Hwaseong, South Korea). The first CT scan, known as the patient CT scan (Figure 8, 9A), involves the CT scanning of the upper and lower edentulous models with

the completed denture and markers in place. This scan captures both the edentulous models and the prosthesis in occlusion (biting position). The second CT scan, known as the prosthesis CT scan (Figure 8, 9B), involves the CT scanning of the prosthesis alone, without the model. The prosthesis is positioned in the same orientation as it was in the first CT scan. Following this, a digital guide is created according to the plan using CAD software. (scan Implant Studio; 3Shape, Copenhagen, Denmark).

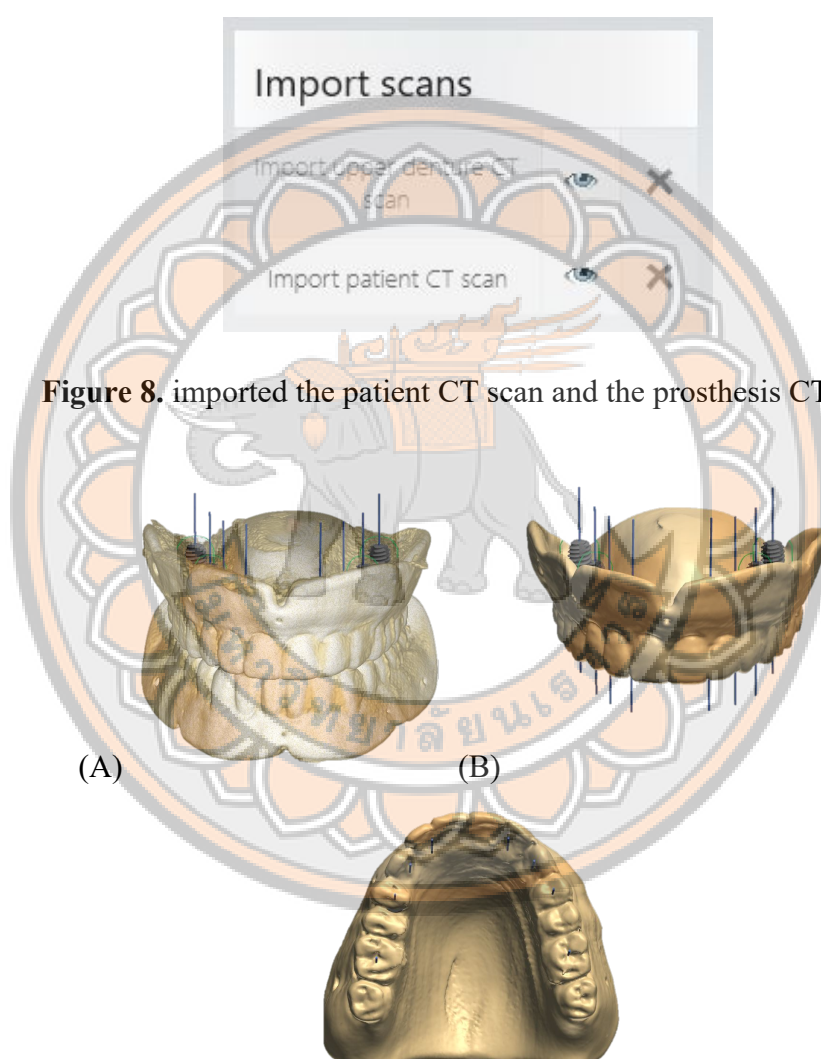


Figure 8. imported the patient CT scan and the prosthesis CT scan

Figure 9. The patient CT scan (A) and the prosthesis CT scan (B)

Implants with diameters of 3.5 mm, 4.0 mm, 4.5 mm, and 5.0 mm and lengths of 10.0 mm, 11.5 mm, and 8.5 mm (TSIII SA; Osstem Co., Seoul, Korea) were placed in the edentulous areas of the lateral incisors, canines, first premolars, and first molars. The

positions of the implant placements are 16, 14, 13, 12, 22, 23, 24, and 26, respectively. (Figure 10)

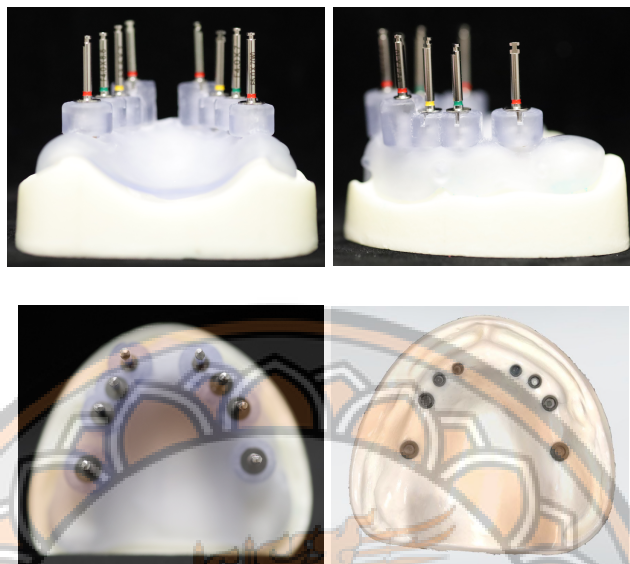


Figure 10. Implant placement in the edentulous areas of the lateral incisors, canines, first premolars, and first molars.

The implant positions were located using mini and short scan body of 8-mm length (Osstem TS Mini/ Regular scanbody; Osstem Co., Seoul, Korea) (Figure 11) and digitized using intra-oral scanner (Trios 3; 3Shape, Copenhagen, Denmark). The scanned model with implant positions was saved as standard tessellation language (STL) files.



Figure 11. The implant positions were located using mini and short scan body



Figure 12. The virtual designed implant-supported full arch provisional prosthesis

The virtual Ti-base abutments (Link abutment; Osstem Co., Seoul, Korea), corresponding to the implant fixtures, were selected. An implant-supported full-arch provisional prosthesis was virtually designed using CAD software (3Shape Dental System 2021; 3Shape, Copenhagen, Denmark) (Figure 12). The design was saved in standard tessellation language (STL) file format. The STL file of the full-arch provisional prosthesis was used as the original design to create 3-unit, 4-unit, 6-unit, and full-arch implant-supported provisional prostheses using the same CAD software (Figures 13–14). Reference markers in the form of 1×1 mm notches were added on the mid-buccal or mid-labial surface of each design using 3D Builder software (Microsoft, Redmond, WA, USA), and then saved as STL files (Figure 15).

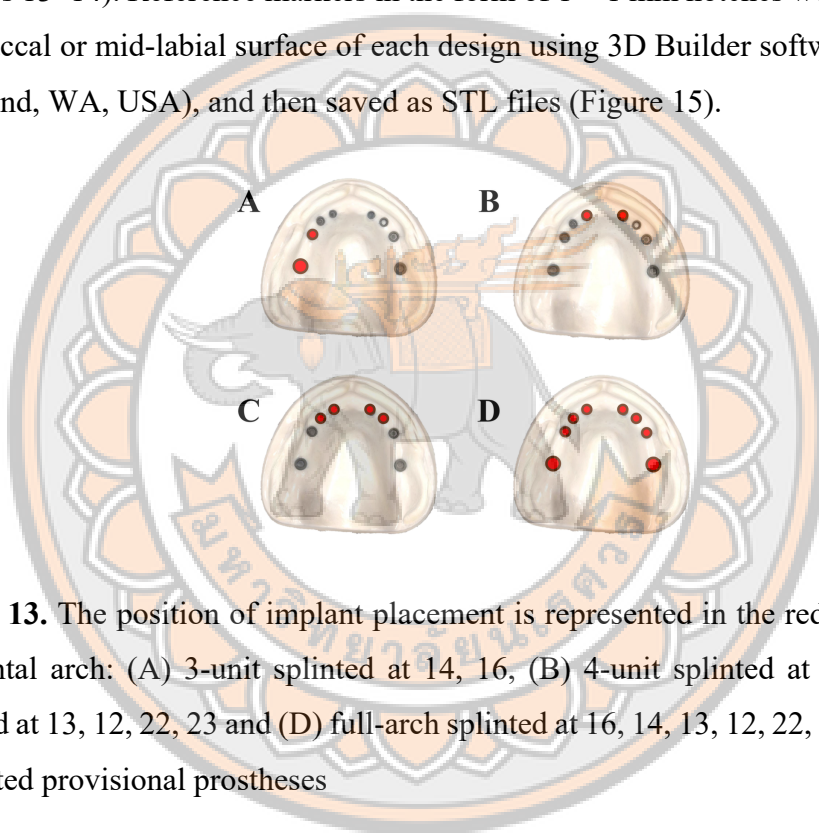


Figure 13. The position of implant placement is represented in the red marker following the dental arch: (A) 3-unit splinted at 14, 16, (B) 4-unit splinted at 12, 22, (C) 6-unit splinted at 13, 12, 22, 23 and (D) full-arch splinted at 16, 14, 13, 12, 22, 23, 24, 26 implant-supported provisional prostheses

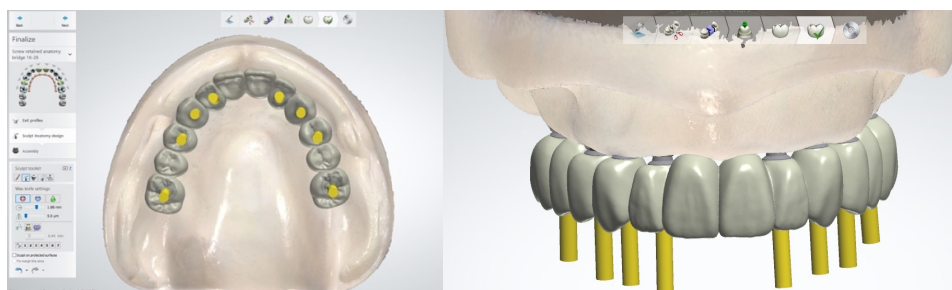


Figure 14. The design of implant-supported provisional prostheses.

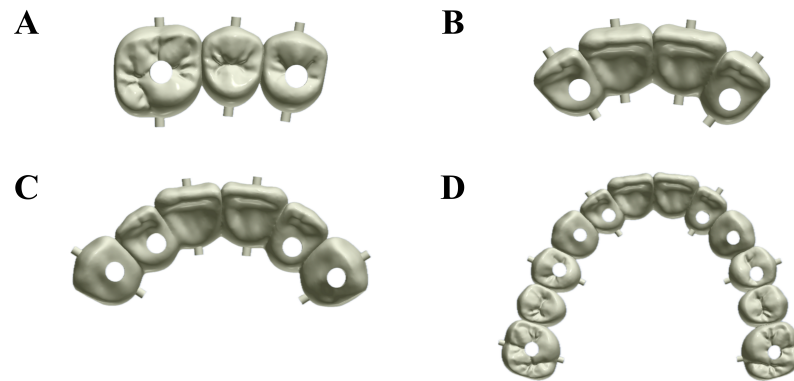


Figure 15. STL files of implant-supported provisional prostheses with reference markers placed on the mid-buccal or mid-labial surface and mid-palatal: (A) 3-unit splinted, (B) 4-unit splinted, (C) 6-unit splinted, and (D) full-arch splinted prostheses.

2.2 Three-dimensional printed specimen preparation and scanning

For the fabrication of 3D-printed implant-supported provisional prostheses, the STL files of the 3-unit, 4-unit, 6-unit, and full-arch designs were oriented with the cervical surface facing downward and positioned at a 90° angle to the build platform.

Support structures were generated using Chitubox software (Shenzhen CBD Technology Co., Ltd., Baoan, Shenzhen, China). (Figure 16)

Slicing was performed using the software corresponding to each 3D printer: PreForm (Formlabs, Somerville, MA, USA) for the SLA printer (Form 3B+, Formlabs, Somerville, MA, USA), Asiga Composer (Asiga, Alexandria, NSW, Australia) for the DLP printer (Asiga Max, Asiga, Alexandria, NSW, Australia), and Chitubox for the LCD printer (Phrozen Sonic Mighty Revo 14K; Phrozen Tech Co., Ltd., Hsinchu City, Taiwan). (Figure 17, Table 1).

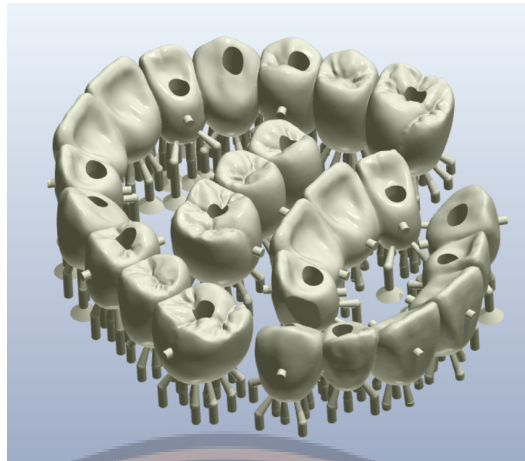


Figure 16. implant-supported provisional prostheses with support structures

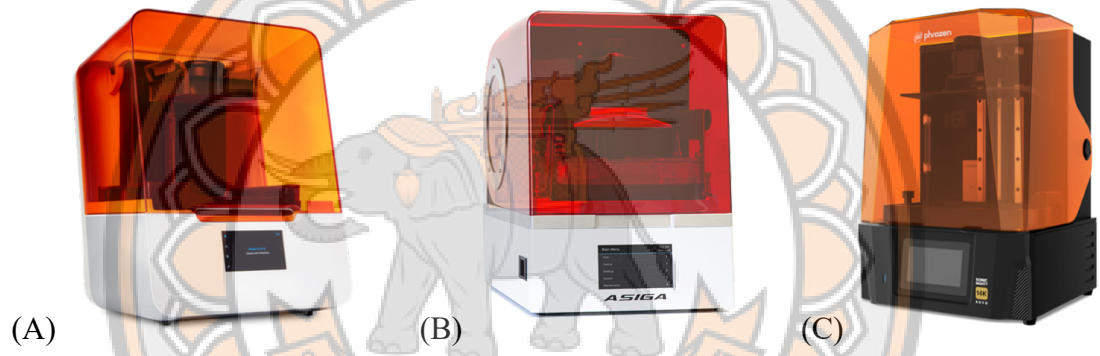


Figure 17. 3D printers: (A) SLA printer (Form 3B+), (B) DLP printer (Asiga max), (C) LCD printer (Phrozen Sonic mighty rev0 14K)

Table1. Specifications of 3D printing devices and corresponding slicing software and resin brands used in this study.

3D Printing Devices Brand	Form3B+	Asiga Max	Phrozen Sonic mighty revo 14K
Printing technology	SLA	DLP	LCD
Light source	Laser (spot 85 μm)	UV LED projector	14K Mono LCD + ParaLED
Wave-length	405 nm	385 or 405 nm	405 nm
XY Resolution	25 μm	62 μm	16.8 x 24.8 μm
Z Resolution / Layer thickness	25 - 300 μm (depending on resin selected)	1 μm , usually 10 – 100 μm	10 - 300 μm
Build Volume (LxWxH)	145 x 145 x 175 mm	119 x 67 x 75 mm	223 x 126 x 235 mm
Slicing software	PreForm	Asiga Composer	Chitubox
Resin Brand	Temporary CB	DentaTOOTH	NextDent C&B MFH

One 3D printer fabricated 5 provisional prostheses per each condition (20 printed specimens per one printing technology) with a layer thickness of 50 μm using methacrylate-based photopolymerizable monomer for provisional prostheses as shown in Table 2. One hundred eighty 3D printed implant-supported provisional prostheses were fabricated in total. By three printing technologies. The 3D printer functions were calibrated by the manufacturer. Photopolymerization, cleaning, and post polymerization were performed according to the manufacturer's recommendations.

Table 2. Summary of monomer compositions and shade colors of resin brands used in this study

Brand	Compositions	Manufacturer	Lot. number
Temporary CB	- Esterification products 4,4 isopropylidenediphenol - Ethoxylated and 2-methylprop-2-enoic acid - Diphenyl (2,4,6-trimethylbenzoyl	Formlabs Inc., Somerville, USA	601313 (Shade A3)
DentaTOOTH	- 7,7,9(or 7,9,9)-trimethyl-4,13-dioxo-3,14-dioxo-5,12-diazahexadecane-1,16-diylbismethacrylate - Tetrahydrofurfuryl methacrylate - Diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide	ASIGA, Sydney, Australia	5000429 (Shade A3)
NextDent C&B MFH	- Bisphenol A-glycidyl methacrylate - Urethane dimethacrylate - Triethylene glycol dimethacrylate - Tetrahydrofurfuryl methacrylate	Vertex-Dental B.V. (NextDent, 3D Systems), Netherlands	WU281N04 (Shade N1.5)

For the SLA 3D-printed group, the specimen will first be detached from the build platform using Build Platform 2's Quick Release Technology. Next, the specimen will be placed in the FormWash automated washing machine (FormWash, Formlabs, Somerville, MA, USA) for 3 minutes, using 99% isopropyl alcohol (IPA) to remove excess resin (Figure 18A). After washing, the specimen will be dried and then transferred to the Form Cure polymerization machine (FormCure, Formlabs, Somerville, MA, USA). There, it will undergo a 20-minute curing process at 60°C to ensure complete polymerization (Figure 18B). The company's recommendations should be followed for this step. The support structures will then be removed, and the specimen will be polished. All specimens will be stored in a metal box at $25 \pm 2^\circ\text{C}$ for one day to prevent further exposure to light.

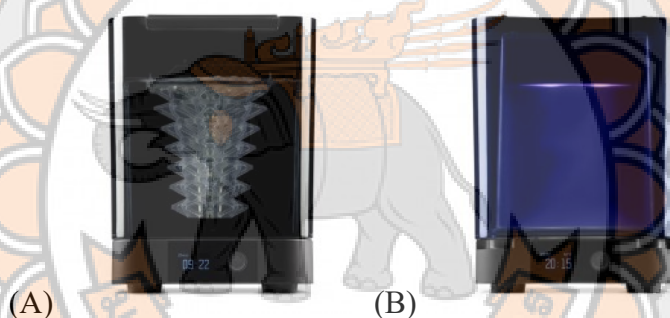


Figure 18. FormCure (A) and FormWash (B) automated washing machine

For the DLP 3D-printed group, the specimen will be carefully detached from the build platform using a scraping tool and then immersed in an ultrasonic bath Sonorex (Super 10P/Banderlin, Austria) containing 99% isopropyl alcohol for 3 minutes (Figure 19A). Afterward, the specimen will be dried with compressed air before being placed in a light polymerization device (HiLite Power 3D, Kulzer, Australia) for 10 minutes to achieve full polymerization (Figure 19B). Follow the company's recommendations for this step. The support structures will then be removed, and the specimen will be polished. All specimens will be stored in a metal box at $25 \pm 2^\circ\text{C}$ for one day to protect them from further light exposure.



Figure 19. Ultrasonic bath Sonorex (A) and light polymerization device (HiLite Power 3D) (B)

For the LCD 3D-printed group, the specimen will be carefully detached from the build platform using a scraping tool. The printed parts will then be cleaned in the Phrozen Wash (Phrozen Wash, Phrozen Tech Co., Ltd., Hsinchu City, Taiwan) with isopropyl alcohol for 3 minutes to remove any excess resin (Figure 20A). Afterward, the parts will be cleaned for an additional 2 minutes in isopropyl alcohol. The total cleaning time should not exceed 5 minutes to prevent defects in the printed parts. Once cleaned and dried, the parts will be allowed to rest for at least 10 minutes to ensure all ethanol residue is removed. Finally, the printed parts will be placed in the Phrozen Cure (Phrozen Cure, Phrozen Tech Co., Ltd., Hsinchu City, Taiwan) for 30 minutes at 60°C to ensure complete polymerization (Figure 20B).. The company's recommendations should be followed for this step. The support structures will then be removed, and the specimen will be polished. All specimens will be stored in a metal box at $25 \pm 2^{\circ}\text{C}$ for one day to protect them from further light exposure.

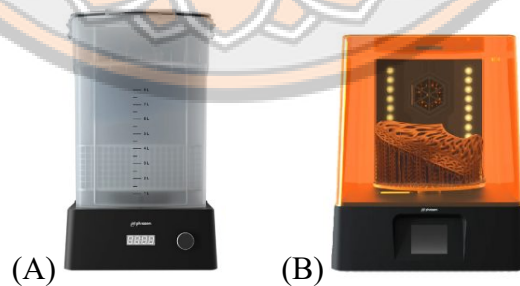


Figure 20. Phrozen Wash (A) and Phrozen Cure (B)

All the printed specimens were scanned using a lab scanner to obtain provisional prostheses STL files. The entire process was performed by an experienced single operator.

3. Analysis and evaluation

3.1 Dimensional accuracy evaluation

3.1.1 Measurement of deviation

The scanned STL files of 3-, 4-, 6-unit and full arch implant-supported provisional prostheses fabricated using 3D printing technologies were superimposed on their reference STL files with initial alignment and best fit alignment using data-matching software (Geomagic Control X, 3D system, Rock Hill, South Carolina, USA) (Figure 21). The deviation between the datasets of the entire surface of each scanned provisional prosthesis and the corresponding reference was calculated for all data points, which were the XYZ coordinates. For each 10 provisional prostheses, the mean of the positive and negative deviation values (average) and the square root of the arithmetic average of the square of the values (root mean square: RMS) were calculated to evaluate the trueness and dimensional accuracy of the provisional prostheses

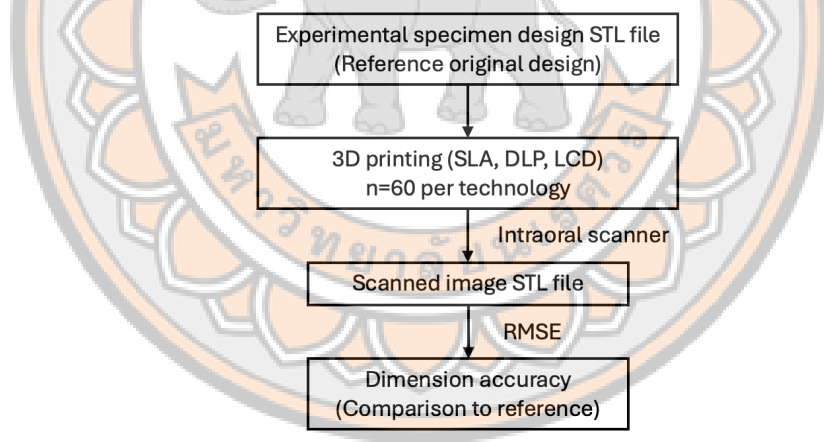


Figure 21. Flowchart of experimental specimen's scanned image preparation process for dimensional accuracy evaluation.

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (y_i - \hat{y}_i)^2}$$

Where N = the measurement points

y_i = the reference data

$\hat{y}_i$ = the scan data for the different group

In particular, the RMS values were used to eliminate the influence of the positive and negative signs of the errors and were squared so that the error distributions could be well reflected. Precision of provisional prostheses with the same design of splinted unit fabricated by each manufacturing process were evaluated from standard deviation of their trueness value. Standard deviation of trueness value nearly zero means high precision. In the present study, the average and standard deviation of the RMSE is referred to as “trueness” and “precision,” respectively.

In this section, a qualitative expression was presented. Surface deviation color maps were visually displayed, and the nominal and maximum critical deviations were set to $\pm 30 \mu\text{m}$ and $\pm 300 \mu\text{m}$, respectively. The surface deviation color map shows the distribution of deviation between original CAD and fabricated provisional prosthesis STLs. To evaluate its displacement and generate a color map indicating the direction of deviation, the total deviation of the entire external surface was calculated. Positive deviation, represented by yellow to red on the color map, indicated portions of the fabricated provisional prosthesis data were larger than the original CAD data. Negative deviation, represented by light blue to blue, indicated portions of the fabricated provisional prosthesis data were smaller than the original CAD data. Light green to green areas indicated acceptable deviation.

4. Statistical analysis

All the data were statistically analyzed using two-way analysis of variance (ANOVA) and Tukey’s multiple comparison test at a significance level of 0.05 ($p < 0.05$). All the statistical analyses were performed using a statistical software program (IBM SPSS Statistics v24; IBM Corp, Chicago, USA)

CHAPTER IV

RESULTS AND DISCUSSION

RESULTS

The dimensional accuracy of implant-supported provisional prostheses was evaluated using RMSE values and 3D surface color mapping. A significant interaction was found between the number of prosthetic units and the 3D printing technology used ($P < 0.05$). Post hoc analyses revealed statistically significant differences in RMSE values among the different printing technologies and among the different unit-span groups.

Across all span lengths, the SLA printer consistently demonstrated the lowest RMSE values, indicating superior dimensional accuracy (Table 3, Figure 22). In the 3-unit group, SLA exhibited the lowest deviation ($23.70 \pm 1.33 \mu\text{m}$), significantly lower than both DLP ($29.76 \pm 1.37 \mu\text{m}$) and LCD ($29.34 \pm 1.52 \mu\text{m}$). Similar results were found in the 4-unit group, where SLA ($25.50 \pm 1.12 \mu\text{m}$) outperformed DLP ($31.06 \pm 0.79 \mu\text{m}$) and LCD ($28.36 \pm 2.45 \mu\text{m}$), although statistical groupings showed some overlap.

In the 6-unit group, SLA ($25.14 \pm 0.66 \mu\text{m}$) maintained superior accuracy compared with DLP ($30.14 \pm 0.34 \mu\text{m}$) and LCD ($28.88 \pm 1.75 \mu\text{m}$). For the full-arch (12-unit) group, SLA ($27.44 \pm 0.27 \mu\text{m}$) and LCD ($27.64 \pm 0.50 \mu\text{m}$) demonstrated similar accuracy, both of which were significantly better than DLP ($29.32 \pm 0.16 \mu\text{m}$).

Within-group comparisons of 3D printing technology showed that the DLP group exhibited relatively stable RMSE values across all span lengths, ranging from $31.06 \pm 0.79 \mu\text{m}$ (4-unit) to $29.32 \pm 0.16 \mu\text{m}$ (12-unit), with no statistically significant differences. The LCD group showed a slight decrease in RMSE as span length increased, but without statistically significant differences. In contrast, the SLA group exhibited a gradual increase in RMSE with increasing span length, with a statistically significant difference between the 3-unit and 12-unit groups. Despite this trend, the SLA group consistently demonstrated the highest overall dimensional accuracy.

Table 3: Mean RMSE ($\pm$ SD) values (μ m) for implant-supported provisional prostheses fabricated using different 3D printing machines and units. Different letters indicate statistically significant difference.

Unit	Printing technologies		
	SLA	DLP	LCD
3	23.70 $\pm$ 1.33 (a)	29.76 $\pm$ 1.37 (de)	31.16 $\pm$ 1.08 (e)
4	25.50 $\pm$ 1.12 (abc)	31.06 $\pm$ 0.79 (e)	30.98 $\pm$ 1.75 (e)
6	25.14 $\pm$ 0.66 (ab)	30.14 $\pm$ 0.34 (e)	28.88 $\pm$ 1.75 (de)
12	27.44 $\pm$ 0.27 (bcd)	29.32 $\pm$ 0.16 (de)	27.64 $\pm$ 0.50 (cd)

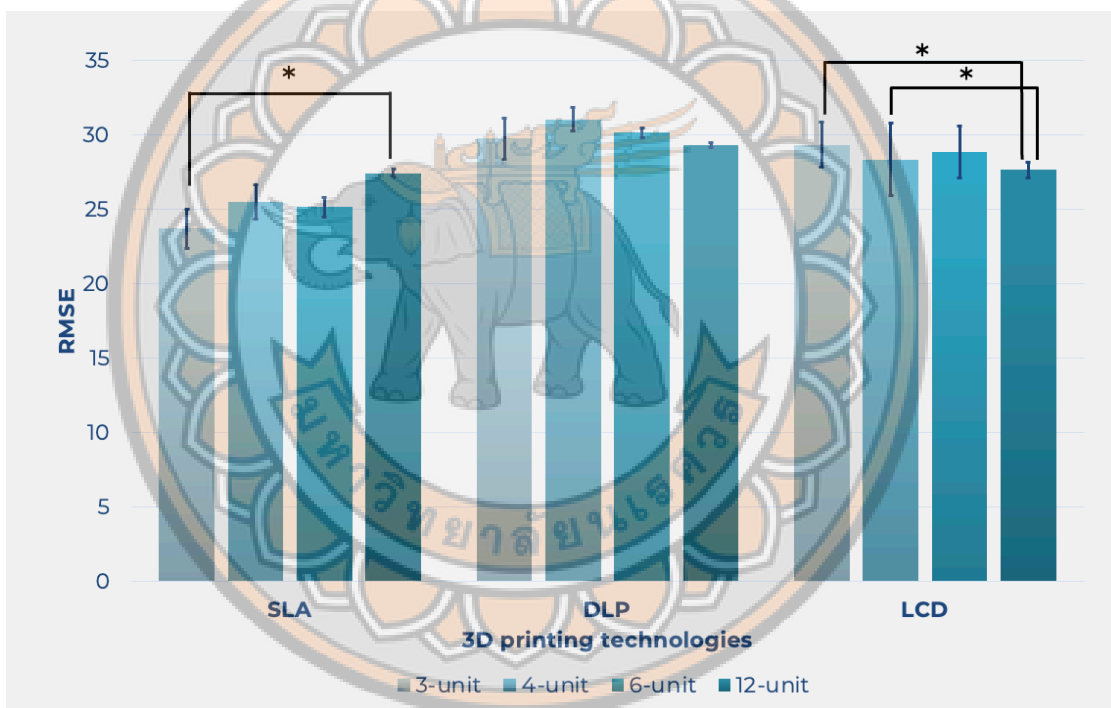


Figure 22. Mean RMS values of 3D-printed implant-supported provisional prostheses grouped by 3D printing technology and span length. Asterisks (*) indicate statistically significant differences ($p < 0.05$).

Surface deviation analysis using 3D color mapping was conducted as a qualitative method to assess the dimensional accuracy of implant-supported provisional prostheses. The color scale ranged from -300μ m (blue, indicating under-contouring or material deficiency) to $+300 \mu$ m (red, indicating over-contouring or material excess),

with green areas representing deviations within the clinically acceptable tolerance range ($\pm 30 \mu\text{m}$).

For the 3-unit prostheses, the SLA group demonstrated superior accuracy, characterized by widespread green regions across all views and minimal yellow areas observed on the occlusal surface. In contrast, the LCD-printed prostheses showed noticeable blue areas, particularly on the mesial and distal surfaces, indicating under-contouring and dimensional shrinkage, which was consistent with the group's higher RMSE values.

In the 4-unit group, a general decline in accuracy was noted across all technologies, particularly within the SLA and LCD groups. While SLA-printed specimens maintained predominantly green regions, they showed increased yellow areas along the buccal and palatal views. The LCD group exhibited pronounced blue regions, especially in the proximal views, reflecting increased shrinkage in longer-span prostheses.

For the 6-unit prostheses, deviation patterns became more pronounced. Both DLP and LCD groups presented extensive blue areas on the distal and palatal aspects, reflecting under-contouring and misfit. The DLP group also revealed a more irregular pattern of both over- and under-contoured areas throughout the arch.

In the full-arch prostheses, all printing technologies demonstrated considerable deviations. The SLA group displayed more yellow areas, especially on the occlusal and palatal surfaces, although green zones still predominated. The DLP group showed dominant blue regions on the buccal and distal surfaces, suggesting shrinkage and potential warpage. The LCD-printed prostheses exhibited the most inconsistent surface adaptation, with alternating over- and under-contoured zones along the arch.

Interestingly, despite these visible deviations, the RMSE values for the full-arch group were occasionally lower than those in the shorter-span LCD and DLP groups. This can be attributed to the mathematical nature of RMSE calculations, which average positive and negative deviations, potentially masking extensive but opposing deviations across different regions. Consequently, these findings highlight the importance of

utilizing both quantitative (RMSE values) and qualitative (color mapping) assessments to comprehensively evaluate the dimensional accuracy of 3D-printed prostheses.

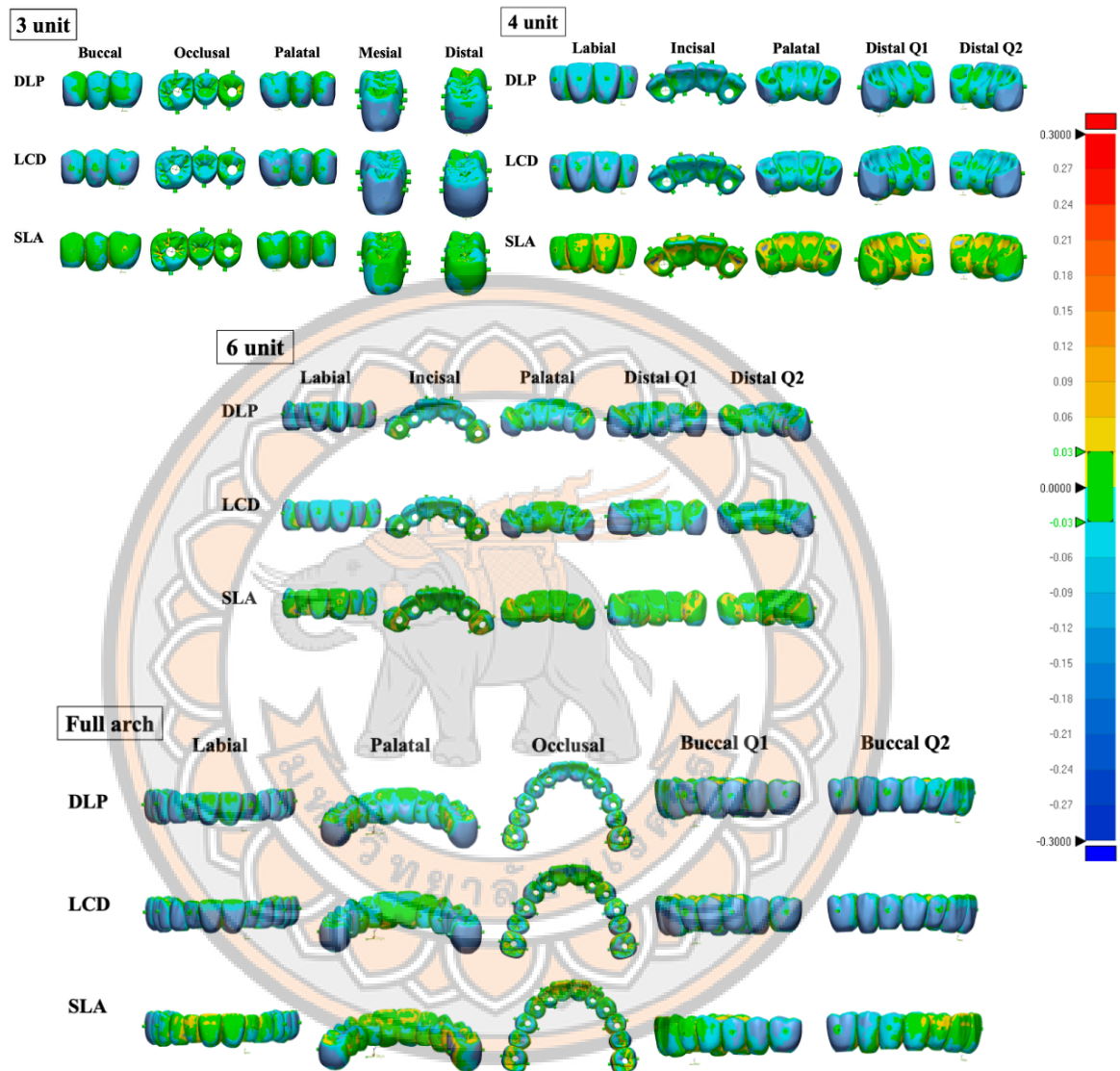


Figure 23. Representative color maps of various view in 3-unit, 4-unit, 6-unit and full-arch splinted implant-supported provisional prostheses. Red represents overcontoured areas, blue undercontoured areas (Nominal values: +300 μm and -300 μm), and green acceptable areas within tolerance range (+30 μm and -30 μm).

Discussion

This study evaluated the dimensional accuracy of implant-supported provisional prostheses fabricated via three 3D printing technologies: Stereolithography (SLA), Digital Light Processing (DLP), and Liquid Crystal Display (LCD), across varying span lengths. Statistical analysis revealed a significant interaction between the 3D printing technology employed and the number of prosthetic units, suggesting that both parameters concurrently influence the final accuracy. The null hypothesis, which stated that there would be no difference in external dimensional accuracy among the different numbers of provisional units and the three printing techniques, was rejected. These findings confirm that both the printing technology and span length significantly affect the dimensional accuracy of implant-supported provisional prostheses, with SLA demonstrating superior accuracy and DLP and LCD demonstrating comparable results.

Among the evaluated technologies, SLA exhibited significantly lower Root Mean Square Error (RMSE) values than the other two technologies in the 3-, 4-, and 6-unit groups, indicating superior dimensional accuracy. In contrast, no statistically significant difference in dimensional accuracy was observed between the LCD and DLP technologies. For the full-arch group, no statistically significant differences in dimensional accuracy were observed among the three technologies.

The enhanced performance of SLA may be attributed to its point-by-point polymerization mechanism; unlike layer-wide exposure systems, SLA utilizes a focused laser to cure resin in a continuous, highly precise manner.^[49, 50] This localized approach facilitates greater control over dimensional stability compared to the simultaneous illumination used in DLP and LCD systems. The present findings are in agreement with previous studies reporting that SLA 3D printers generally achieve higher accuracy than DLP printers.^[51, 52] In addition, SLA printers employ a relatively high-intensity laser that directly scans and polymerizes the resin, promoting more complete polymerization and thereby reducing the likelihood of polymerization shrinkage. This finding is consistent with the study by Sim et al.^[53], which reported that SLA exhibited higher surface accuracy compared with specimens fabricated using DLP and LCD printing technologies.

Both DLP and LCD printing technologies are categorized under mask image projection-based vat photopolymerization (MIP-VPP), in which an entire layer of photopolymer resin is simultaneously exposed to form the printed object layer by layer. As both technologies rely on discrete pixels or micromirror arrays for simultaneous layer projection, this pixelated architecture may inherently induce voxel stepping and surface irregularities, particularly across curved or complex geometries.^[54, 55]

In DLP technology, the light projection is controlled by a Digital Micromirror Device (DMD). This system consists of a large array of microscopic mirrors that individually reflect and direct light to specific regions of the resin surface, thereby defining the geometry of each layer. Because the entire layer is projected simultaneously, the printed object may exhibit less smooth edge transitions compared with those fabricated using SLA technology. However, compared with LCD systems, DLP typically yields smoother surfaces with reduced aliasing because of its more refined light modulation.^[54,55]

In contrast, LCD printing technology also cures resin layer by layer, but the light passes through the pixel matrix of an LCD screen, which acts as a fixed grid mask. During exposure, the projected light follows the discrete pixel pattern of the LCD panel. LCD systems often exhibit more pronounced pixelation artifacts because of their rigid fixed-pixel grids, resulting in more stepped surface boundaries compared with DLP systems.^[54, 55] However, although LCD systems traditionally exhibit lower resolution because of attenuated light intensity, the specific LCD printer used in the present study (Phrozen Sonic Mighty Revo 14K) provides a high XY resolution ($16.8 \times 24.8 \mu\text{m}$), which may have compensated for the lower curing intensity. This finding suggests that modern LCD printers equipped with enhanced optical systems may achieve clinically acceptable accuracy, particularly in shorter-span prostheses. Nevertheless, despite their high-resolution capabilities, the relatively lower intensity of the light source may still result in dimensional precision inferior to that of DLP systems.^[5] These theoretical differences were corroborated by the findings of the present study, in which LCD-printed surfaces displayed visible layer lines and pixelation, reflecting stair-stepping effects and reduced surface smoothness compared with the superior morphology observed in SLA and DLP specimens.^[20]

When these layer-by-layer projections are translated into a three-dimensional structure, they may contribute to surface irregularities, particularly in curved or geometrically complex structures, where the discrete pixel resolution and layer stacking can further reduce surface smoothness.^[11]

Consistent with the RMSE findings, the qualitative color-map analysis demonstrated similar deviation patterns. SLA prostheses generally exhibited predominantly green regions with fewer deviations, indicating superior dimensional accuracy. In contrast, the DLP and LCD groups showed increased blue and yellow regions as span length increased, particularly along the palatal surfaces and distal ends of long-span prostheses, indicating greater dimensional distortion, shrinkage, and surface irregularities. These deviation patterns became more pronounced in the 6-unit and full-arch groups across all technologies.

These deviations were mainly located in the palatal and occlusal regions, particularly around areas with anatomical grooves. A similar pattern was reported by Refaie et al.^[56], who observed yellow zones in the central groove region in their color-mapping analysis. This finding suggests that minor deviations are more likely to occur in anatomically complex occlusal areas, where fine morphological details and groove structures may increase the susceptibility to localized inaccuracies during the fabrication process.

Furthermore, the DLP and LCD groups demonstrated more prominent blue regions along the mesial, distal, and buccal surfaces, particularly in the full-arch prostheses, suggesting polymerization shrinkage and distortion toward the distal ends of the arch. These findings indicate that dimensional changes become more pronounced as span length increases, potentially affecting the adaptation and overall fit of long-span prostheses. Similar findings were reported by Jin SJ et al.^[57], who also observed blue zones in the buccal posterior region in their color-mapping analysis.

Interestingly, only the SLA group demonstrated the expected trend of progressively increasing RMSE values with increasing span length, indicating that dimensional deviation increased consistently as the prosthesis span became longer. Although RMSE values in the SLA cohort increased incrementally as span length

extended, its dimensional accuracy remained significantly superior to that of the other technologies. In contrast, the DLP and LCD groups exhibited greater variability across span lengths, including unexpected reductions in deviation in the full-arch configurations, suggesting less predictable dimensional behavior in long-span prostheses.

These findings differ from those reported by Moon et al., who observed progressively higher RMS values with increasing span lengths in both DLP and LCD systems, particularly in the 6-unit and full-arch restorations for DLP and in the 5-unit, 6-unit, and full-arch restorations for LCD.^[11] This discrepancy may be related to differences in printing parameters, post-processing protocols, resin materials, prosthesis design, and the inclusion of additional reference markers among the studies, which likely facilitated more precise superimposition alignment during the digital analysis. Furthermore, the DLP and LCD systems in the present study utilized different resin materials, which possess distinct monomer compositions, viscosities, and polymerization shrinkage characteristics that may have influenced dimensional stability and printing behavior.

This study has several limitations. Firstly, only one printer per technology was evaluated, which may limit the generalizability of the findings to other commercially available systems. Secondly, only one resin material was tested for each printer, despite the possibility that variations in filler content, viscosity, and photoinitiator systems may significantly influence dimensional accuracy. Thirdly, the inclusion of additional reference markers may have artificially enhanced superimposition accuracy during digital analysis.

Future research should therefore explore a wider range of printer and resin types within each printing technology to improve the generalizability of the findings. Investigations under simulated intraoral conditions or thermal cycling may also help evaluate the long-term dimensional stability of printed prostheses. In addition, incorporating supplementary assessment methods, such as fit analysis on clinical abutments, may provide more comprehensive insights into the clinical applicability of additively manufactured provisional prostheses.

Furthermore, the digital workflow relied on an intraoral scanner to acquire cross-arch data for the design of implant-supported provisional prostheses. While digital impressions have demonstrated acceptable accuracy for single-unit and short-span restorations, their reliability for complete-arch implant-supported prostheses remains controversial, particularly due to the accumulation of stitching errors over long scanning distances.^[58] Previous studies have reported that full-arch intraoral scans may be susceptible to cumulative stitching errors, potentially compromising the accuracy of the digital model.^[59] As a result, some fabricated prostheses could not be seated accurately on the original abutments of the edentulous model. Therefore, the present study focused primarily on evaluating overall dimensional accuracy rather than assessing clinical fit. Future studies should consider alternative impression techniques for fully edentulous arches with multiple implants, such as the use of intraoral photogrammetry systems, which have demonstrated higher accuracy in capturing implant positions.^[60] The adoption of these techniques may facilitate the fabrication of prostheses that can be fully seated on the corresponding abutments, thereby enabling additional evaluations of marginal adaptation and internal fit, which are clinically relevant parameters for implant-supported provisional restorations.

CHAPTER V

CONCLUSIONS

Conclusion

Within the limitations of this study, SLA demonstrated the highest dimensional accuracy for implant-supported provisional prostheses with span lengths of ≤ 6 units, exhibiting significantly lower RMSE values and fewer surface deviations compared with DLP and LCD technologies. In contrast, DLP and LCD demonstrated comparable dimensional accuracy across most span configurations.

In the full-arch group, no statistically significant differences in dimensional accuracy were observed among the three printing technologies, although greater surface deviations and distortion patterns were noted in all groups as span length increased. Furthermore, only the SLA group demonstrated a consistent trend of increasing RMSE values with increasing span length, indicating more predictable dimensional behavior in long-span prostheses.

The qualitative color-map analysis further supported the quantitative findings, with SLA prostheses showing predominantly green regions, whereas DLP and LCD prostheses exhibited increased blue and yellow deviation areas, particularly along the palatal and distal regions of long-span prostheses. These findings suggest that both printing technology and prosthesis span length play important roles in determining the dimensional accuracy and surface adaptation of additively manufactured implant-supported provisional prostheses.



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