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Effect of post-rinsing time and method on accuracy of denture base manufactured with stereolithography

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PURPOSE. This *in vitro* study investigates the effect of different post-rinsing times and methods on the trueness and precision of denture base resin manufactured through stereolithography. **MATERIALS AND METHODS.** Ninety clear photopolymer resin specimens were fabricated and divided into nine groups (n = 10) based on rinsing times and methods. All specimens were rinsed with 99% isopropanol alcohol for 5, 10, and 15 min using three methods-automated, ultrasonic cleaning, and hand washing. The specimens were polymerized for 30 min at 40°C. For trueness, the scanned intaglio surface of each SLA denture base was superimposed on the original standard tessellation language (STL) file using best-fit alignment (n = 10). For precision, the scanned intaglio surface of the STL file in each specimen group was superimposed across each specimen (n = 45). The root mean square error (RMSE) was measured, and the data were analyzed statistically through one-way ANOVA and Tukey test ($\alpha < .05$). **RESULTS.** The 10-min automated group exhibited the lowest RMSE. For trueness, this was significantly different from specimens in the 5-min hand-washed group ($P < .05$). For precision, this was significantly different from those of other groups ($P < .05$), except for the 15-min automated and 15-min ultrasonic groups. The color map results indicated that the 10-min automated method exhibited the most uniform distribution of the intaglio surface adaptation. **CONCLUSION.** The optimal postprocessing rinsing times and methods for achieving clear photopolymer resin were found to be the automated method with rinsing times of 10 and 15 min, and the ultrasonic method with a rinsing time of 15 min. [J Adv Prosthodont 2022;14:45-55]

KEYWORDS
Additive manufacturing; Stereolithography; Trueness; Precision; Post rinsing

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INTRODUCTION

The application of computer-aided design and computer-aided manufacturing (CAD-CAM) has significantly impacted restorative dentistry, including the fabrication of complete dentures (CDs).[1-4] CAD-CAM prostheses can be fabricated using either additive manufacturing (AM) or subtractive manufacturing (SM).[5-8] AM methods implement the fabrication of 3D objects in a layer-by-layer process,[9] which offers high-resolution printing of complex geometries, including surgical or occlusal devices, dental casts, dentures, and maxillofacial prostheses, while reducing waste material and time consumption.[10-12]

Stereolithography (SLA) is an alternative vat polymerization method based on the processing of ultraviolet (UV) light-activated photosensitive liquid polymers.[13,14] The manufacturing of a vat polymerized product is divided into data processing, manufacturing, and postprocessing.[15] Data processing involves standard tessellation language (STL) file slicing of the virtual design of the dental device and subsequent modification of 3D printing parameters. Manufacturing is the process of dental device printing via vat polymerization in a layer-by-layer manner.[16,17] The postprocessing steps consist of the post-rinsing and post-polymerizing processes.[18] During post-rinsing, the specimen is washed with a solvent to remove any superficial uncured resin, such as isopropanol alcohol (IPA) or tripropylene glycol monomethyl ether (TPM). The post-polymerizing process includes monomer-polymer conversion. These steps are essential for completing the final polymerization and can affect the accuracy of the interim prosthesis.[19] However, the recommendations for optimal solvent, rinsing times, and methods for washing printed SLA objects remain unclear.

Accuracy is classified into trueness and precision (ISO 5725-1).[20] Trueness indicates the closeness of a measured value to a true value, while precision is the closeness of repeated measurements to each other. Previous studies have reported the accuracy of the postpolymerizing process.[2,21-23] Katheng *et al*.[24] evaluated the degrees of polymerization and accuracy of SLA denture bases fabricated under varying postpolymerizing times and temperatures. Kim *et al*.[19] evaluated the dimensional accuracy and adaptation of different postpolymerization methods of SLA interim full-arch fixed prosthesis. However, few studies have highlighted the potential difference between the accuracy on denture base obtained under different rinsing times and methods of AM. Through comparison, Ammoun *et al*.[25] found that hand washing with ultrasonics appeared to be consistently better than the automated method. Mostafavi *et al*.[26] reported that washing the specimen with the TPM solvent group obtained higher trueness and precision values compared to the IPA solvent group. Lee *et al*.[27] reported that interim crowns rinsed with IPA for 10 minutes exhibited high accuracy. Xu *et al*.[28] reported no apparent surface alterations that could be detected on the devices post rinsed with IPA for less than 1 h. Mayer *et al*.[29] reported that specimens treated with IPA exhibited lower fracture loads than those cleaned with centrifugal force or Yellow Magic. In addition to the type of resin, printing parameters, and light intensity, the accuracy of the AM methods may also be influenced by the degree of residual resin removal with different post rinsing times and methods of the postprocessing step.

Even though each manufacturer should provide guidelines for their specific materials and printers, dental literature analyzing the influence of rinsing times and rinsing methods on manufacturing accuracy is nonexistent. Furthermore, there are no *in vitro* studies on the use of SLA to manufacture denture bases under varying post rinsing times and methods. Thus, this study aimed to investigate the effects of different post rinsing times and methods on the trueness and precision of SLA denture base resin. The null hypothesis is that there will be no significant difference in trueness and precision under different post rinsing times and methods.

MATERIALS AND METHODS

Figure 1 illustrates the study design for measuring the accuracy of denture base resin fabricated using SLA for varying rinsing times and methods. The geometry of the specimen was designed to simulate a maxillary complete denture using a CAD software program (Geomagic Freeform; 3D Systems, Rock Hill, SC, USA)

(Fig. 2). The original STL file of the denture base was imported into a 3D printing software (PreForm software; Formlabs, Somerville, MA, USA). A photopolymer resin (Clear resin; Formlabs, Somerville, MA, USA) was used in this study. Ninety specimens with orientation at an angle of 45 degrees (Fig. 3) and a thickness of 1.5 mm at a 100-μm layer height were fabricated using a 3D printer (Form 2; Formlabs, Somerville, MA, USA). The details of the resin and 3D printer have been described in a previous study.[24] To standardize

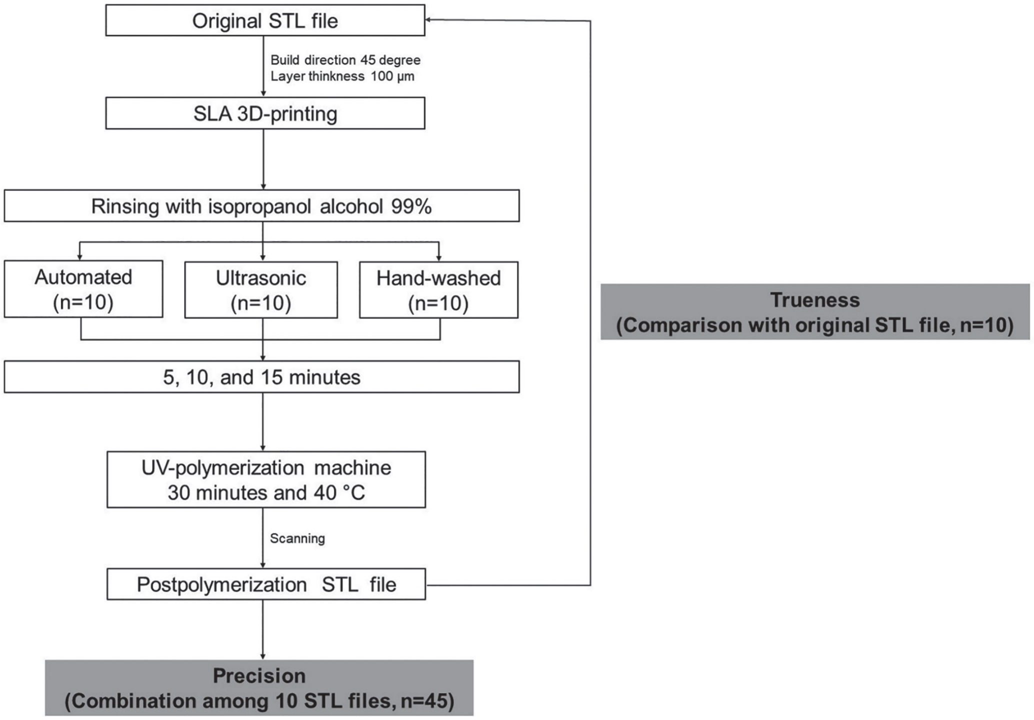

Fig. 1. Flowchart of study design of specimens fabricated using SLA for different rinsing times and methods.

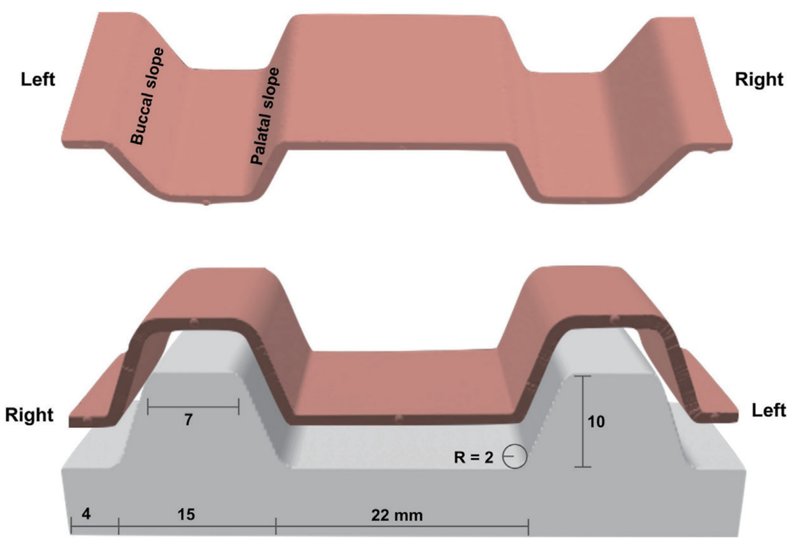

Fig. 2. Size and shape of specimens.

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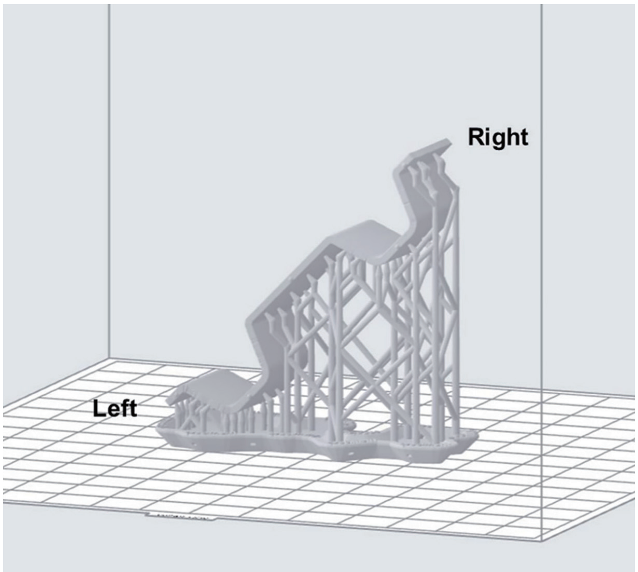

Fig. 3. Printed specimen at an angle of 45 degrees and designed support structures.

the manufacturing procedures, the 3D printer was calibrated according to the manufacturer's recommendations. All procedures were performed by a single trained researcher (A.K.). After printing, the specimens were carefully removed from the built platform using a spatula. Because the intaglio surface of the denture base was to be examined, support structures were located only on the polished surface. All nine groups of specimens were assigned to three rinsing methods-automated (A), ultrasonic (U), and hand washing (H) (Fig. 4)-for three different rinsing times of 5, 10, and 15 min each (n = 10, Table 1). All specimens were cleaned with 99% IPA (KT Chemicals, Nishi, Osaka, Japan) fresh solvent to remove any excess resin. The automated group underwent the manufacturer's recommended method of using the automated process (Form Wash; Formlabs, Somerville, MA, USA). The printed specimens remained on the print-

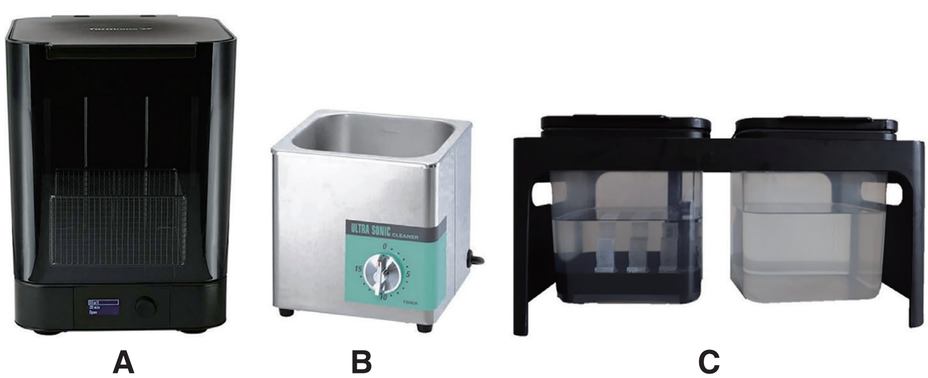

Fig. 4. Three types of devices were used for each rinsing method; (A) automated method, (B) ultrasonic method, and (C) hand-washing method.

Table 1. Rinsing procedure divided according to rinsing times and methods, resulting in a total of nine test groups (n = 10)

Group	Rinsing time (min)	Method	Postpolymerization
5A	5	Automated cleaning with form wash	30 min and 40°C
5U	5	Ultrasonic cleaning	
5H	5	Hand-washed with finish kit	
10A	10	Automated cleaning with form wash	
10U	10	Ultrasonic cleaning	
10H	10	Hand-washed with finish kit	
15A	15	Automated cleaning with form wash	
15U	15	Ultrasonic cleaning	
15H	15	Hand-washed with finish kit	

A: Automated; U: Ultrasonic; H: Hand-washed.

ed platform throughout the rinsing process for the varying rinsing times. Subsequently, the specimens were carefully removed from the built platform using a spatula. For the ultrasonic method, the specimens were rinsed with 99% IPA in a wash bottle for approximately 30 seconds (sec) and subsequently were fully submerged in a glass container with IPA in an ultrasonic bath (AU-16C Ultrasonic cleaner; Aiwa Medical Industry, Bunkyo, Tokyo, Japan) for varying rinsing times. For the hand-washing method, the specimens were rinsed with 99% IPA using the Formlabs Finish Kit (Finish Kit; Formlabs, Somerville, MA, USA), containing two plastic buckets of size 16 × 16 × 16 cm^3. The IPA solvent was filled to two-thirds of the rinse bucket volume. The specimens were placed in the rinse basket and were first rinsed by shaking the rinse basket for 30 sec. Then, the basket and specimens were completely submerged in the solvent bath. Subsequently, the rinse bucket lid was closed, and the rinse basket and specimens were soaked for approximately half the total rinsing time. Thereafter, the rinse basket was shifted to the second rinse bucket and shaken for 30 sec; subsequently, the basket and specimens were soaked for the remaining rinsing time. For volatile solvents, all the specimens were dried using compressed air for 30 min after washing to allow the solvent to completely evaporate from the surfaces. All the specimens were polymerized using a postpolymerization machine (Form Cure; Formlabs, Somerville, MA, USA) at 40°C for 30 min. Three specimens were simultaneously printed. One of the specimens was scanned immediately after postprocessing. The other specimens were stored in a lightproof container until measurements were completed.

To analyze the accuracy, the intaglio surfaces of the postpolymerization specimens were lightly coated with titanium dioxide powder (High-resolution scanning spray; 3M, St. Paul, MN, USA) with an average particle size of 3 µm. The specimens were mounted in a similar position, and support structures were not removed. Specimens were digitized using a light scanner (NeWay Optical 3D Scanner; Open Technologies, Rezzato, Italy) with a scanning trueness of 5 µm and a scanning precision of 2 µm. Before implementing the best-fit alignment, unnecessary parts of the STL file (regions other than the intaglio surfaces) were removed. All the scanned files were converted to the STL format. For trueness, the scanned intaglio surface of each SLA denture base was superimposed on the original STL file using the best-fit alignment in a surface matching software (Geomagic Freeform; 3D Systems, Rock Hill, SC, USA). For precision, the scanned intaglio surface from each STL file in each group was superimposed with the combinations of 10 datasets using the combination formula (${}^{10}C_2$=45). Deviation analysis was performed using CAD software (CATIA V5; Dassault Systems, Vélizy–Villacoublay, France) by calculating the root mean square error (RMSE) in µm and illustrated using a color deviation map.[30,31] The maximum critical and maximum nominal values were set to ± 300 µm and ± 60 µm, respectively. The RMSE values of the precision and trueness were calculated using the following formula[32,33]:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_{1,i}-x_{2,i})^2}{n}}$$

where $x_{1,i}$ denotes the reference data point, $x_{2,i}$ is the point of measurement, and n is the total number of measuring points per specimen. A higher RMSE value indicates a larger error because both the positive and negative values represent the differences among the data points.[34-36]

A statistical software program (IBM SPSS Statistics, v24.0; IBM Corp., Armonk, NY, USA) was used to analyze the results. The Shapiro-Wilk test reported normal distributions of the data. The trueness and precision were analyzed using two-way ANOVA and the corresponding results revealed no significant interaction between two independent variables rinsing time and method. Therefore, the whole data were pool and analyzed using one-way ANOVA and compared with the other groups using the post-hoc Tukey test (α = .05). An analysis software program (G*Power 3.1.9.2; Kiel University, Kiel, Schleswig-Holstein, Germany) was used to determine the sample size required for this study (n = 10).

RESULTS

The choice of rinsing times and methods affected the accuracy of the SLA-manufactured denture base. For trueness, the average range of RMSE was 71 - 86 µm.

The lowest RMSE was observed in the 10A group (71 ± 8), which was significantly different from that of the 5H (86 ± 11) (P < .05) group (Fig. 5) but was comparable to those of groups 5A (78 ± 13), 5U (84 ± 11), 10U (80 ± 3), 10H (79 ± 12), 15A (76 ± 9), 15U (72 ± 5), and 15H (76 ± 12). The highest RMSE was obtained for the 5H group. For precision, the average RMSE range was 40 - 66 µm. The lowest RMSE corresponded to the 10A (40 ± 7) group, which was significantly different from those of groups 5A (62 ± 11), 5U (66 ± 13), 5H (50 ± 10), 10U (51 ± 6), 10H (49 ± 10), and 15H (47 ± 6) (P < .05; Fig. 6) but comparable to those of groups 15A (3 ± 6) and 15U (45 ± 6). Thereby, the highest RMSE was observed in the 5U group.

The color map deviations for both trueness and precision are depicted in Figure 7 and Figure 8. In terms of trueness, the color map data showed that the deviation patterns ranged from light green to green at the palatal surface for all specimens except for those under the 5U group, which exhibited a partially negative deviation (blue) (Fig. 7). The left and right buccal slopes indicated a partial normal deviation to positive deviation, ranging from partial green to yellow and red in all groups except the 10A group. This group exhibited a green intaglio surface at the palatal surface, palatal slope, alveolar ridge, and buccal slope. In

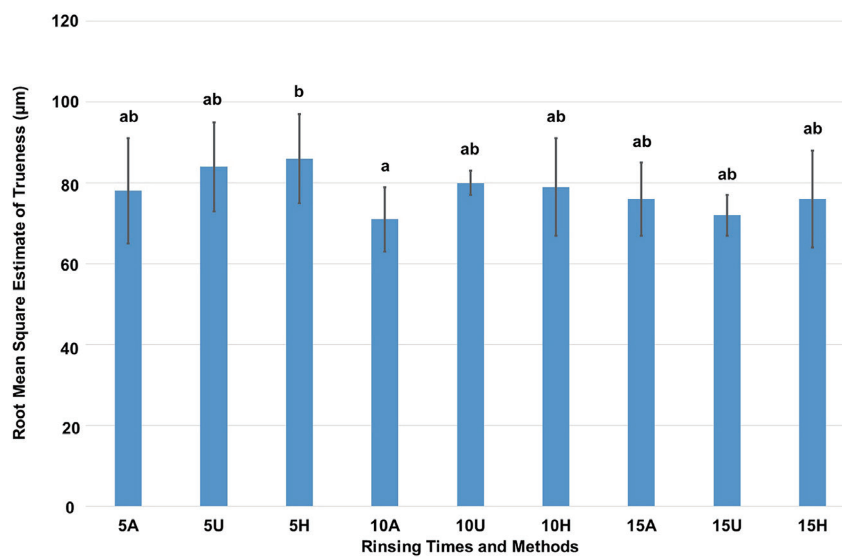

Fig. 5. Mean of RMSE values of trueness obtained for different rinsing times and methods. Different letters indicate significant differences among groups (P < .05). Numbers 5, 10, and 15 denote rinsing rimes of 5, 10, and 15 min, respectively. Letters A, U, and H stand for automated, ultrasonic, and hand washing, respectively.

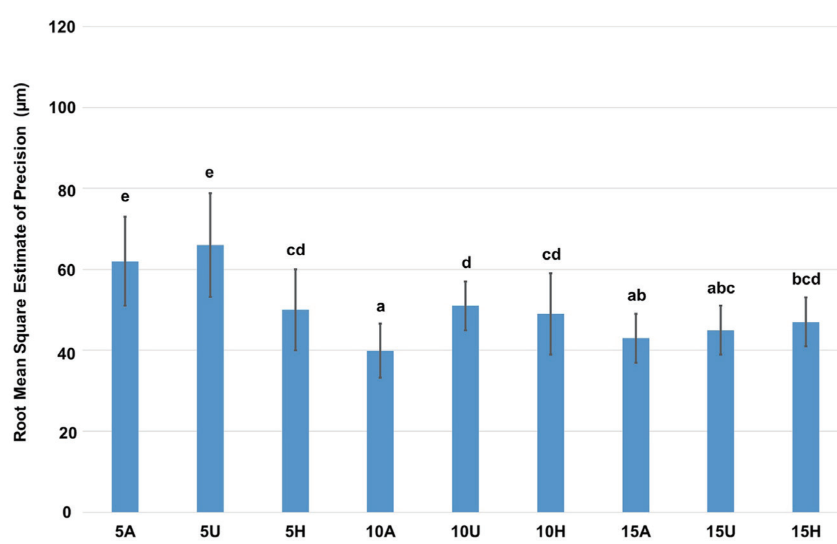

Fig. 6. Mean of RMSE values of precision obtained for different rinsing times and methods. Different letters indicate significant differences among groups (P < .05). Numbers 5, 10, and 15 denote rinsing rimes of 5, 10, and 15 min, respectively. Letters A, U, and H stand for automated, ultrasonic, and hand washing, respectively.

contrast, the right and left alveolar ridges and palatal slopes ranged from green to light blue in all groups. The line angle between the palatal slope and the alveolar ridge displayed yellow to red on the right side in all groups, except 10A group. Moreover, a complex deviation pattern was observed in the 5U group. In terms of precision, it was observed that deviations in the intaglio surface were generally within acceptable ranges (normal deviation; green) for all groups (Fig. 8).

DISCUSSION

This study examined the effect of the postprocessing rinsing time and method on the accuracy of denture bases fabricated using SLA. In general, the rinsing time depends on the 3D printed material. However, the post rinsing times and methods of the SLA process should be selected based on the required trueness and precision of the restoration. Based on the

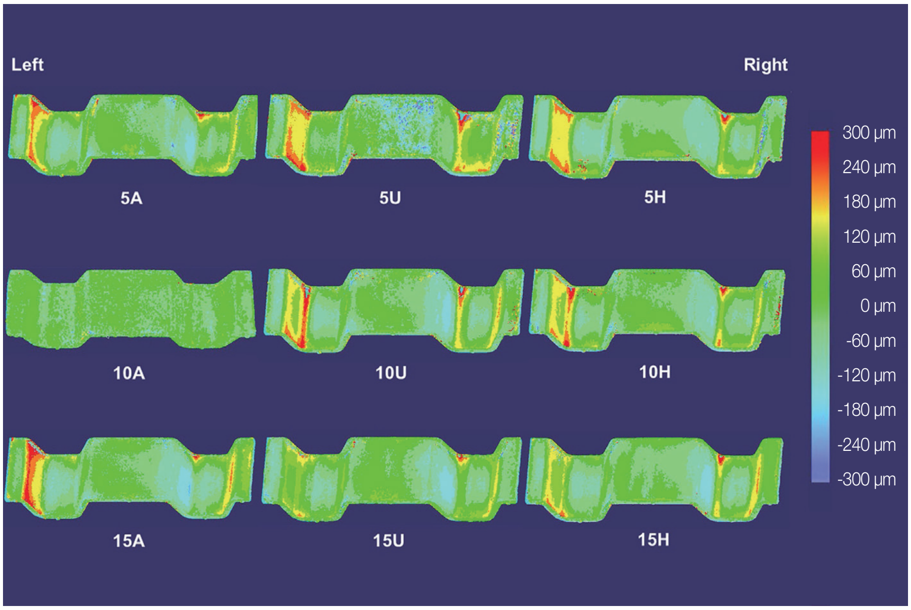

Fig. 7. Color map deviation patterns of trueness for different post rinsing times and methods. Positive deviation displayed with yellow to red, and negative deviation with blue to navy blue. Numbers 5, 10, and 15 denote rinsing rimes of 5, 10, and 15 min, respectively. Letters A, U, and H stand for automated, ultrasonic, and hand washing, respectively.

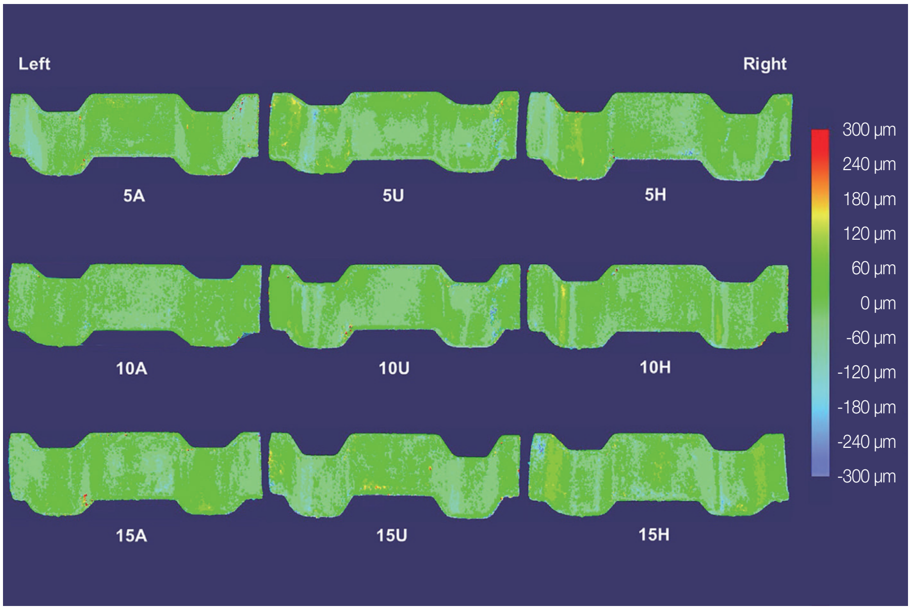

Fig. 8. Color map deviation patterns of precision for different post rinsing times and methods. Positive deviation displayed with yellow to red, and negative deviation with blue to navy blue. Numbers 5, 10, and 15 denote rinsing rimes of 5, 10, and 15 min, respectively. Letters A, U, and H stand for automated, ultrasonic, and hand washing, respectively.

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results of this study, the post rinsing time and method significantly influence the manufacturing accuracy of the clear photopolymer resin in at least one group; therefore, the null hypothesis was rejected.

In terms of trueness, the RMSE of the 10A group was significantly lower than that of the 5H group, wherein the highest RMSE was obtained. The rinsing time of 5 min exhibited a higher distortion compared to other rinsing times because of the inability to clean the unpolymerized resin on the intaglio surface during rinsing.[27] However, there was no significant difference between the RMSE values obtained from the three methods when the rinsing time increased. There seems to be a tendency of the RMSE of trueness to decrease with increasing rinsing time for the ultrasonic and hand-washing methods. This result was consistent with those of previous studies,[27,28] which reported that prolonging the post rinsing time may result in a better outcome in the removal of any residual monomers. Nevertheless, this may also adversely affect the mechanical strength.[37,38]

For precision, the post rinsing times and methods influenced the RMSE. Comparing the rinsing methods, the RMSE of the 10A group was significantly lower than those of the 10U and 10H groups. In addition, the RMSE of the 5H group was significantly lower than those of the 5A and 5U groups. However, there was no significant difference between the RMSE values obtained for the three rinsing methods of 15 min. The RMSE of precision for the ultrasonic method tended to decrease significantly with increasing rinsing time. Because the specimens were placed in a glass container with 99%IPA in an ultrasonic baht. Therefore, the ultrasonic vibration force could not be transferred directly to the specimen. The RMSE of precision for the hand-washing method also tended to decrease but was not significantly different when the rinsing time increased. This may be because there was no movement of the IPA solvent in this method.

The results of this study indicate that the automated (form wash) method with a post rinsing time of 10 min has the lowest RMSE of trueness, and there is significant difference between groups 10A and 5H, while other groups were not significantly different. For precision, the lowest RMSE corresponded to group 10A but is comparable to those of the 15A and 15U groups. Moreover, the processing of the 10A group is in accordance with the instructions of the Formlabs company. However, based on the results of trueness and precision in this study, it can be inferred that the lowest RMSE of the 10A group was similar to or better than those of the other groups; however, the difference was minimal and unlikely to be clinically significant. Therefore, the automated method with rinsing times of 10 and 15 min, and the ultrasonic method with a rinsing time of 15 min were determined to be the optimal methods for facilitating the overall trueness and precision of the intaglio surface of denture prostheses fabricated using SLA. Accordingly, in the situation where there is no automated (form wash) machine, the postprocessing ultrasonic method with a rinsing time of 15 min can also optimize the accuracy of the SLA denture.

In the color map deviation pattern for trueness, a positive deviation (yellow to red) was presented for the left and right buccal slopes in all groups. However, the 10A group exhibited the most uniform color of the intaglio surface (Fig. 7). The deviation pattern indicates a normal distribution, particularly at the palatal surfaces. This is because the presence of complex surfaces and the implementation of complicated slicing techniques along the z-direction, e.g., curves, grooves, and angles, may result in a higher distortion.[16,34-35] Moreover, the observed positive deviations on the left side were higher than those on the right side of the specimen, which can be explained by the shorter supports on the left side and the greater number of support structures than those on the right side (Fig. 3). The support structures in these areas may result in excessive polymerization during the processing of the subsequent layer of the SLA system. Negative deviations were observed in the right palatal slope in all groups except the 10A group. This can be explained by the shrinkage in the z-direction due to the slicing of the photopolymerized resin layer-by-layer and longer support in this area.[7,8,30] Positive deviations of trueness were obtained in many groups at line angles between the alveolar ridge, palatal slope, and buccal slope (Fig. 7) owing to the inability of rinsing to wash away the residual resin, especially in the hand-washed groups. In this method, the specimen was only shaken in the IPA solvent for a short time and then soaked in a bucket without any movement of the IPA solvent.

Distortion patterns are related to clinical situations. A negative discrepancy (blue) demonstrated that the test values were larger than the master values or the reference values are smaller than the test which implies tissue impingement, resulting in mucosal pain or denture retention in some areas. For trueness, most specimens displayed tissue compression (blue) at the right and left alveolar ridges and partially on the right palatal slopes. A positive deviation (red) indicates that the test values were smaller than the master values, implying spacing between the denture and cast, which can reduce the retention of the prosthesis. For trueness, all groups, except 10A, exhibited higher trends of positive deviation for the left and right buccal slopes. An acceptable discrepancy, indicated in green, represents a good fit. This was mostly observed for the trueness at the palatal surface of the specimen and was obtained for the precision in all groups of the specimen. Nevertheless, previous studies reported that the denture base sinks approximately 300 µm after insertion because the occlusal force causes the deformation of the oral mucosa. Thus, an average value of less than 300 µm deviation for denture base adaptation is assumed to be clinically acceptable.[9,14,32] Based on the results of this study, the RMSE values of trueness ranged from 71 to 86 µm, while the precision RMSE ranged from 40 to 66 µm, below the limit of 300 µm, indicating that the accuracy of SLA 3D-printed dentures is within the clinically accepted range.

The limitations of this study include the *in vitro* design, excluding variations in intraoral conditions. The limited rinsing solvents were compared, and the standardized design geometry of the specimens was designed to have less complex morphologies than those of the complete maxillary dentures. Moreover, clear photopolymer resin was selected for this study because it was an *in vitro* study. We also conducted material property tests of the same materials and designs. Therefore, we believe it is important to verify the accuracy using standardized materials and designs. However, since there exist various types of photopolymer resins other than the ones used in this study, it is necessary to investigate the most accurate denture with various types of 3D printers, photopolymer resins, or a combination of these. Consequently, these cannot be generalized for other materials. Moreover, different prosthesis designs may also have some effects on the postprocessing step. Therefore, future studies should investigate the effects of rinsing time on the accuracy using various rinsing solvents for different material types and prostheses.

CONCLUSION

Within the limitations of this study, the optimal post-processing rinsing times and methods for achieving the accuracy of the clear photopolymer resin were found to be the automated method with rinsing times of 10 and 15 min, and the ultrasonic method with a rinsing time of 15 min. Moreover, in the situation where there is no automated machine, the selection should be made based on the rinsing method. In such a situation, the ultrasonic method with a 15-min rinsing time can optimize the accuracy of the SLA denture.

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