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Evaluating the accuracy (trueness and precision) of interim crowns manufactured using digital light processing according to post-curing time: An *in vitro* study

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PURPOSE. This study aimed to compare the accuracy (trueness and precision) of interim crowns fabricated using DLP (digital light processing) according to post-curing time. **MATERIALS AND METHODS.** A virtual stone study die of the upper right first molar was created using a dental laboratory scanner. After designing interim crowns on the virtual study die and saving them as Standard Triangulated Language files, 30 interim crowns were fabricated using a DLP-type 3D printer. Additively manufactured interim crowns were post-cured using three different time conditions-10-minute post-curing interim crown (10-MPCI), 20-minute post-curing interim crown (20-MPCI), and 30-minute post-curing interim crown (30-MPCI) (n = 10 per group). The scan data of the external and intaglio surfaces were overlapped with reference crown data, and trueness was measured using the best-fit alignment method. In the external and intaglio surface groups (n = 45 per group), precision was measured using a combination formula exclusive to scan data ($_{10}C_2$). Significant differences in accuracy (trueness and precision) data were analyzed using the Kruskal-Wallis H test, and post hoc analysis was performed using the Mann-Whitney U test with Bonferroni correction (α=.05). **RESULTS.** In the 10-MPCI, 20-MPCI, and 30-MPCI groups, there was a statistically significant difference in the accuracy of the external and intaglio surfaces (P<.05). On the external and intaglio surfaces, the root mean square (RMS) values of trueness and precision were the lowest in the 10-MPCI group. **CONCLUSION.** Interim crowns with 10-minute post-curing showed high accuracy. [J Adv Prosthodont 2021;13:89-99]

KEYWORDS
Digital light processing; Interim crown; Trueness; Precision; Post-curing time

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INTRODUCTION

In fixed dental prosthodontics, interim restorations are used after abutment preparation and before final cementation. In general, interim restorations play an important role in protecting abutments, preventing dental caries, protecting periodontal tissue, restoring occlusal function, and improving esthetics.[1,2] Interim restorations are usually made from auto-polymerized resin, which is inexpensive and strong. However, it undergoes shrinkage and volume change due to free radical polymerization, and its manufacturing process is inefficient.[3,4]

To compensate for the shortcomings of the manual method, additive manufacturing of interim crowns using computer aided design/computer aided manufacturing dental (CAD/CAM) has emerged as an alternative method.[5,6] Using this approach, the material is continuously stacked to match the layer thickness entered in the three-dimensional (3D) printing software. Hence, a precise and complex tooth structure can be formed and the material consumption is low.[7,8] These advantages make this technique ideal for manufacturing interim crowns.[6,9]

The stereolithography apparatus (SLA) and digital light processing (DLP) types of dental 3D printers use the vat photo-polymerization method.[7,9-11] In particular, DLP can reduce polymerization shrinkage and manufacturing time because it produces dental restorations by projecting images in units of pixels using a project beam light source transmitted through a digital micro mirror device.[12] The DLP-type 3D printer has attracted much interest in dental research recently because of this time efficiency.[12,13]

In the vat photo-polymerization type 3D printer, post-processing is essential after the object has been manufactured.[9] In general, 3D printer software programs are used before post-processing to set printing variables such as layer thickness, build orientation, object arrangement in a virtual build platform, and support settings.[9] Several previous studies have assessed these variables.[14-18]

Post-processing is performed after object processing has been completed in the vat photo-polymerization 3D printer. In particular, the cleaning process removes residual resin from the fabricated object, and a post-curing process binds the photoreactive resin liquid that has not been completely polymerized.[9,19] In general, when processing of the interim crown has been completed using the vat photo-polymerization 3D printer method, a rinsing process is performed and the post-curing step is entered.[19] At this time, 95 - 98% of the additive manufactured object has been cured, but the residual photoreactive resin liquid between the layers has not.[20] In post-curing, mechanical processes cure the residual resin between the layers and improve durability, strength, and toughness.[20,21] In addition, surface roughness disappears.[22]

Using the SLA or DLP methods, shrinkage due to internal stress during post-curing can affect the accuracy of the interim restoration.[23,24] In this context, accuracy comprises both trueness and precision; trueness refers to how close the reference data are to the scan data, while precision denotes how similar the measured values are within the scan data.[23,25] Nowadays, such accuracy and error can be measured and observed in 3D using an inspection software and a high-accuracy dental laboratory scanner according to the method proposed by the International Organization for Standardization.[15,16,25-29] Despite this, few studies have focused on the accuracy (trueness and precision) of interim crowns manufactured using the DLP method according to post-curing time.

Therefore, this *in vitro* study aimed to evaluate the accuracy (trueness and precision) of interim crowns manufactured using the DLP method according to post-curing time. The null hypothesis was that there is no difference in the accuracy (trueness and precision) of interim crowns according to the different post-curing times.

MATERIALS AND METHODS

The study flowchart is shown in Figure 1. The maxillary right first molar (ANA-3 ZPVK 16, Frasaco GmbH, Tettnang, Germany) was adopted as a model to manufacture the abutment. To design the interim crown, an occlusal height of 1.5 mm, an axial wall of 1.5 mm, and a 1-mm deep chamfer on the margin were preprared. The abutment was made using a dental replica silicone mold (Deguform, Degudent GmbH, Hanau-Wolfgang, Germany). A stone study die was

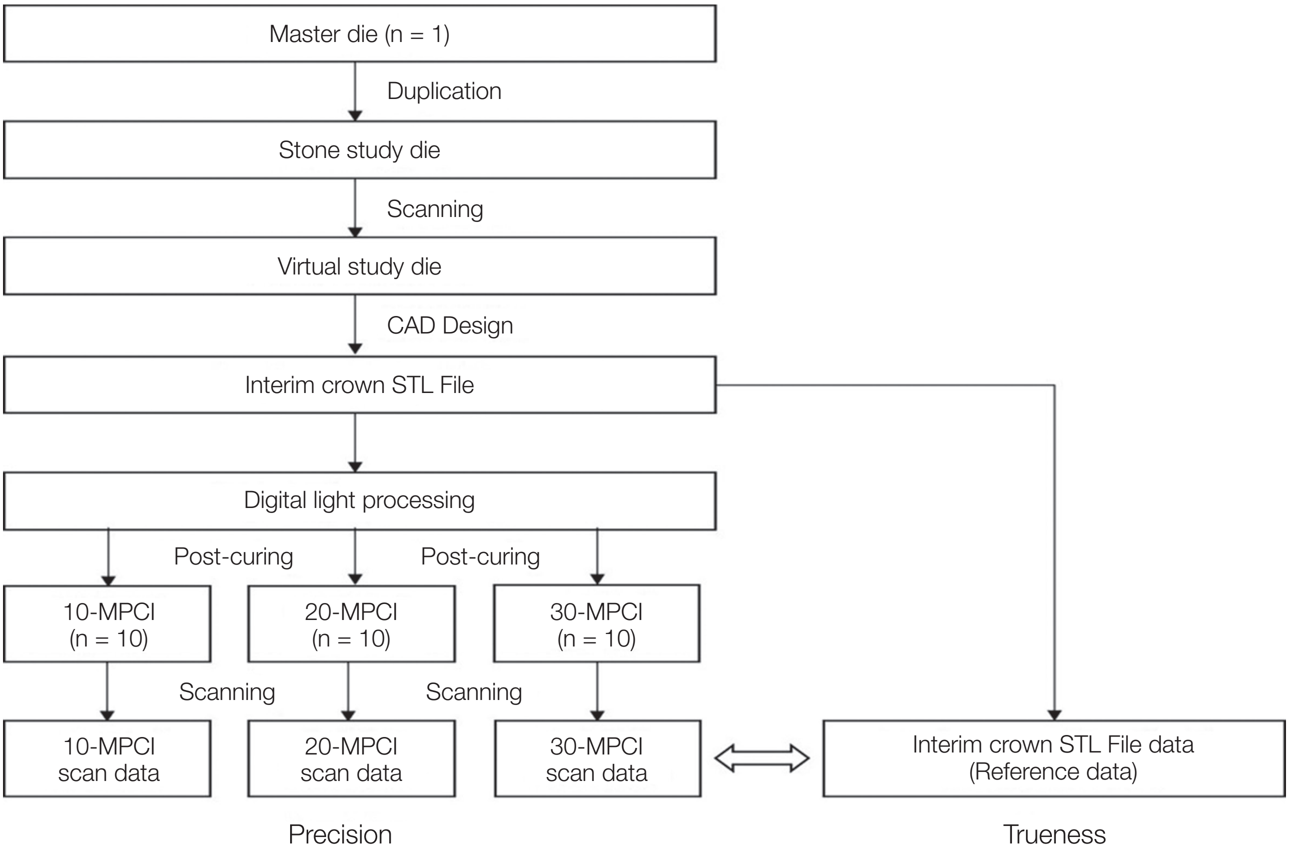

Fig. 1. Flowchart of research protocol. 10-MPCI: 10-minute post-curing interim crown, 20-MPCI: 20-minute post-curing interim crown, 30-MPCI: 30-minute post-curing interim crown.

fabricated by mixing and pouring dental hard stone (GC Fujirock EP, GC Corp., Leuven, Belgium) into a silicone mold based on the water: powder ratio suggested by the manufacturer.

The stone study die was scanned to form a virtual study die using a dental laboratory scanner (E3, 3Shape, Copenhagen, Denmark), which has a resolution of 7 µm according to the manufacturer.[28] The scanned virtual study dies were saved in the Standard Triangulated Language (STL) file format for interim crown design. After importing the virtual study die STL file into the CAD software program (Dent CAD, Delcam PLC, Birmingham, UK), the upper right first molar interim crown CAD was designed and saved in STL format to be used as reference data to make the interim crown using the DLP method and measure the trueness. The interim crown STL files were placed using a 3D printer-specific program (FlashDLPrint, Flashforge, CA, USA) to form the supports. At this time, the interim crown was set at an angle of 45° (135°) on the virtual build platform, the layer thickness was set at 50 µm, and thin supports were created on the external surface.[16-18]

The material properties of the interim prosthodontic 3D printer resin liquid used in this study are presented in Table 1.[9] Before the PMMA resin liquid for interim crowns (NextDent C&B, NextDent, Soesterberg, Netherlands) was injected into the resin bath, the bottle was shaken by hand for 5 minutes. To ensure uniform mixing, the bottles were mixed for 2 hours and 50 minutes using a dedicated mixer (LC-3D Mixer, NextDent, Soesterberg, Netherlands). After the calibration test was performed using a DLP-type 3D printer (NextDent 5100, NextDent, Soesterberg, Netherlands) with a wavelength of 405 nm and an accuracy of ± 57 nm, as suggested by the manufacturer, the PMMA res-

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Table 1. Material properties of interim restoration resin liquid used in this study

Mechanical property	Value
Colors	A2 - A3.5 (tested by TM18)
Brookfield viscosity at 23° Celsius	0.9 - 1.4 Pa·s (tested by ASTM D2162)
Flexural strength	85 - 100 MPa (tested by ISO 10477:2003)
Flexural modulus	2.300 - 2.500 MPa (tested by ISO 10477:2003)
Charpy impact strength unnotched	12 - 15 kJ/m^2 (tested by ISO 179: 2010)
Water sorption	< 30 μg/mm^2 (tested by ISO 10477:2004)
Water solubility	< 5 μg/mm^2 (tested by ISO 10477:2004)
Hardness Shore D	80 - 90 (tested by ISO 868:2003)
Wavelength	Blue UV-A (315 - 400) + UV-blue (400 - 550)
Certification provided	1. Microfilled material 2. Class IIa CE-certified 3. FDA-approved

in liquid (NextDent C&B, NextDent, Soesterberg, Netherlands) for interim crowns was injected into the resin bath. The liquid was stirred for 30 seconds before the DLP printer was operated; 30 interim crowns were manufactured (Fig. 2). These were separated from the build platform and rinsed for 5 minutes using 96% isopropyl alcohol in an ultrasonic cleaner.[30]

After rinsing, the interim crown was subjected to final polymerization using a post-curing unit (LC 3DPrint Box, NextDent, Soesterberg, Netherlands) with three post-curing times-10 minutes (10-minute post-curing interim crown [MPCI]), 20 minutes

Fig. 2. Interim crown manufactured using digital light processing.

(20-MPCI), and 30 minutes (30-MPCI, Fig. 3; n = 10 in each group). Four 18W/71 Dulux L blue lamps and four 18W/78 Dulux blue UV-A lamps were used in the post-curing unit to provide a blue UV-A wavelength of 315 - 400 nm and an output of 129.6 kJ.[30] At this time, after the post-curing treatment of the first group is completed, the internal residual heat source may cause deformation of the interim crown during post-curing of the next group. Therefore, in this study, after removing the internal heat source at a time interval of about 30 minutes, post-curing of the next group was processed to perform self-calibration. The manufacturer recommends a post-curing time of 30 minutes, so the 30-MPCI group was designated as the control group, while the 10-MPCI and 20-MPCI groups were designated as the experimental groups. After the final post-curing step, the interim crown was carefully removed from the support attached to the external surface using a diamond disc, a dedicated bur, and a rubber point.

After final shape correction, the external and intaglio surfaces of the interim crowns were scanned using a high-accuracy blue light scanner (E3, 3shape, Copenhagen, Denmark) with a low error of ± 7 μm. The scans were then saved in the STL file format.[28] After the scan data were acquired, the calibration test was performed before new scan data were acquired.

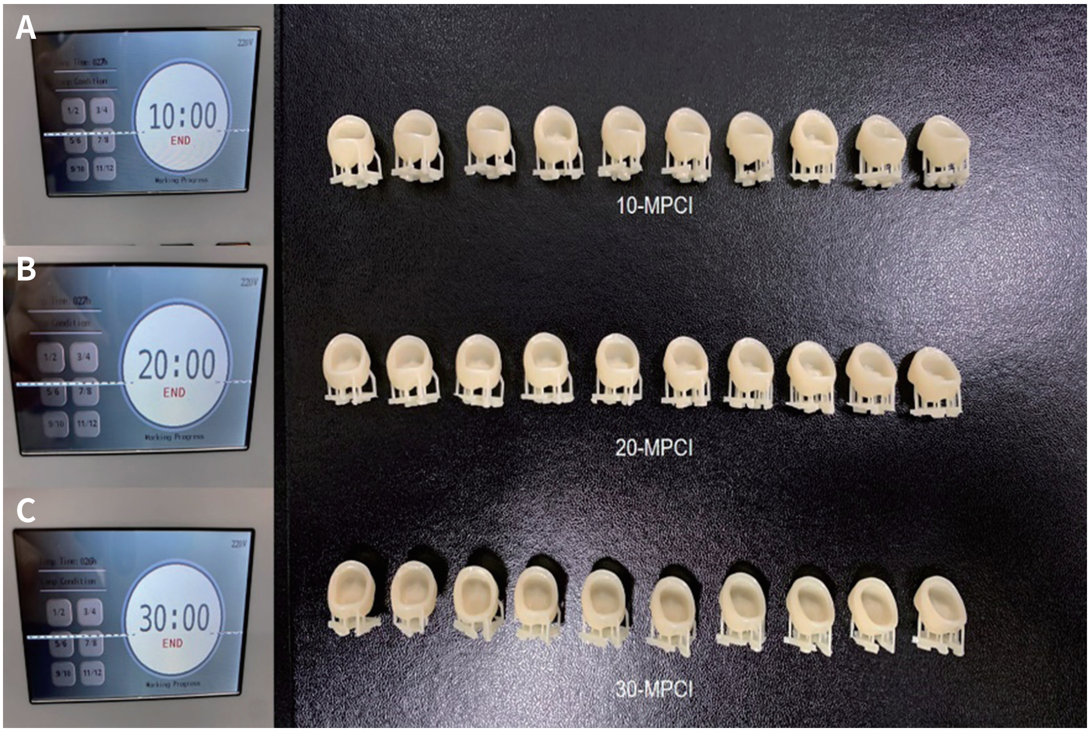

Fig. 3. Interim crowns manufactured using different post-curing processes. (A) 10-minute post-curing time (10-MPCI), (B) 20-minute post-curing time (20-MPCI), (C) 30-minute post-curing time (30-MPCI; n = 10 in each group).

The accuracy (trueness and precision) measurements of the interim crowns was analyzed using 3D inspection software (Geomagic Verify 2015, 3D systems, Morrisville, NC, USA). Prior to measurement, the unnecessary parts of the external and intaglio surfaces were corrected and deleted.

To determine the trueness value, automatic alignment was performed on the reference crown and external and intaglio surface scan data of the 10-MPCI, 20-MPCI, and 30-MPCI groups. The data values were then acquired using the best-fit alignment method. To ascertain the precision value, the external and intaglio surface scan data in the 10-MPCI, 20-MPCI, and 30-MPCI groups were automatically aligned and then superimposed using the best-fit alignment method. Forty-five precision data values were calculated for each group using a dedicated combination formula ($_{10}C_2$).

The root mean square (RMS) value was used to evaluate the accuracy (trueness and precision) of interim crowns made using different post-curing times, and the visual evaluation was analyzed by applying a visual deviation map.[6,11,15-17,23,26-29] For accuracy measurement, the allowable deviation of the intaglio surface was ± 50 µm, and the maximum allowable deviation was ± 100 µm. For the external surface, the allowable deviation was ± 50 µm, and the maximum allowable deviation was ± 150 µm.[23,26]

To analyze the mean and standard deviation of the measured accuracy values, significant differences were tested using IBM SPSS statistics (IBM SPSS statistics v25.0, IBM Corp., Armonk, NY, USA). First, the normality of the accuracy (trueness and precision) values was analyzed using the Kolmogorov-Smirnov and Shapiro-Wilk tests, but the normality was not satisfied ($P < .05$). Therefore, significant differences were analyzed among the three groups using the non-parametric Kruskal-Wallis H test, and post hoc analysis was performed using the Mann-Whitney U-test with Bonferroni correction ($P = .017$). The type 1 error was set to 0.05 ($\alpha = .05$).

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RESULTS

The accuracy (trueness and precision) of the interim crowns was evaluated according to the different post-curing times. Significant differences were found in the external and intaglio surfaces ($P < .05$). For both surfaces, the RMS values of trueness and precision were the lowest in the 10-MPCI group and the highest in the 30-MPCI group (Table 2 and Table 3).

The post hoc trueness analysis of the external and intaglio surfaces showed significant differences in the 10-MPCI and 30-MPCI groups ($P < .011$), while post hoc precision analysis showed significant differences in the 10-MPCI, 20-MPCI, and 30-MPCI groups ($P < .001$).

In the visual deviation analysis, error analysis was performed using a 3D color-coded deviation map, with the green range representing the allowable deviation, the red range representing the positive deviation, and the blue range representing the negative deviation.

With regard to the trueness of the external surface, complex deviations were observed in the occlusal surface in the 10-MPCI, 20-MPCI, and 30-MPCI groups (Fig. 4A), while positive deviations were observed in all surfaces (buccal, lingual, mesial, and distal surfaces), except the occlusal surface. Regarding the precision of the external surface, the 10-MPCI group showed slight positive and negative deviations within the allowable deviation range (Fig. 4B). However, in the 20-MPCI and 30-MPCI groups, complex deviations occurred in all surfaces (occlusal, lingual, mesial, and distal surfaces), except the buccal surface (Fig. 4B).

With respect to the trueness of the intaglio surface, the 10-MPCI group showed a positive deviation in the axial wall of the intaglio buccal surface, while most of the other surfaces (intaglio lingual, occlusal, mesial, distal surfaces) were within acceptable deviations (Fig. 5A). In the 20-MPCI and 30-MPCI groups, there were complex positive and negative deviations in the occlusal surface, while most of the axial walls showed positive deviations (Fig. 5A). The precision of the inta-

Table 2. Interim crown external surface trueness and precision root mean square values according to post-curing time

External surface		10-MPCI (μm)	20-MPCI (μm)	30-MPCI (μm)	P*
Trueness	Mean (± SD)	87.8 (± 3.9)[a]	89.7 (± 7.8)[a,b]	96.6 (± 9.2)[b]	.029
	95% CI	85 - 90.6	84.1 - 95.3	90.1 - 103.2	
	Median	86.9	87.3	94.5	
Precision	Mean (± SD)	41.3 (± 5.3)[a]	54.5 (± 5.6)[b]	63.1 (± 6.9)[c]	.001
	95% CI	39.7 - 42.9	52.8 - 56.2	60.9 - 65.2	
	Median	43	53	61.2	

[a,b,c] Values followed by a different letter indicate statistical significance based on the Mann-Whitney U test with Bonferroni correction (significant $P < .05/3 = 0.017$)
*Analyzed using the Kruskal-Wallis test (α = .05)
SD: Standard Deviation, CI: Confidence Interval

Table 3. Interim crown intaglio surface trueness and precision root mean square values according to post-curing time

Intaglio surface		10-MPCI (μm)	20-MPCI (μm)	30-MPCI (μm)	P*
Trueness	Mean (± SD)	78.2 (± 7.2)[a]	86.61 (± 10.3)[ab]	89.5 (± 6.1)[b]	.012
	95% CI	73.1 - 83.3	79.2 - 94	85.1 - 93.9	
	Median	80.7	85.3	90.6	
Precision	Mean (± SD)	29.1 (± 2.9)[a]	38.8 (± 3.3)[b]	43.5 (± 3.9)[c]	.001
	95% CI	28.1 - 29.9	37.9 - 39.8	42.3 - 44.7	
	Median	29.7	39	41.6	

[a,b,c] Values followed by a different letter indicate statistical significance based on the Mann-Whitney U test with Bonferroni correction (significant $P < .05/3 = 0.017$)
*Analyzed using the Kruskal-Wallis test (α = .05)
SD: Standard Deviation, CI: Confidence Interval

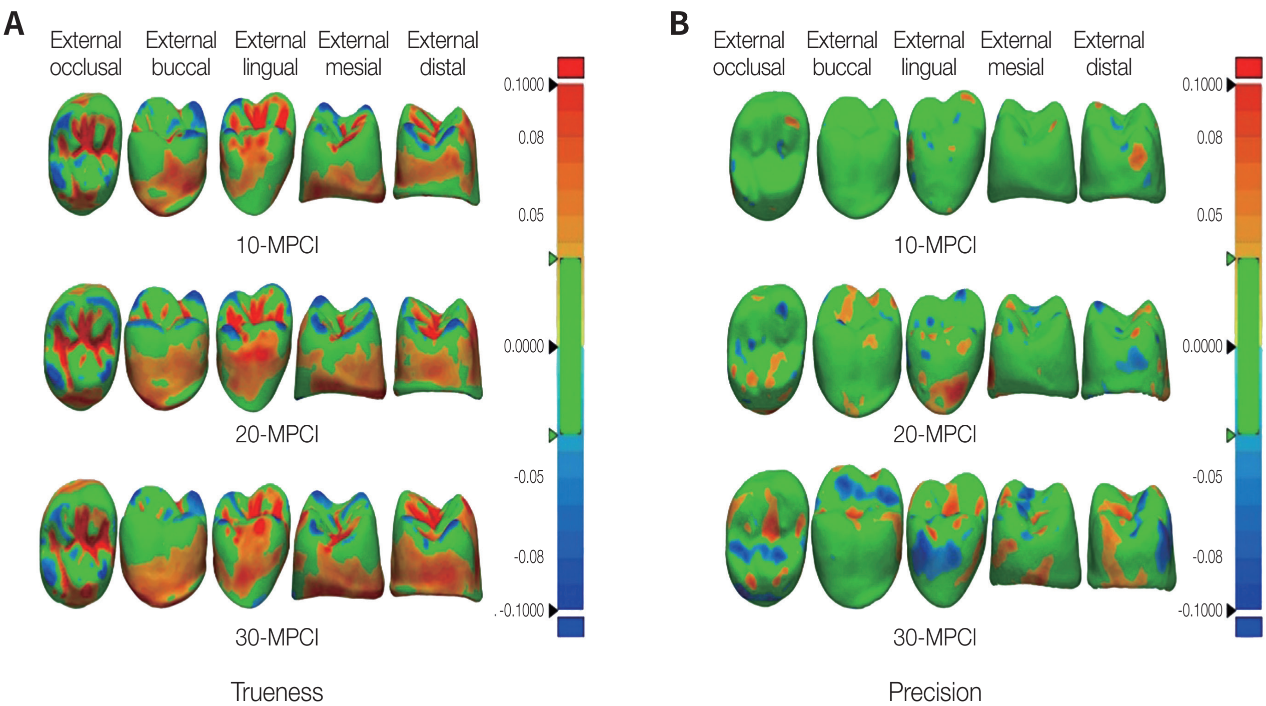

Fig. 4. Visual deviation analysis of external surface using color deviation map. (A) trueness, (B) precision. Green area represents good accuracy, yellow or red area represents positive error, blue area represents negative error.

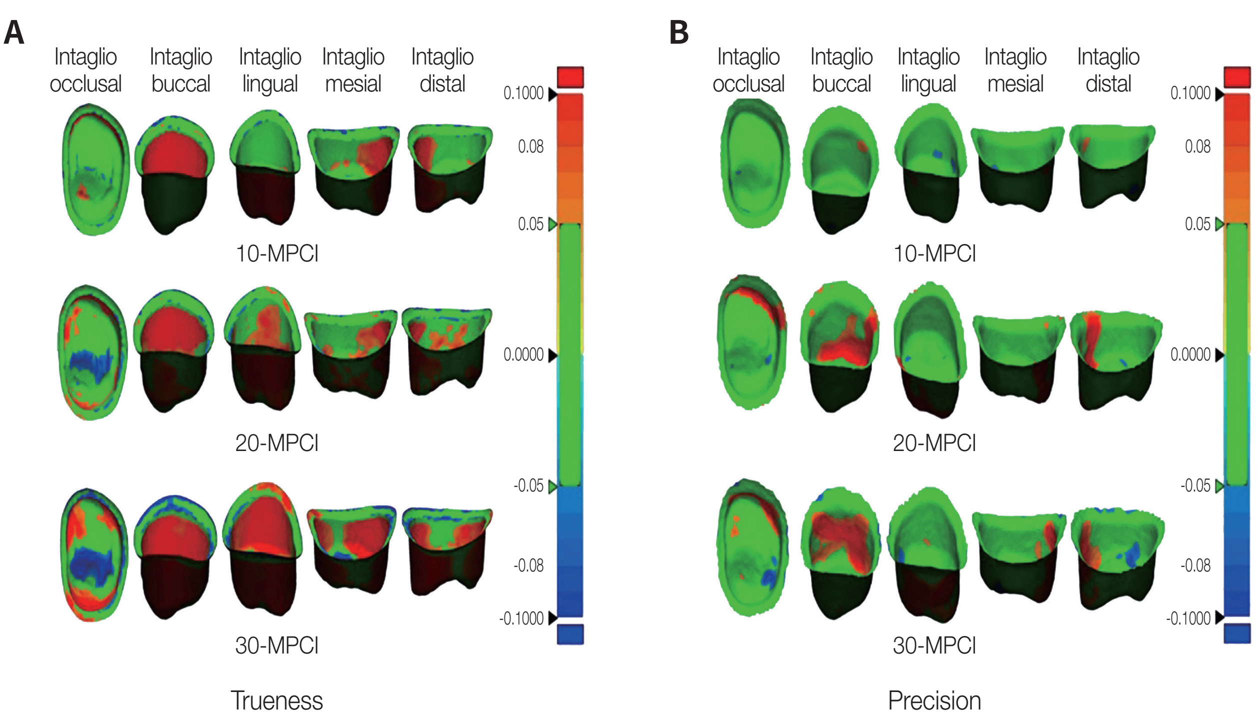

Fig. 5. Visual deviation analysis of intaglio surface using color deviation map. (A) trueness, (B) precision. Green area represents good accuracy, yellow or red area represents positive error, blue area represents negative error.

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glio surface was within the allowable deviation range in the 10-MPCI group, while it showed positive deviations on the buccal surface and partially negative deviations in the 20-MPCI and 30-MPCI groups (Fig. 5B).

DISCUSSION

In this *in vitro* study, the accuracy of the interim crown manufactured using the DLP method was evaluated according to different post-curing times. In general, there are various post-curing units for each company, and the recommended post-curing time varies from 10 minutes to 30 minutes.[3,5,6,8,9,11,13-21,23,29] In this study, in order to classify the post-curing time regularly, accuracy was evaluated by classifying it into three groups of 10 minutes, 20 minutes, and 30 minutes. The null hypothesis was rejected because there was a significant difference in accuracy between the external and intaglio surfaces of the interim crown according to post-curing time (Table 2 and Table 3).

The layer thickness was set to 50 µm[3,18,31] and the build orientation was set to 45° (135°).[17] A thin support was used[16] and errors due to 3D printing variables were minimized. The accuracy of the blue light-based dental laboratory scanner used was ± 7 µm; hence, it did not affect the error in measuring the trueness and precision.[28] When using a dental laboratory scanner, previous studies have applied scan spray to minimize errors due to light reflection[15,26]; however, in the present study, no scan spray was applied. This allowed us to investigate errors in accuracy due to different post-curing times.

In the quantitative analysis of trueness, the mean, SD, 95% CI, and median values of the 10-MPCI group were lower than those of the 20-MPCI and 30-MPCI groups for the external and intaglio surfaces (Table 2 and Table 3). In the visual deviation analysis, the visual deviation differed between the external and intaglio surfaces (Figs. 4A and 5A). In the external surface, positive deviations occurred in all three groups, except with regard to the trueness of the occlusal surface (Fig. 4A). This error probably occurs because of a deflection phenomenon on the rear area surface to which no support is attached during additive manufacturing.[3,6,13,19,32] In addition, during additive manufacturing of the interim crown, the build platform repeatedly moves up and down. This can introduce errors due to curl and warpage of the new layer on the hardened layer.[33] In the case of the external occlusal surface, complex deviations occurred (Fig. 4A), seemingly because of a stair-step effect on occlusal surfaces with a complex shape.[23,27] Wang *et al*.[27] reported that the stair-step effect causes an error on curved or occlusal surfaces and that line angle and groove trueness analysis is limited.

In all three groups, the trueness of the intaglio surface showed positive deviations on the buccal surface (Fig. 5A). This error is probably due to the gravity effect during additive manufacturing of photoreactive resin.[3,16] The deflection of the intaglio buccal surface due to gravity may occur because the outer support is attached on the opposite side.[13,16] A negative deviation occurred on the intaglio occlusal surface (Fig. 5A), which appears to have influenced the trueness analysis due to centripetal shrinkage from the outer surface to the inner surface.[15,26,34] In addition, Ishida and Miyasaka[35] reported that shrinkage occurs at the inner diameter and at the outer diameter, which affects the dimensional accuracy. In the marginal area of the intaglio surface, there were partially negative and positive deviations (Fig. 5A). Rounding effect may influence the trueness analysis, whereby sharp parts such as marginal areas are distorted in the process of obtaining intaglio surface scan data.[6,27,36]

In the quantitative analysis of precision, similarly to that of trueness, the 10-MPCI group showed lower mean, SD, 95% CI, and median values than the other groups (Table 2 and Table 3). In the visual deviation analysis, unlike trueness, the 10-MPCI group showed many green areas (Figs. 4B and 5B). Statistical errors in the external and intaglio surfaces of precision are likely caused by optical diffraction, which occurs during irradiation of the interim crown in post-curing.[14,23,37] In addition, UV-induced bending became more severe as the post-curing time increased; this affected the precision analysis of the external and intaglio surfaces.[38] In addition, factors influencing the trueness analysis likely influenced the precision analysis error, including stair-step effect, centripetal contraction, dimensional distortion, deflection due to gravity, and some rounding effects.[3,6,13,15,16,27,31,35,36]

In the present study, the interim crown was the most accurate in the 10-MPCI group. In addition, although various factors influenced the accuracy analysis, the low mean RMS, SD, 95% CI, and median values of the 10-MPCI group affected the accuracy of the interim crown. A study by Ender *et al*.[39] reported that deviations of ≥ 100 μm can lead to inaccurate fit of the final restoration. In the present study, the RMS accuracy value was within 100 μm, consistent with the results reported by Yu *et al*.[6] In addition, there are various post-curing units for each company, and the results of this study are expected to be used as reference materials in manufacturing interim crowns by DLP method. In particular, internal accuracy affects fit with the abutment; hence, future studies should be conducted to evaluate marginal and internal gaps.[3,6,8,13,14,15,29] In another sense, when the post-curing unit is continuously used, the residual heat source existing inside may affect the accuracy of the interim prosthodontic, so future studies will need to evaluate the accuracy according to the presence or absence of the residual heat source inside the post-curing unit.

There were several limitations in this study. First, only one piece of equipment was used as the post-curing unit, and only the DLP method was considered for 3D printing. Second, no strength test was conducted according to the degree of polymerization and post-curing time. Therefore, future studies should evaluate accuracy according to the post-hardening time of interim crowns manufactured using the SLA method. In addition, post-curing affects strength, durability, and surface roughness; hence, studies should be conducted to compare the degree of polymerization and material properties.[4,7,29] Likewise, since each manufacturer provides various post-curing units with different recommendations, a study should be performed to evaluate accuracy and physical properties using various post-curing units.[4,7,9,19] Along with the evaluation of the strength of the material, the post-curing process also affects the biological stability, which leads to the elution of the monomer, so future studies should also proceed with the toxicity evaluation.[40] Furthermore, it seems that *in vivo* studies in the oral cavity should be conducted.[2,39]

CONCLUSION

Within the limits of this *in vitro* study, the following conclusions were drawn:

Post-curing time affected the accuracy of the interim crown external and intaglio surfaces. Post-curing time of 10 minutes interim crown showed high accuracy. In order to be applied clinically in the future, additional studies on the strength and biological stability of the material will be required.

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