

RESEARCH AND EDUCATION

Assessment of the trueness and tissue surface adaptation of CAD-CAM maxillary denture bases manufactured using digital light processing



Hyun-Ji Hwang, DDS,^a Sang J. Lee, DMD, MMSc,^b Eun-Jin Park, DDS, PhD, MMSc,^c and Hyung-In Yoon, DDS, MSD, PhD^d

With the development of dental material and technology, computer-aided design and computer-aided manufacturing (CAD-CAM) technology has become popular for the production of fixed prostheses. With the widespread adoption of intraoral scanners, digital methods have been applied throughout clinical dentistry, including the manufacture of implant superstructures, orthodontic devices, and removable partial denture frameworks.¹⁻⁵

In the field of removable prosthodontics, adopting digital technologies for prosthesis fabrication has been more difficult, with capturing edentulous impressions and multi-step laboratory procedures proving challenging. CAD-CAM complete dentures were first described in 1994⁶ and now represent an improvement over conventional denture production.^{7,8} Reduced chair time, decreased number of patient visits, and simplification of the

ABSTRACT

Statement of problem. Limited information is available evaluating the trueness and tissue surface adaptation of computer-aided design and computer-aided manufacturing (CAD-CAM) maxillary denture bases fabricated using digital light processing (DLP).

Purpose. The purpose of this in vitro study was to evaluate the trueness of DLP-fabricated denture bases and to compare the tissue surface adaptation of DLP with milling (MIL) and pack and press (PAP).

Material and methods. The maxillary denture bases were virtually designed on the reference cast and were fabricated using DLP and MIL. Their intaglio surfaces were scanned and superimposed on the reference computer-aided design denture base to evaluate the trueness. A total of 20 denture bases (10 per technique) were also fabricated on the duplicated master casts using DLP and MIL. Ten denture bases were additionally made using PAP. The intaglio surfaces of the dentures were scanned and superimposed on the corresponding casts to compare the degree of tissue surface adaptation among the 3 techniques. The Mann-Whitney test and Kruskal-Wallis ANOVA were used for statistical analyses ($\alpha=.05$).

Results. The trueness of the DLP denture base was significantly better than that of the MIL denture base ($P<.001$). Statistically significant differences were detected with respect to tissue surface adaptation of the denture base among the groups ($P<.001$). The DLP denture base showed the best denture base fit among the 3 techniques with a small interquartile range.

Conclusions. Within the limitations of this in vitro study, the DLP maxillary denture base showed better trueness and tissue surface adaptation of $\leq 100 \mu\text{m}$ of the 3-dimensional surface deviation than the MIL and PAP denture bases. (J Prosthet Dent 2019;121:110-7)

laboratory process are benefits of denture fabrication using CAD-CAM.^{8,9} CAD-CAM produces fewer errors during the denture making process and can allow the efficient fabrication of a replacement prostheses based on

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^aResident, Department of Prosthodontics, School of Medicine, Ewha Womans University, Seoul, Republic of Korea.

^bAssistant Professor, Department of Restorative Dentistry and Biomaterials Sciences, Harvard School of Dental Medicine, Boston, Mass.

^cProfessor and Chairman, Department of Prosthodontics, School of Medicine, Ewha Womans University, Republic of Korea.

^dAssistant Professor, Department of Prosthodontics, School of Dentistry and Dental Research Institute, Seoul National University, Seoul, Republic of Korea.

Clinical Implications

Both the digital light processing (DLP) and milled maxillary denture bases showed compatible tissue surface adaptation to the edentulous residual ridges. The DLP denture bases reproduced the morphologic irregularity of the residual ridge, while the milled denture bases had minor inaccuracies.

stored data.^{8,9} In addition, radiologic or surgical templates can be easily produced by using data retrieved from the patient.³

Computer-aided technology comprises product design, analysis, and manufacturing. Three-dimensional (3D) printing, which refers to the additive manufacturing process, is a method based on CAD design of adding materials directly without using molds or cutting tools. Compared with the milling (MIL) method, the 3D printing method has no limitations regarding the design of geometric shapes.^{2,3,10,11} Of the various 3D printing techniques, digital light processing (DLP) is increasingly used in the dentistry^{8,12} and directly uses 3D CAD data to build a structure by exposing photopolymerizable liquid monomer layers to ultraviolet light. In this technique, the slits of a mask image from the 3D model are defined by using a digital micromirror device, and ultraviolet light is projected onto the surface of the photopolymerizable liquid polymer. Thus, the exposed polymer layer is polymerized to a certain thickness (resolution), leading to a bottom-up stacking approach to form a complex 3D physical body. A 3D printable acrylic resin and a corresponding DLP additive manufacturing system have recently become commercially available for digitally fabricated complete denture bases.^{10,11,13}

Good adaptation of the denture base to the denture bearing tissues is essential for the adequate retention and stability of the complete denture. The accuracy and reproducibility of CAD-CAM milled denture bases have been compared with conventionally fabricated (injection or compression molding) denture bases.^{14,15} Goodacre et al¹⁴ reported significantly higher accuracy and reproducibility for CAD-CAM milled denture bases than conventional denture bases. Chen et al¹⁶ reported comparable tissue surface adaptation of 3D printed wax pattern of maxillary denture base manufactured using MultiJet printing. However, research that compares the trueness and tissue surface adaptation of 3D printing technique to conventional or milling techniques for fabricating the definitive complete denture base is lacking. Trueness refers to the closeness of agreement between the expectation of a measurement result and a true value.^{17,18}

Therefore, the purpose of this *in vitro* study was to assess the trueness of the DLP and MIL techniques for

denture fabrication and to compare the tissue surface adaptation of denture bases fabricated by 3 different methods (DLP, MIL, and pack and press). The first null hypothesis was that no difference would be found in the trueness between 2 CAD-CAM denture fabrication techniques. The second null hypothesis was that no difference would be found among the 3 fabrication techniques in the tissue surface adaptation of a denture base to an edentulous maxillary cast.

MATERIAL AND METHODS

The flowchart of this study protocol is presented in [Figure 1](#). The mechanical properties of the materials used in this study, as described by the manufacturer, are presented in [Table 1](#). Five edentulous maxillary casts for definitive complete dentures were obtained from 2 dental laboratories. To eliminate any laboratory- or patient-related identifiers, all the collected casts were pooled. No patient-related clinical records were used in this research. Institutional approval was determined not to be necessary for this study.

Among the casts, according to the classification system of the American College of Prosthodontists, an edentulous maxillary cast with Class I, Type A, residual ridge morphology and no severe undercuts ([Fig. 2A](#)) was selected as a reference cast.¹⁹ The other 4 casts, which had severe tissue undercuts and residual ridge atrophy, torus, or with cast defects, were excluded. The selected maxillary cast was scanned with a blue light-emitting diode (LED)-based digital scanner (Identica blue; Medit) at a 10 μm accuracy to construct a virtual model as a reference cast scan ([Fig. 1](#)).

A dental technician with 20 years of experience designed the reference CAD maxillary complete denture base using a reference cast scan and CAD software (3Shape Dental Designer; 3Shape A/S). A total of 10 identical master casts were fabricated by duplicating the selected cast with a silicone material (Vivid Image; Pearson Dental) and a Type IV dental stone (Fujirock; GC Corp). After 24 hours of dry storage, a master cast scan was prepared by digitizing each duplicated cast. A virtual CAD maxillary denture base was designed on each master cast scan (3Shape Dental Designer; 3Shape A/S).

From the reference CAD maxillary denture base, 10 DLP denture bases ([Fig. 2B](#)) were fabricated with a 3D printable material (NextDent Base; NextDent) and a DLP printer (Bio 3D W11; NextDent). The light source of the DLP printer was a 405 nm wavelength LED, and the printing layer thickness was 100 μm . The support structure was attached on the labial surface of the denture base, with a 100-degree build angle. After printing, the denture bases were cleaned in an ultrasonic bath with isopropyl alcohol for 10 minutes. The denture bases were postpolymerized for 15 minutes using ultraviolet polymerization unit (LC 3DPrint Box; Bio3D) according to the

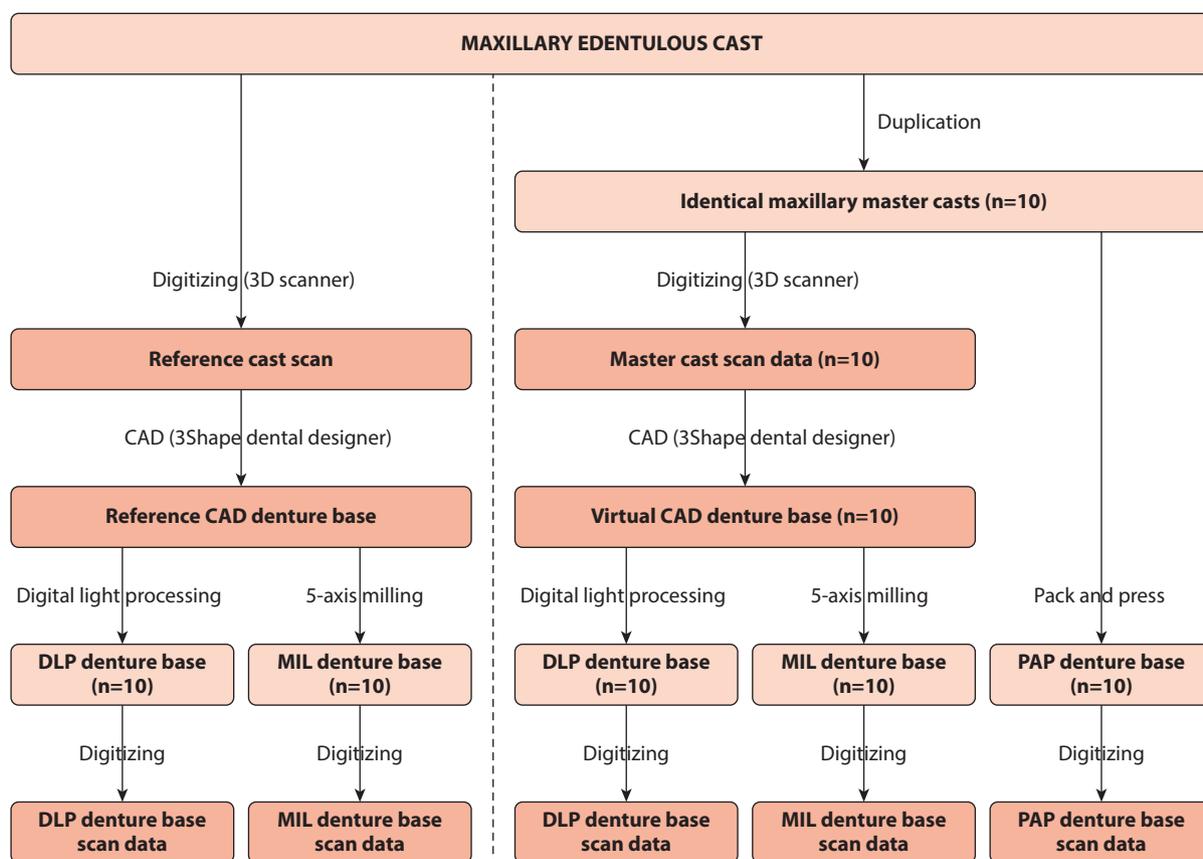


Figure 1. Flowchart of research protocol. DLP, digital light processing; MIL, computer-aided milling; PAP, pack and press.

Table 1. Mechanical properties of materials used as described by manufacturer

Material	Property	Value
NextDent Base	Brookfield viscosity at 23°C (Pa·s)	1.0-1.5
	Flexural strength (MPa)	80-95
	Flexural modulus (MPa)	2,000-2,400
	Charpy impact resistance (kJ/m ²)	10-14
	Water sorption (µg/mm ²)	<32
	Water solubility (µg/mm ²)	<4
VIPI Block GUM	Residual monomer (%)	<1
	Hardness (Shore D)	80-90
	Modulus of elasticity (MPa)	>2,200
	Bending resistance (MPa)	>100
	Charpy impact resistance (kJ/m ²)	>10
	Impact wear resistance (MPa)	>3.5
SR Triplex Hot	Strength resistance (MPa)	>1
	Water absorption (µg/mm ²)	<20
	Water solubility (µg/mm ²)	<0.8
	Residual monomer content (%)	<0.7
	Vickers hardness	>110

manufacturer's instructions. Using the same method, 10 DLP denture bases (DLP group) were designed and manufactured on the basis of the data of 10 master cast scans.

A total of 10 maxillary denture bases were milled on the basis of the reference CAD denture base. A gingival-colored polymethyl methacrylate (PMMA) block (VIPI Block GUM; VIPI) and a 5-axis milling machine (ARUM 5X-200; Doowon) with an accuracy of 5 µm were used for milling. Subsequently, 10 milled denture bases (MIL group), virtually designed from the master cast scan data, were manufactured using the same method.

For the pack and press (PAP) technique, a silicone putty mold (Exaflex putty; GC Corp) was prepared from one of the milled denture bases to make standardized duplicates. With this putty mold, 10 wax denture bases were fabricated in the identical shape and thicknesses of the corresponding master casts. Finally, 10 PAP denture bases (PAP group) were made by the split-mold flask (HANAU Varsity Flask; Whip Mix Corp) pack-and-press technique using heat-activated PMMA material (SR Triplex Hot; Ivoclar Vivadent AG).

The intaglio surfaces of the denture bases were spray coated (EZ scan; Alphadent) with an average particle size of 3 µm and then digitized using a model scanner (Identica blue; Medit). A silicone repositioning index was used to ensure an identical location and angulation for each specimen. The following 3D scanned data of the denture bases were saved in a standard tessellation

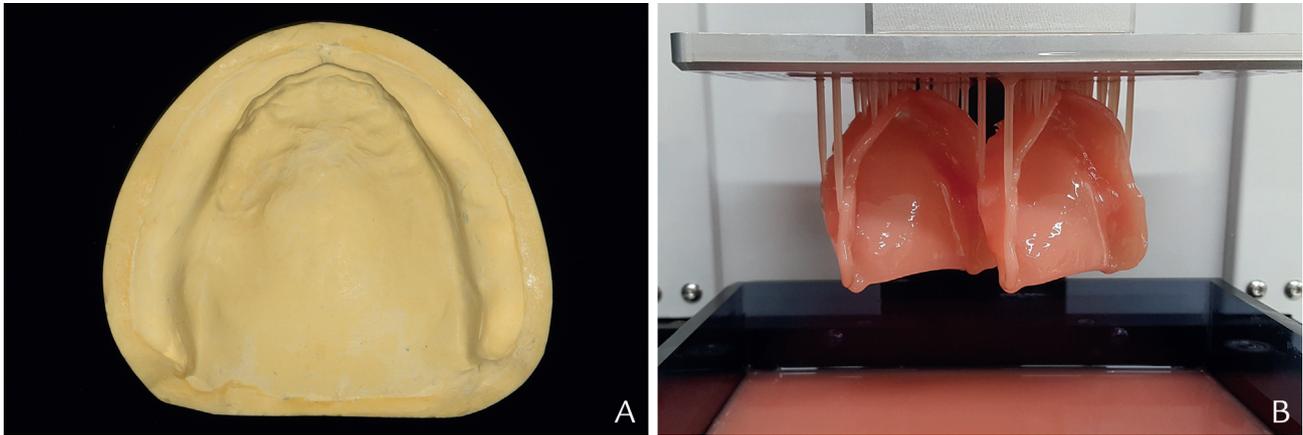


Figure 2. A, Maxillary edentulous master cast. B, Maxillary denture bases fabricated using digital light processing.

language (STL) format and input into the inspection software (Geomagic Verify; 3D Systems). To evaluate the trueness of 2 CAD-CAM techniques (DLP and MIL), each STL file of the scanned denture base was superimposed on that of a reference CAD maxillary denture base.

To compare the degree of tissue surface adaptation among the 3 different techniques (DLP, MIL, and PAP groups), each scanned file of the maxillary master cast was superimposed on the STL file of the intaglio surface of the corresponding maxillary denture base (n=10 per group). The entire tissue surfaces of the denture bases were superimposed with only the corresponding denture bearing area of the master cast. Measurements were made using a point-to-point matching, and best-fit alignment was applied using the iterative closest point algorithm of the software. The nominal deviation for the superimposition analyses was set at $\pm 50 \mu\text{m}$ and the critical deviation at $\pm 300 \mu\text{m}$.^{14,20,21} The root-mean-square estimates (RMSE) and positive and negative average deviation values were also obtained for each specimen.^{10,22} The color-coded 3D surface deviation maps were visually displayed. Each scanning and superimposition process was performed by a single investigator (H.J.H.).

The means, standard deviations, medians, and interquartile ranges of all the measured surface deviations (RMSE, positive average, and negative average) were statistically analyzed by statistical software (IBM SPSS Statistics, v22.0; IBM Corp). A Mann-Whitney test was conducted to examine the trueness of the DLP technique compared with the MIL technique. The Kruskal-Wallis ANOVA was used to evaluate the statistical significance of the differences between each fabrication technique group. The Mann-Whitney test for post hoc analysis and the Bonferroni method for multiple comparisons were used ($\alpha=.05$).

RESULTS

Compared with the reference CAD denture base, the mean \pm SD and median values of the measured RMSE of

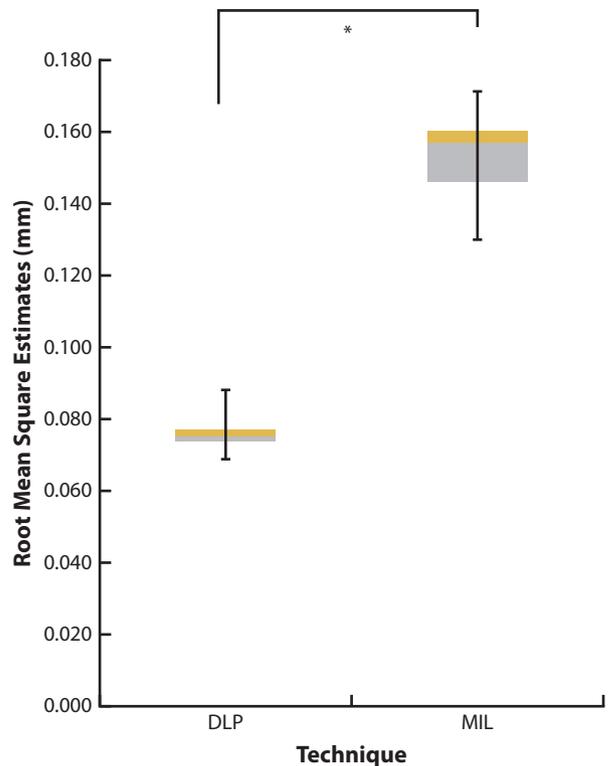


Figure 3. Trueness of intaglio surfaces of maxillary denture bases fabricated using 2 different CAD-CAM techniques. Line where red box meets green box represents median. *Statistically significant difference ($P<.001$). CAD-CAM, computer-aided design and computer-aided manufacturing; DLP, digital light processing; MIL, computer-aided milling.

the DLP group were $0.076 \pm 0.005 \text{ mm}$ and 0.075 mm , while those of the MIL group were $0.154 \pm 0.012 \text{ mm}$ and 0.157 mm . Regarding the trueness of the 2 CAD-CAM denture bases, the MIL had a significantly higher ($P<.001$) RMSE value than the DLP (Fig. 3). The DLP denture base had a positive deviation (yellow to red) on the posterior ridge crest, palatal rugae, and buccal slope

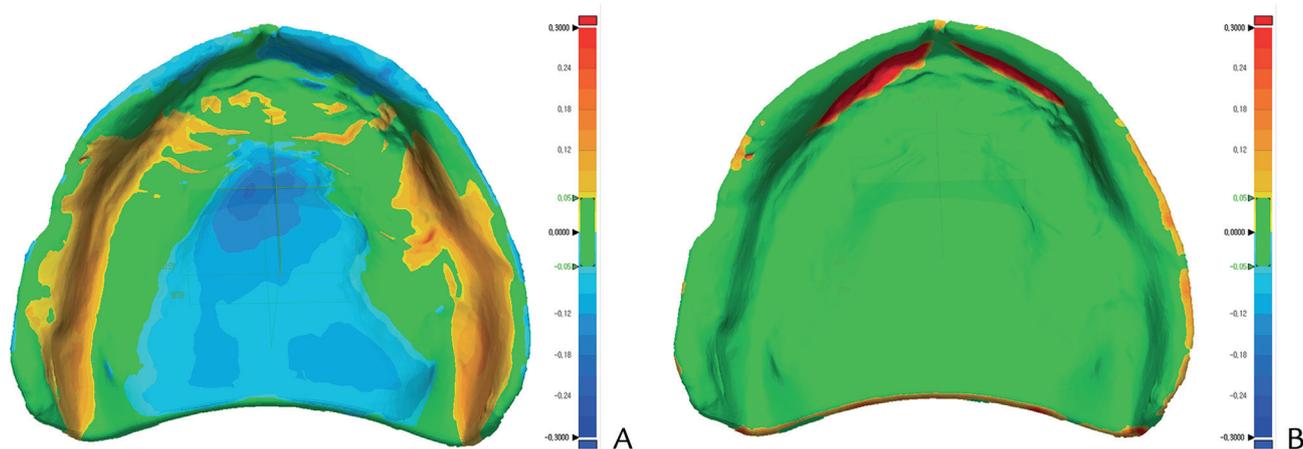


Figure 4. Color maps of intaglio surface of maxillary denture base. A, Fabricated using digital light processing. B, Fabricated using computer-aided milling. Positive deviation, yellow to red. Negative deviation, cyan to blue. Measured surface deviation below 50 μm , green.

Table 2. Measured surface deviations between scanned master casts and maxillary denture bases fabricated by 3 different techniques

Characteristic	DLP				MIL			PAP		
	RMSE	Positive Average	Negative Average	% Reduction	Mean Reduction \pm SD (mm)	Negative average	% Reduction	Mean Reduction \pm SD (mm)	Negative average	
Mean \pm SD	0.074 \pm 0.005	0.062 \pm 0.004	-0.063 \pm 0.005	0.177 \pm 0.003	0.013 \pm 0.001	-0.084 \pm 0.005	0.165 \pm 0.056	0.097 \pm 0.025	-0.042 \pm 0.007	
Median	0.074	0.062	-0.062	0.178	0.012	-0.084	0.154	0.090	-0.042	
Third quartile	0.076	0.063	-0.059	0.179	0.014	-0.081	0.206	0.111	-0.038	
First quartile	0.072	0.059	-0.065	0.175	0.012	-0.086	0.131	0.081	-0.046	

DLP, digital light processing; MIL, computer-aided milling; PAP, pack and press; RMSE, root-mean-square estimate

area and a negative deviation (blue) on the labial slope of the anterior ridge and palatal area (Fig. 4A). Although the color deviation pattern of the MIL denture base was mainly within nominal deviation (green), severe surface deviation was detected in the labial slope area of the anterior ridge (Fig. 4B).

Table 2 presents the descriptive statistics of the measured surface deviations of the CAD-CAM and PAP denture bases. Statistically significant differences were found for RMSE values among the groups ($P < .001$). With regard to tissue surface adaptations, a significantly lower RMSE value was recorded in the DLP group than in either the MIL group or PAP group (both $P < .001$) (Fig. 5A). No statistical difference was found in the surface deviation measurement between the MIL and PAP groups ($P = .143$). The interquartile range of the measured RMSE value was wide in the PAP group, whereas those of the DLP and MIL groups were relatively narrow. Regarding the average positive value of 3D surface deviation measurement, the PAP group showed the highest, while the MIL group was the lowest (Fig. 5B). The DLP group was lower than the PAP group and higher than the MIL group, both with statistical significance ($P < .001$). With respect to the average negative value, the PAP group was the lowest and the MIL group was the highest (Fig. 5C). The DLP group was lower than the PAP group and higher than

the MIL group, both with statistical significance ($P < .001$).

The color deviation map of the DLP group represented mucosal compression (negative deviation, blue; Fig. 6A) at the buccal slope and posterior alveolar ridge crest. It also showed some space from the tissue surface at the mid-palate, posterior palatal seal, and labial flange areas (positive deviation, yellow to red; Fig. 6A). The MIL group had significant mucosal compression on the labial slope of the anterior ridge (Fig. 6B). The PAP group showed some tissue impingement on the tuberosity, distal area of the palatal vault, and a small area on the anterior ridge crest. It also showed some gaps in a small area on the posterior ridge and midpalatal area (Fig. 6C).

DISCUSSION

The results of this study suggest that the trueness of the DLP denture base was significantly different from that of the MIL denture base. Hence, the first null hypothesis was rejected. Moreover, statistically significant differences of the RMSE values were found among the denture base groups (DLP, MIL, and PAP), particularly between the DLP-MIL and DLP-PAP groups. Therefore, the second null hypothesis was also rejected. According to a previous study, the PAP denture base demonstrated a similar overall surface deviation measurement (median

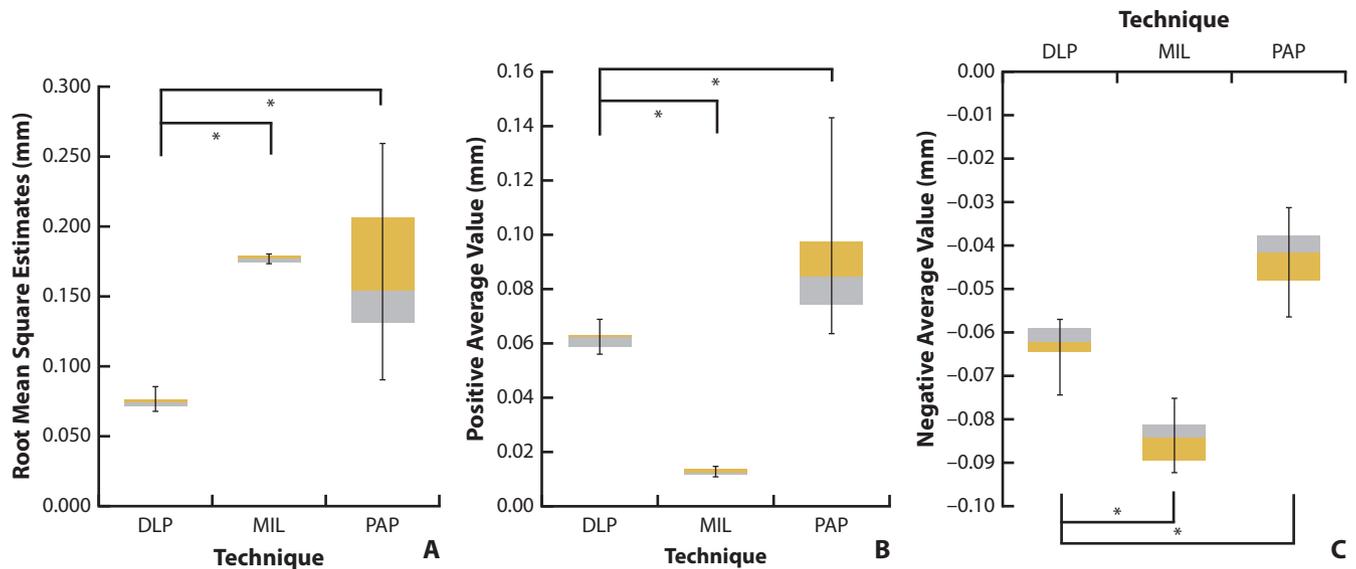


Figure 5. Comparison of intaglio surface deviations of denture bases fabricated using 3 different techniques. A, Root-mean-square estimates. B, Positive average values. C, Negative average values. Line where red box meets green box represents median. DLP, digital light processing; MIL, computer-aided milling; PAP, pack and press.

RMSE) to the MIL denture base, although its interquartile range of the measured values was wide.¹⁴ The narrow interquartile range of RMSE values in the DLP and MIL groups suggests a highly uniform 3D surface deviation. Although some areas of deviations existed, the overall intaglio surfaces of the DLP denture base demonstrated a high trueness and tissue surface adaptation of $\leq 100 \mu\text{m}$ of the 3D surface deviation.

The retention of a complete denture depends on tissue surface adaptation, border seal, and salivary flow-related effects associated with the flow, viscosity, and film thickness of the oral fluid.^{23,24} Deformation of denture bases during processing is affected by the shape (palatal vault and residual ridge), thickness, denture base materials, and denture processing steps.^{20,21} Minimal distortion in processing is essential for mucosal adaptation, which is associated with retention, stability, and support.¹⁴ In conventional fabrication techniques, factors such as the complexity of manipulation, the time-consuming procedures of waxing, investing, and wax elimination and the deformation of heat-polymerized PMMA might diminish the degree of base adaptation.^{20,21,25} Based on the findings of this study, the DLP denture base is a suitable alternative to conventionally fabricated and computer-aided milled denture bases.

On the color-coded map for evaluating 3D surface deviation, a positive deviation (displayed as yellow to red by the extent of deviation) implies that the intaglio surface of the test denture base is located above the surface of the master cast, referring to tissue compression or impingement. In contrast, a negative deviation (blue)

indicates that the intaglio surface of the test denture base is located below the master cast surface, referring to space. The surface deformation patterns of the DLP denture base can be associated with the nature of the 3D printing technique and materials. In this study, the supporting structures were attached to the labial flange area of the denture base with a 100-degree build angle. Studies have reported that the condition of support and build angle may affect the geometric accuracy and mechanical properties of objects manufactured by the DLP method.^{10,26} The build angle and the sagging of the material under its own weight because of the liquid form of the printable material could explain the positive and negative deviation geometry of the intaglio surface.

Although the MIL group exhibited a generally intimate tissue surface adaptation, significant impingement on the labial slope of the anterior ridge was evident in the color deviation map. The milling tool was presumed to be inaccessible in the deepest area of the anterior ridge area of the intaglio denture surface, despite a master dental technician using a 5-axis milling machine. The intaglio surface contour of the MIL denture bases may be affected by the axis number and size of the milling instruments. Considering the edentulous ridge form requiring complete denture treatment, the path of insertion may not be a single axis, but in a certain range (multiple axes). Although the classification of the maxillary edentulous ridge was Class I and type A, some area of the labial slope area of the anterior edentulous ridge can be irregular. This suggests that additive manufacturing rather than milling may be considered for patients with complex, irregular edentulous ridge forms.

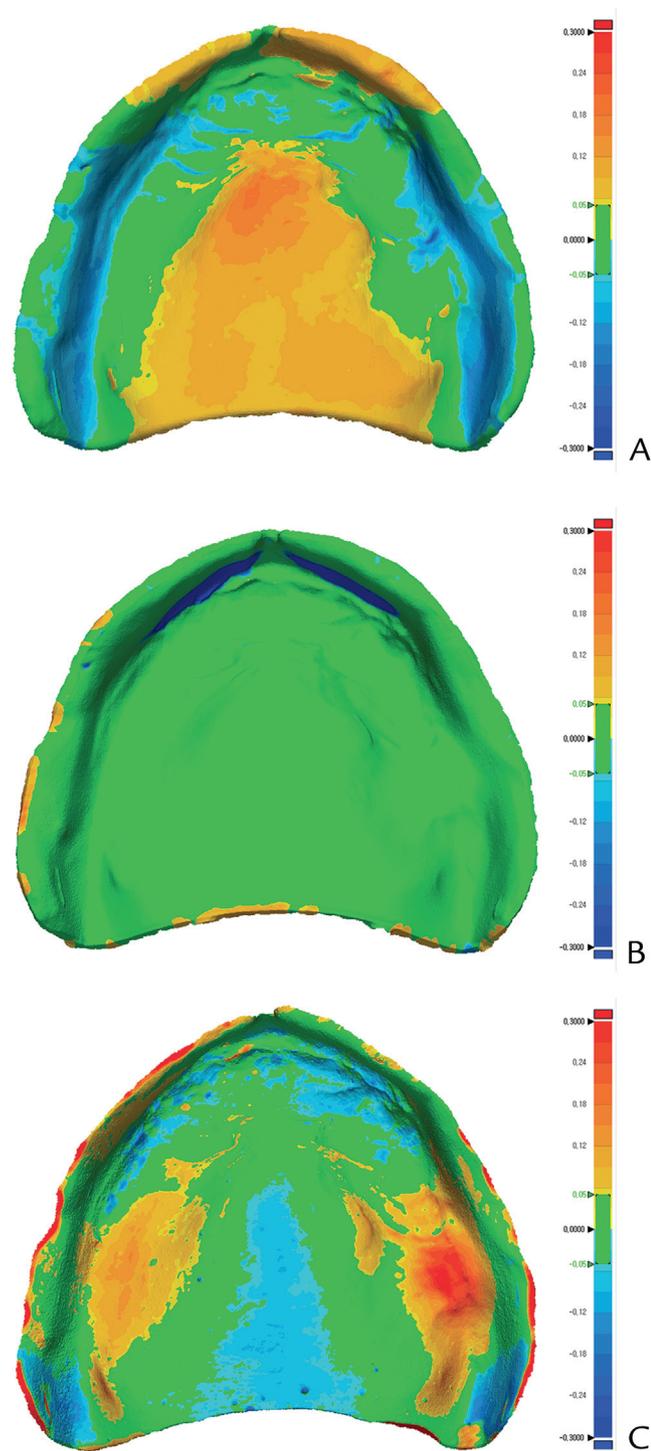


Figure 6. Color maps of intaglio tissue surface adaptation of maxillary denture bases. Positive deviation (yellow to red) misfit with space; negative deviation (cyan to blue) tissue compression; measured deviation below 50 μm (green). A, Digital light processing technique. B, Computer-aided milling technique. C, Pack and press technique.

Unlike fixed prostheses,²⁷ the tolerance of soft tissue displacement of a removable denture can be large due to the dynamic movement of the mucosa.²⁸ A study on

macaque monkeys applying constant or dynamic loading on the maxilla fitted with a denture baseplate revealed a compressive mucosal displacement in the range of 375 and 500 μm .²⁸ This range of values is approximately 3-fold higher than the variation observed in the current study. Although an appropriate amount of compression can help increase retention, repeated compression and abrasion of the mucosa might induce inflammation and degeneration, as well as reducing denture retention.²⁹ Therefore, with a lower value of the 3D surface deviation, the tissue surface adaptation of the DLP denture base could be clinically acceptable.

A limitation of this in vitro study was that the tissue surface adaptation of a denture base was only evaluated in an extraoral condition between the denture base and edentulous cast. The dynamic characteristics of compressed soft tissue during masticatory function of the denture base could not be measured. In addition, various factors such as the water (or saliva) immersion time, morphology of the residual ridge, thicknesses of the denture base specimens, and possible scanning errors were not considered in this study. Moreover, further studies are warranted to assess conditions such as the location of the build platform, position of the support structure, and degree of build angle, which might affect the deformity of denture bases made using the DLP technique.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. The DLP denture base had better trueness than the MIL denture base.
2. The tissue surface adaptation of the DLP denture base was within the 100 μm accuracy, which was the best among the 3 different techniques.
3. The DLP denture base reproduced the morphologic irregularity of the residual ridge, while the MIL denture base showed minor inaccuracies.

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Corresponding author:

Dr Hyung-In Yoon
Department of Prosthodontics
School of Dentistry and Dental Research Institute
Seoul National University
101, Daehak-ro, Jongro-gu, Seoul, 03080
REPUBLIC OF KOREA
Email: drhiy226@snu.ac.kr

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