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Research article

Effect of different post-processing conditions on the accuracy of liquid crystal display-printed orthognathic surgical splints

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A R T I C L E I N F O

Keywords:
Orthognathic surgery
Splint
CAD/CAM
3D printer

A B S T R A C T

Objectives: To evaluate the accuracy (trueness and precision) of liquid crystal display (LCD)-printed orthognathic surgical splints under two different post-processing conditions—rinsing solvent and post-polymerization time.

Materials and methods: An LCD 3D printer was used to create 48 surgical splints using the same reference standard tessellation language (STL) files. They were randomly assigned to two experimental studies. In the rinsing solvent study, 24 surgical splints were divided into three groups ($n = 8$) based on their rinsing solvents: isopropyl alcohol (IPA), ethanol, and water. In the post-polymerization time study, 24 surgical splints were divided into three groups ($n = 8$) based on the post-polymerization time: (3, 6, and 10 min). The surgical splints were covered with an opaque scanning spray, scanned, and converted into STL files. The images were trimmed and superimposed onto the reference STL file to evaluate trueness and precision, and the deviation was calculated using the root mean square (RMS) formula. Color map data were also obtained. The RMS was statistically analyzed using one-way analysis of variance and Tukey's test ($\alpha < 0.05$).

Results: The lowest RMS values of trueness and precision were observed in the IPA group and the 6-min post-polymerization time groups ($p < 0.05$). The IPA-rinse and 6-min polymerization groups ($p < 0.05$) demonstrated the highest accuracy for LCD-printed orthognathic surgical splint fabrication.

Conclusion: The dimensional accuracy of LCD-printed surgical splints is affected by the post-processing conditions, including the rinsing solvent and polymerization time. The RMS and color map data associated with the IPA-rinse and 6-min polymerization corresponded to the highest accuracy.

1. Introduction

Orthognathic surgical splints are essential for orthognathic osteotomy and fixation. They stabilize occlusion and allow easy fixation

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of the jaw segments [1]. Therefore, accuracy (trueness and precision) and occlusal adaptation are crucial factors affecting the outcomes of postsurgical occlusion and orthodontic treatment. The use of more precise splints lead to better projected results. The conventional fabrication method for a surgical splint, the surgical plaster dental model, is time-consuming and error-prone. Currently, three-dimensional (3D) planning is used in conjunction with computer-aided design (CAD) and computer-aided manufacturing (CAM) to generate 3D images of jaw movements and surgical splints. This provides surgeons with the best preoperative treatment planning scenario and allows for the fabrication of surgical splints using 3D printing [2].

3D printing, an additive manufacturing technique, creates an object layer-by-layer until it forms a complete 3D structure [3]. There are several 3D printing techniques, of which vat polymerization is the most common. This technique involves a vat and a building platform, where a liquid photopolymer resin is added to the vat to produce a printing model [4]. The main differences among photocuring 3D printing technologies, from laser-scanning stereolithography to digital light projection to the latest liquid crystal display (LCD) printing techniques, are the light source and imaging system, with small changes in the control and stepping mechanisms [4,5].

The production workflow of a vat polymerization 3D printer is divided into three major stages: data processing, manufacturing, and post-processing. Post-processing is essential for the workflow. This includes rinsing the surface of the unpolymerized resin and completing post-polymerization procedures to achieve complete polymerization of the printed object [6]. The rinsing procedure involves washing the superficial unpolymerized resin with a solvent, such as isopropyl alcohol (IPA) [6,7], or water [8]. Rinsing solvents can reportedly affect the dimensional accuracy of dental materials [6,7]. In the post-polymerization procedure, time and temperature are important factors that control the mechanical properties and degree of polymerization [9–11]. These factors can reduce shrinkage and deformation of resin materials during post-polymerization [10]. Overall, post-processing conditions such as rinsing solvents and post-polymerizing times affect the accuracy of 3D printed dental materials. This is particularly critical for orthognathic surgical splints made of photopolymer resins, where dimensional accuracy is vital for treatment success. To date, no research has been conducted to evaluate the effect of post-processing conditions on the accuracy of 3D printed surgical splints. Therefore, the goal of this study was to assess the effects of various post-processing conditions on the accuracy of 3D-printed orthognathic surgical splints.

2. Materials and methods

2.1. Sample size determination

Analysis software (G*power 3.1.9.6 software: Kiel University) was used to calculate the sample size. A previous study examining the accuracy of different post-polymerization conditions [11] was used as a reference to determine the appropriate effect size ($f = 0.7$). The alpha and power values were set to 0.05 and 0.8, respectively. Based on these parameters, the sample size required for this study was eight specimens per condition.

2.2. Fabrication of 3D-printed surgical splints

The workflow of this study is illustrated in Fig. 1. Surgical splint master data were designed using ProPlan CMF (Depuy Synthes, Solothurn, Switzerland, and Materialise, Leuven, Belgium) using a dental model (NISSIN Dental Products, Inc. Kyoto, Japan, lot. 287783 D18FE-500H [GUB]-QF). The master data were saved as a standard tessellation language (STL) file in Ackuretta's ALPHA AI Slicing Software and then sent to 3D printer software (SOL, Ackuretta, Taiwan). According to the manufacturer's instructions, a commercially available methacrylate-based photopolymer resin (CURO Guide resin, Ackuretta, Taiwan) was printed using their SOL

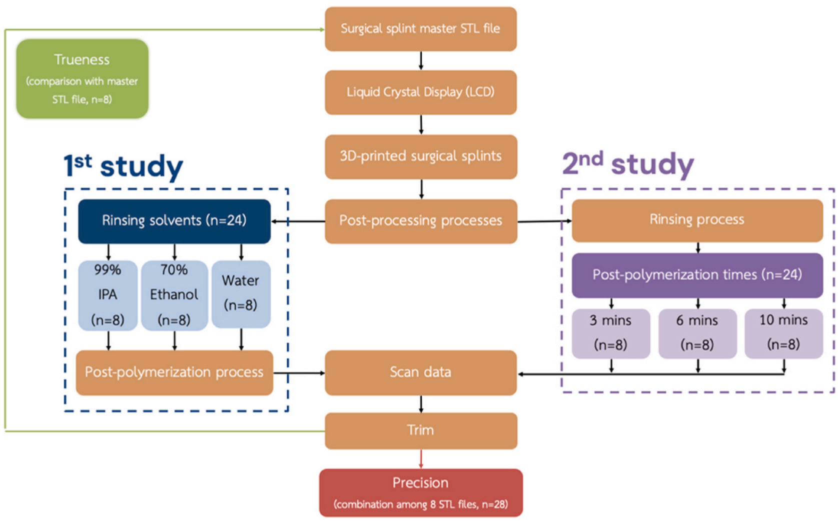

Fig. 1. Workflow of the overall research process including the post-processing conditions and types of experiment.

3D printer (Ackuretta) at a 100 μm layer height and oriented at a 90-degree angle (Fig. 2).

2.3. Post-rinsing solvent study

Three sample groups were generated based on the rinsing solvent selected for the post-processing rinsing procedure: 99 % IPA (Herbal Skin Co., Ltd., Thailand) (n = 8), 70 % ethanol (All Chemical and Supply Co., Ltd., Thailand) (n = 8), and distilled water (n = 8). The same operator performed all post-processing procedures. After printing, all the splints were carefully removed from the building platform using a spatula. Subsequently, the specimens were fully submerged and washed in CLEANI (Ackuretta, Taiwan) containing 99 % IPA (n = 8), 70 % ethanol (n = 8), and distilled water (n = 8). Each group was washed twice for 3 min each time. The specimens were then carefully dried with a paper towel before being polymerized in a UV polymerization machine (CURIE, Ackuretta, Taiwan) for 6 min according to the manufacturer's instructions (Fig. 3). All the specimens were sprayed with an antireflective spray (Renfert Scan Spray, Germany) by the same operator before being scanned using an E3 lab scanner (3Shape, Copenhagen, Denmark). The scan results were converted to STL files.

2.4. Post-polymerization time study

Three groups of 3D-printed surgical splints were assigned three post-polymerization times: 3 min (n = 8), 6 min (n = 8), and 10 min (n = 8). Following printing, the specimens were washed twice for 3 min each time (CLEANI, Ackuretta, Taiwan) with 99 % IPA according to the manufacturer's instructions, and the excess resin was removed and carefully dried with a paper towel before post-polymerization. The post-polymerization system used a 405 nm wavelength light motion drive UV LED system at ambient temperature (CURIE, Ackuretta, Taiwan). The support structures were cut and trimmed using a flush cutter (Fig. 4). All 3D-printed surgical splints were sprayed with an antireflective spray (Renfert Scanspray, Germany) by the same operator and scanned using an E3 lab scanner (3Shape, Copenhagen, Denmark). The scanned files were then converted into STL files.

2.5. Accuracy evaluation protocol

The STL files obtained after scanning the 3D-printed surgical splints were trimmed using Exocad software (Exocad DentalCAD; Exocad GmbH) to cut the touch points of the printed supports and locate the area of interest, extending distally to the buccal groove of the upper first molar. To evaluate accuracy, the data files were superimposed over five reference points on the deepest contact point of the upper anterior teeth (Fig. 5). The STL files were superimposed onto the master data file (n = 8 in each group) to evaluate trueness and between two sets of the same conditions using a dedicated combination formula ($_8C_2$) (n = 28 in each group) to evaluate precision [12]. The root mean square (RMS) was calculated using CloudCompare software (v.2.13alpha, edf, Paris, France). A low RMS value indicates a high degree of 3D matching, which translates into a high degree of trueness and precision [13]. The test-retest reliability using intraclass correlation coefficients (ICC) of the superimposition protocol was determined by repeated data acquisition from the IPA post-rinsing solvent study group. To evaluate the displacement of the surface of the 3D-printed surgical splints and generate overall color map data indicating the direction of deviation, the total deviation was obtained. A surface matching of ±0.1 mm was displayed in green. The areas in blue (negative deviation) indicate a smaller 3D printed surgical splint than the corresponding master STL file. Conversely, areas in yellow, orange, and red (positive deviation) had a larger 3D-printed surgical splint [12].

2.6. Statistical analysis

Statistical evaluation of the data was performed using IBM's SPSS Statistics, v23 (IBM Corp., USA). The Kolmogorov–Smirnov test

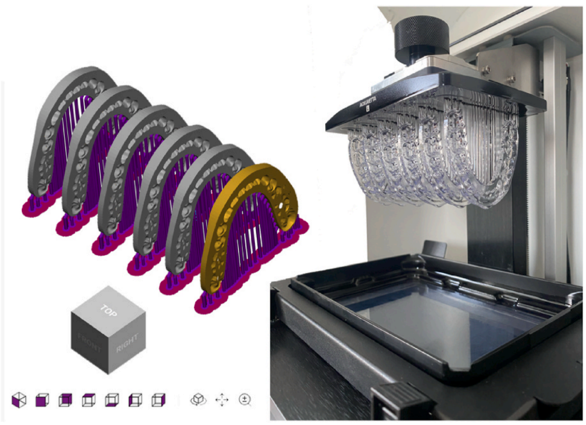

Fig. 2. Printed specimen at a 90-degree angle.

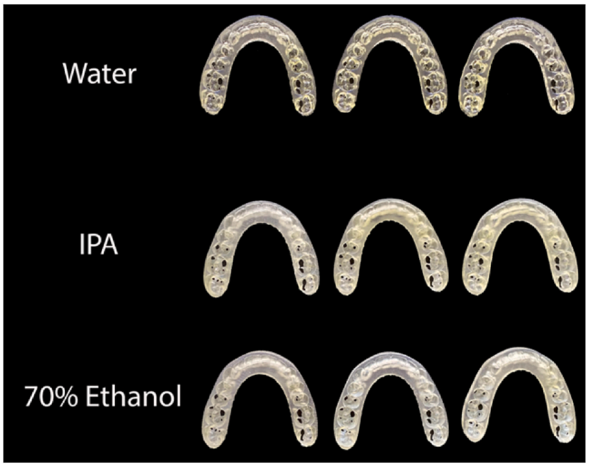

Fig. 3. Surgical splints manufacturing using different post-rinsing solvents.

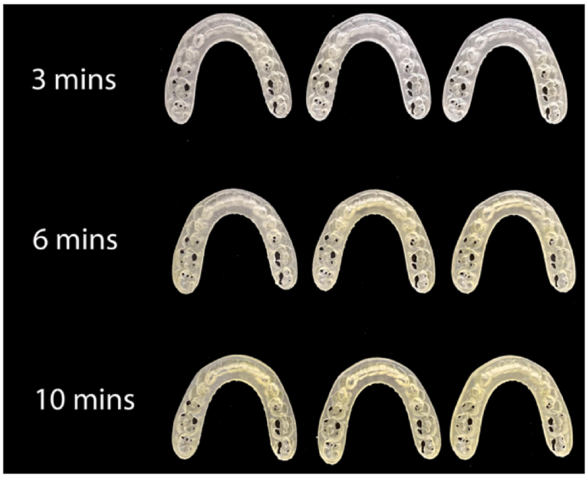

Fig. 4. Surgical splints manufacturing using different post-polymerization times.

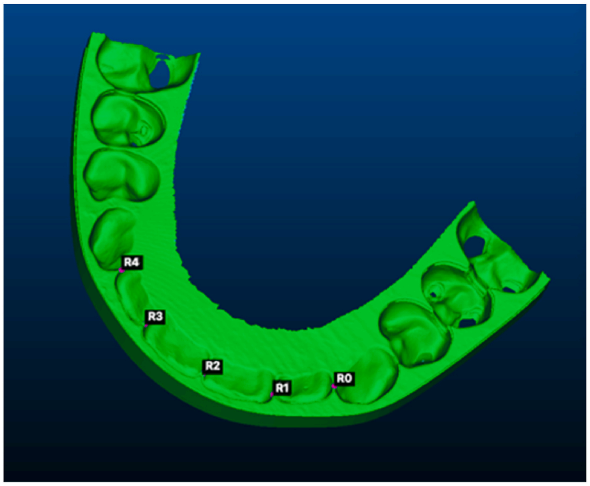

Fig. 5. Five reference points were on the deepest contact point of the upper anterior teeth.

was used to validate the normality assumption of the RMS value of accuracy (Tables 1–4). A one-way analysis of variance (ANOVA) was used to compare the RMS values between the post-processing rinsing solvents and post-polymerization times. Additionally, pairwise comparisons within groups were examined using Tukey's highly significant difference (HSD) test for the post-hoc comparison ($\alpha = 0.05$).

3. Results

3.1. Test-retest reliability of superimposed protocol

The ICC estimates and their 95 % confidence intervals were calculated based on an average measurement type, absolute-agreement, and two-way mixed-effects model. The ICC was 0.813, 95 % C.I.189-.961 indicating good reliability for the superimposed protocol.

3.2. Post-rinsing solvent study

The comparison of surgical splint accuracy was based on the three rinsing solvent groups. The IPA group exhibited the lowest RMS values for both trueness and precision ($p = 0.000$ and 0.019, respectively), whereas the water group exhibited the highest RMS values (Table 5, Figs. 6 and 7). The post-hoc analysis of trueness revealed statistically significant differences between the IPA and 70 % ethanol ($p = 0.018$) and water ($p = 0.000$) groups. There was also a significant difference between the 70 % ethanol and water groups ($p = 0.042$) (Table 6). The post-hoc test for precision analysis revealed statistically significant differences between the water and IPA ($p = 0.036$) and 70 % ethanol ($p = 0.042$) groups. However, there was no significant difference between the IPA and 70 % ethanol groups ($p = 0.998$) (Table 7).

Error analysis was performed using a 3D color-coded deviation map for visual deviation analysis. The green, red, and blue ranges represent the allowable, positive, and negative deviations, respectively. The deviation patterns at the incisal edge of the incisal, the mesial marginal ridge of the canine, the buccal cusp and palatal cusp of the premolar, and the mesiobuccal cusp and mesial side of the first molar for all groups, especially in the water-rinsing group, ranged from yellow to light red according to the color map data for trueness (Fig. 8A). In the precision color map data (Fig. 8B), the IPA and 70 % ethanol groups exhibited a uniformly distributed green color, except for the incisal edge of the central incisors, which displayed deviation patterns ranging from yellow to light red. The water rinsing group exhibited deviation patterns ranging from yellow to light red at the incisal edge of the central incisors, mesial marginal ridge of the canine, buccal cusp and palatal cusp of the premolar, mesiobuccal cusp, and mesial side of the first molar.

3.3. Post-polymerization time study

The dimensional accuracy was evaluated at different post-polymerization times. The RMS values for accuracy were found to be the lowest in the 6-min curing group (Table 8, Figs. 9 and 10). The post-hoc test for trueness analysis showed significant differences in the 6-min curing group compared with the 3-min curing ($p = 0.000$) and the 10-min curing ($p = 0.001$) groups. However, there was no statistically significant difference in the RMS values between the 3-min curing and 10-min curing groups ($p = 0.948$) (Table 9). The post-hoc precision analysis showed significant differences in the 6-min curing group compared to the 3-min curing ($p = 0.033$) and the 10-min curing ($p = 0.000$) groups. However, the difference between the 3-min and the 10-min curing groups was not statistically significant ($p = 0.226$) (Table 10).

A color map deviation analysis was performed for accuracy. Positive deviations were observed in the incisal edge of the incisors, mesial cusp ridge of the canines, buccal and palatal cusps of the premolars, and mesial surface of the first molar in all groups. Furthermore, the 3-min curing group demonstrated positive deviation at the palatal cusp tip of the premolars, while the 10-min curing group exhibited positive deviation in both the mesial and distal cusp ridges of the canines (Fig. 11A). For precision, all groups showed a slight positive deviation at the incisal edge of the incisal teeth, canine mesial cusp ridge, and buccal and palatal cusps of the posterior teeth (Fig. 11B).

4. Discussion

This study focused on how post-processing affects surgical splint accuracy. Post-processing is essential for retaining the 3D-printed product's physical properties and desired dimensions. The polymer structure of the freshly printed object is not completely

Table 1
Normality test for the RMS value of the trueness of surgical splints manufacturing using different post-rinsing solvents.

	Trueness	Kolmogorov–Smirnov[a]			Shapiro–Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
RMS	IPA	0.162	8	0.200[a]	0.939	8	0.599
	Ethanol	0.210	8	0.200[a]	0.846	8	0.087
	Water	0.191	8	0.200[a]	0.921	8	0.438

[a]. This is the lower bound of the true significance.

[a]. Lilliefors Significance Correction.

Table 2
Normality test for the RMS value of the precision of surgical splints manufacturing using different post-rinsing solvents.

	Precision	Kolmogorov–Smirnov[a]			Shapiro–Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
RMS	IPA	0.147	28	0.124	0.919	28	0.033
	Ethanol	0.076	28	0.200[a]	0.985	28	0.949
	Water	0.094	28	0.200[a]	0.965	28	0.450

[a]. This is the lower bound of the true significance.
[a]. Lilliefors Significance Correction.

Table 3
Normality test for the RMS value of the trueness of surgical splints manufacturing using different post-polymerization times.

	Post-polymerization times	Kolmogorov–Smirnov[a]			Shapiro–Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
RMS of Trueness	3 min	0.213	8	0.200[a]	0.908	8	0.337
	6 min	0.258	8	0.127	0.912	8	0.367
	10 min	0.223	8	0.200[a]	0.951	8	0.723

[a]. This is the lower bound of the true significance.
[a]. Lilliefors Significance Correction.

Table 4
Normality test for the RMS value of the precision of surgical splints manufacturing using different post-polymerization times.

	Post-polymerization times	Kolmogorov–Smirnov[a]			Shapiro–Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
RMS of Precision	3 min	0.091	28	0.200[a]	0.957	28	0.291
	6 min	0.140	28	0.173	0.924	28	0.043
	10 min	0.099	28	0.200[a]	0.956	28	0.275

[a]. This is the lower bound of the true significance.
[a]. Lilliefors Significance Correction.

Table 5
Surgical splint trueness and precision RMS values according to post-rinsing solvents.

Post-rinsing solvents		IPA (μm)	Ethanol (μm)	Water (μm)	**p**[a]
Trueness	Mean (±SD)	121.1 (±6.8)[a]	132.9 (±5.6)[b]	143.1 (±10.2)[c]	.000[a]
	95 % CI	115.4–129.7	128.2–137.6	134.6–151.8	
	Median	121.4	135.0	142.3	
Precision	Mean (±SD)	74.7 (±21.6)[a]	75.0 (±18.6)[a]	87.2 (±14.8)[b]	.019[a]
	95 % CI	66.3–83.0	67.7–82.2	81.4–92.9	
	Median	79.5	74.5	86.2	

[a,b,c] Different superscript letters indicate statistically significant differences based on the Tukey HSD test with post-hoc comparison (α = 0.05).
SD: Standard Deviation, CI: Confidence Interval.
[a] Analyzed using one-way analysis of variance (ANOVA) (α = 0.05).

polymerized before post-processing. The polymerization process continues during post-processing, with UV light used to achieve adequate crosslinking of the polymer structure, thus improving the mechanical properties of the product. Post-processing can also reduce polymerization shrinkage, which affects the accuracy of printed products [9]. Owing to challenges in printing at a 45-degree angle—the most precise and accurate printing direction for vat polymerization technology [14]—the build orientation angle was adjusted to 90-degrees in our study, and the layer thickness was set to 100 μm as the standard. An auto-generated structure-type support with an adjusted point size of 1.50 mm was built to prevent the 3D object from falling off the support, and some positions were manually adjusted to avoid the dental area. An antireflective spray was applied to all specimens by the same operator to reduce errors caused by the spray approach and light reflection [15,16]. The accuracy of the E3 lab scanner is accredited to within 7 μm (ISO 12836) [14] such that the measurement error owing to varying post-polymerization times remained unaffected. Furthermore, the area distal to the buccal and palatal grooves of the upper first molar was trimmed because of a scanning process limitation in which these areas were attached to the platform during a scan, and the same outline was recreated in all splint STL files.

In this study, the efficacy of different rinsing agents was determined by comparing surgical splints rinsed with IPA (99 %), ethanol (70 %), and distilled water. IPA is the most common solvent used in cleansing procedures to remove unpolymerized resin from surfaces. The high vapor pressure of IPA makes it highly volatile and prone to evaporation. Additionally, IPA is a flammable liquid that

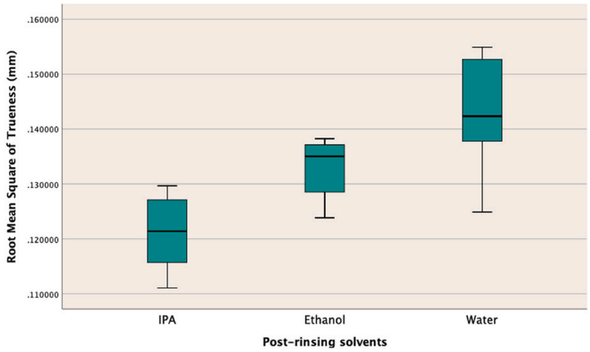

Fig. 6. RMS value of accuracy (mm) of LCD-printed surgical splints under different post-rinsing solvents.

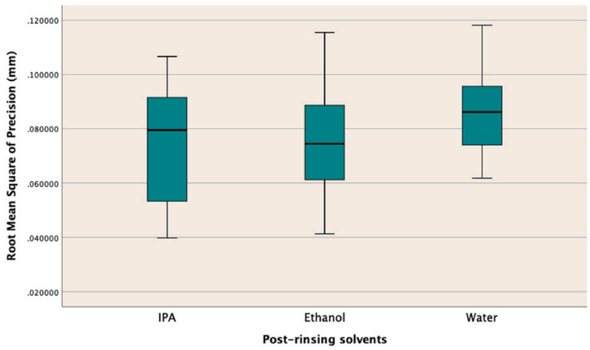

Fig. 7. RMS value of precision (mm) of LCD-printed surgical splints under different post-rinsing solvents.

Table 6
Post-hoc test for the RMS value of the trueness of surgical splints manufacturing using different post-rinsing solvents.

Multiple Comparisons						
Dependent Variable: RMS						
Tukey's HSD						
(I) Trueness	(J) Trueness	Mean Difference (I-J)	Std. Error	Sig.	95 % Confidence Interval	
					Lower Bound	Upper Bound
IPA	Ethanol	−0.0118029[a]	0.003927800	0.018	−0.02170317	−0.00190258
	Water	−0.0220468[a]	0.003927800	0.000	−0.03194705	−0.01214645
Ethanol	IPA	0.01180287[a]	0.003927800	0.018	0.00190258	0.02170317
	Water	−0.0102439[a]	0.003927800	0.042	−0.02014417	−0.00034358
Water	IPA	0.02204675[a]	0.003927800	0.000	0.01214645	0.03194705
	Ethanol	0.01024388[a]	0.003927800	0.042	0.00034358	0.02014417

[a] The mean difference was significant at the level of 0.05.

requires specific safety precautions [6]. Ethanol, a volatile, combustible, and colorless liquid, is an alcohol with the formula C_2H_6O (CH_3CH_2OH or C_2H_5OH [an ethyl group connected to a hydroxyl group]). The post-rinsing solvent for the LCD process must be chosen based on the required precision and accuracy. The null hypothesis was rejected because the specimens produced using LCD 3D printing under various post-rinsing solvents demonstrated statistically significant differences compared with the other conditions. Based on the findings of this study, rinsing solvents and post-curing procedures significantly affect the manufacturing accuracy of surgical splints.

In the quantitative analysis of trueness and precision, the mean, standard deviation, 95 % confidence interval, and median values of the IPA group were lower than those of the 70 % ethanol and distilled water groups (Table 5) because IPA is the most commonly used solvent for rinsing procedures to remove unpolymerized resin from the surface [6]. By contrast, the mean RMS value, standard deviation, 95 % confidence interval, and median RMS value of the water rinsing group were higher than those of the 70 % ethanol and IPA groups (Table 5). This can be explained by the fact that methacrylate-based resins are insoluble in water but soluble in most organic solvents; the clinically acceptable average range is less than 100 μm [16]. The RMS precision value ranged from 74.7 to 87.2 μm in this study; in contrast, the RMS value of trueness ranged from 121.1 to 143.1 μm, which was considered greater than the

Table 7
Post-hoc test for the RMS value of the precision of surgical splints manufacturing using different post-rinsing solvents.

Multiple Comparisons						
Dependent Variable: RMS						
Tukey's HSD						
(I) Trueness	(J) Trueness	Mean Difference (I-J)	Std. Error	Sig.	95 % Confidence Interval	
					Lower Bound	Upper Bound
IPA	Ethanol	−0.00027981	0.004951921	0.998	−0.01210276	0.01154313
	Water	−0.0124722[a]	0.004951921	0.036	−0.02429511	−0.00064922
Ethanol	IPA	0.000279814	0.004951921	0.998	−0.01154313	0.01210276
	Water	−0.0121923[a]	0.004951921	0.042	−0.02401530	−0.00036940
Water	IPA	0.01247216[a]	0.004951921	0.036	0.00064922	0.02429511
	Ethanol	0.01219235[a]	0.004951921	0.042	0.00036940	0.02401530

[a] The mean difference was significant at the level of 0.05.

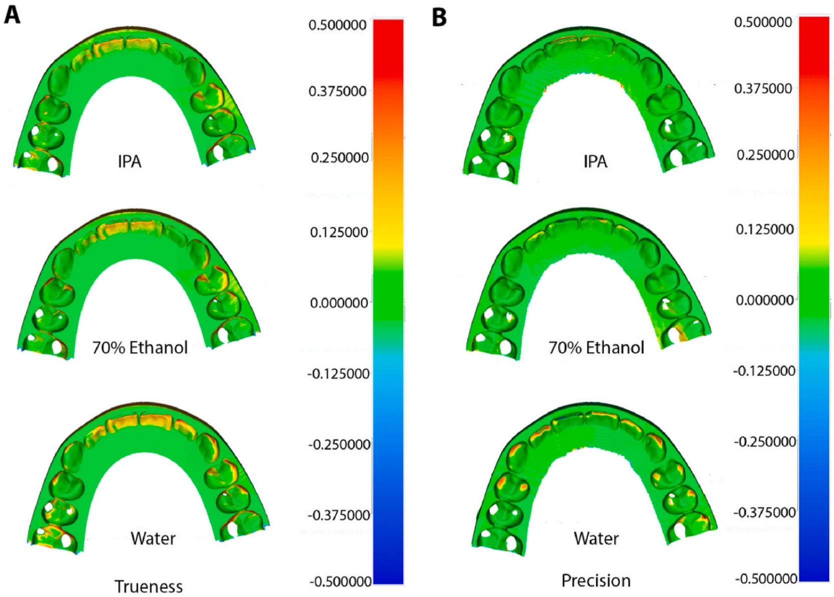

Fig. 8. Trueness (A) and precision (B) color map deviation patterns under different post-rinsing solvents. The green area indicates good accuracy; the yellow, orange, and red areas signify positive deviation, while the blue area indicates negative deviation.

Table 8
Surgical splint trueness and precision RMS values according to post-polymerization times.

Post-polymerization times		3-min (μm)	6-min (μm)	10-min (μm)	p[a]
RMS value of Trueness	Mean (±SD)	141.8 (±8.8)[a]	119.8 (±5.1)[b]	140.3 (±12.4)[a]	0.000
	95 % CI	134.4–149.1	115.6–124	129.9–150.7	
	Median	139.1	118	144	
RMS value of Precision	Mean (±SD)	89.1 (±18.9)[a]	74.8 (±21.7)[b]	98.4 (±22)[a]	0.000
	95 % CI	81.7–96.4	66.3–83.2	89.8–106.9	
	Median	89	79.2	101.5	

[a,b,c] Different superscript letters indicate statistically significant differences based on the Tukey HSD test with post-hoc comparison (α = 0.05).
SD: Standard Deviation, CI: Confidence Interval.
[a] Analyzed using one-way analysis of variance (ANOVA) (α = 0.05).

previously reported clinically acceptable average range. This could be attributed to errors in the parameter configuration or anti-reflective sprinkling procedure. Even when sprayed by a single operator, maintaining the thickness of the powder and increasing the size of the surgical splint and scanning procedure can be challenging. Each phase of the 3D printing process is susceptible to additive errors, which can result in clinically unacceptable models. The printer parameters have a significant impact on the 3D printing output. It is crucial to optimize printing parameters such as build angle, layer thickness, and support, which can affect the accuracy and

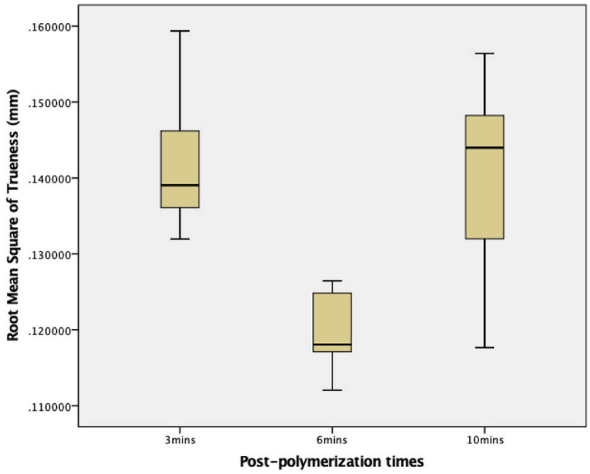

Fig. 9. RMS value of accuracy (mm) of LCD-printed surgical splints under different post-polymerization times.

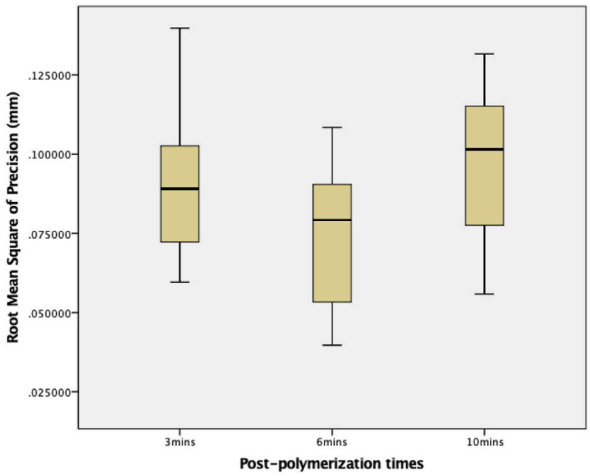

Fig. 10. RMS value of accuracy (mm) of LCD-printed surgical splints under different post-polymerization times.

Table 9
Post-hoc test for the RMS value of the trueness of surgical splints manufacturing using different post-polymerization times.

Multiple Comparisons						
Dependent Variable: RMS						
Tukey's HSD						
(I) Trueness	(J) Trueness	Mean Difference (I-J)	Std. Error	Sig.	95 % Confidence Interval	
					Lower Bound	Upper Bound
3 min	6 min	0.02195200[a]	0.004628440	0.000	0.01028569	0.03361831
	10 min	0.001447625	0.004628440	0.948	−0.01021868	0.01311393
6 min	3 min	−0.0219520[a]	0.004628440	0.000	−0.03361831	−0.01028569
	10 min	−0.0205044[a]	0.004628440	0.001	−0.03217068	−0.00883807
10 min	3 min	−0.00144762	0.004628440	0.948	−0.01311393	0.01021868
	6 min	0.0205438[a]	0.004628440	0.001	0.00883807	0.03217068

[a] The mean difference was significant at the level of 0.05.

precision of the printing splint [6,11,17].

Because the methacrylate-based resin is insoluble in water but soluble in most organic solvents, the water rinsing group showed the maximum color deviation in the trueness RMS data in the color mapping superimposition. A positive deviation (red) was observed for

Table 10
Post-hoc test for the RMS value of the precision of surgical splints manufacturing using different post-polymerization times.

Multiple Comparisons						
Dependent Variable: RMS						
Tukey's HSD						
(I) Trueness	(J) Trueness	Mean Difference (I-J)	Std. Error	Sig.	95 % Confidence Interval	
					Lower Bound	Upper Bound
3 min	6 min	0.01432515[a]	0.005593439	0.033	0.00097055	0.02767975
	10 min	−0.00930299	0.005593439	0.226	−0.02265759	0.00405161
6 min	3 min	−0.0143252[a]	0.005593439	0.033	−0.02767975	−0.00097055
	10 min	−0.0236281[a]	0.005593439	0.000	−0.03698275	−0.01027355
10 min	3 min	0.009302993	0.005593439	0.226	−0.00405161	0.02265759
	6 min	0.02362815[a]	0.005593439	0.000	0.01027355	0.03698275

[a] The mean difference was significant at the level of 0.05.

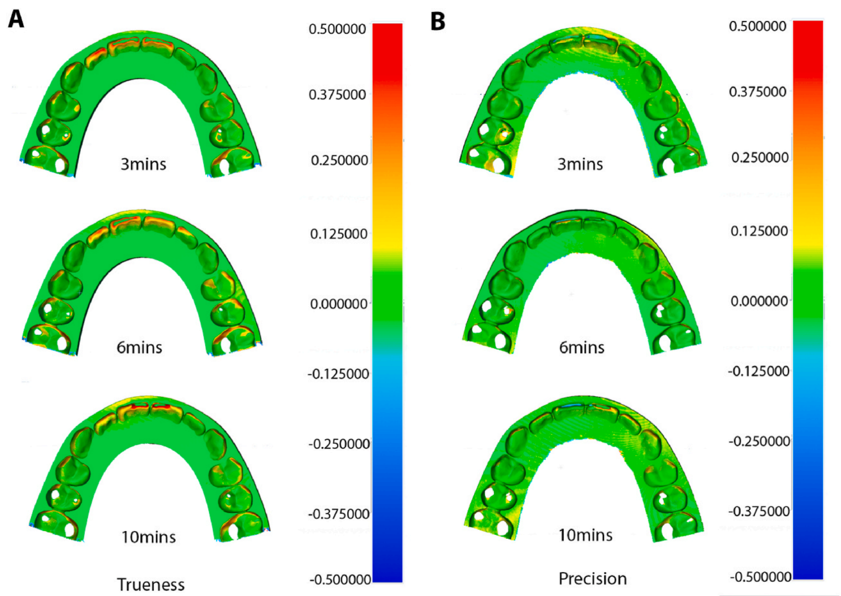

Fig. 11. Trueness (A) and precision (B) color map deviation patterns under different post-polymerization times. The green area indicates good accuracy; the yellow, orange, and red areas show positive deviation, and the blue area indicates negative deviation.

the incisal edge of the incisors, mesial marginal ridge of the canine, buccal and palatal cusps of the premolar, mesiobuccal cusp, and mesial side of the first molar (Fig. 8A). This study was designed to print surgical splints at a 90-degree angle (Fig. 2). This printing position makes the resin susceptible to gravity and allows it to flow down to the anterior and mesial surfaces of the teeth, thereby increasing the polymerization shrinkage of the printing materials. According to the literature, a complex design featuring curves, cusps, and angles displays a greater deviation than a planar design. Depending on the system employed and the geometry of the scanned object, such as depth, slope, and curvature, scanning can affect accuracy. In addition, rounding effects may occur when scanning pointed edges, thereby reducing the effectiveness of the margin evaluation [11]. For the color map data of precision, the IPA and 70 % ethanol rinsing groups exhibit similar deviation patterns (green) (Fig. 8B), indicating that both rinsing agents can provide high fabrication precision (i.e., high repeatability). Distortion is a result of the clinical circumstances.

Abedalrahman et al. (2014) studied the effect of the accuracy of surgical wafers on clinical situations and found that the fabrication error was in the range of 0.04–1.73 mm. Evaluating the accuracy of surgical wafers by articulating them with the upper and lower plaster study models revealed that any error in the surgical wafers would be transferred to the mandibular position of the dental cast, while the maxillary position remains unchanged. Clinical results using surgical wafers with the highest absolute error (1.73 mm) demonstrated that the mandible's position deviated from the intended position [18].

The post-polymerization time was studied for practical purposes; the ideal polymerization time should be as fast as possible while still allowing complete polymerization and providing the least amount of distortion and the best dimensional accuracy. In general, different post-polymerization times are recommended based on the post-polymerization units of each manufacturer. It was concluded that dimensional accuracy, in terms of the accuracy and precision of 3D-printed products, relies on the post-polymerization time conditions [13,19]. In this study, the accuracy was determined by categorizing the post-polymerization curing time into three groups:

3, 6, and 10 min. The null hypothesis was rejected because the post-polymerization curing times showed significant differences in terms of accuracy and precision. In the accuracy, the 6-min curing group had lower mean, SD, 95 % CI, and median values than those of the 3-min and 10-min curing groups, while the difference between the 3-min and 10-min curing groups was not statistically significant (Table 8). This finding differs from those of previous studies that investigated the effect of post-polymerization time, ranging from 10 to 30 min, on the accuracy of 3D-printed products using vat polymerization technology and found that the RMS tended to increase with longer post-polymerization times [11,14]. Because the 3-min curing group had the shortest polymerization time in this study, the surgical splint was probably not polymerized sufficiently, and there were more unpolymerized materials left in the 3-min curing group, resulting in shrinkage and deformation of the resin material and a higher RMS than the 6-min curing group. Color deviation map analysis of accuracy demonstrated positive deviations on the incisal edge of the incisal teeth, mesial cusp ridge of canines, buccal and palatal cusps of premolars, and mesial surface of the first molar in all three groups (Fig. 11). The surgical splints were set at a 90-degree angle on the printing table (Fig. 2), and the gravity effect during the additive manufacturing of the photoreactive resin caused the aforementioned areas of the printing splint to accumulate liquid resin. As the amount of resin increases, so does the polymerization shrinkage [20]. Furthermore, scan accuracy may be influenced by characteristics such as depth, steepness, and multiple-angled curvatures, because the value of scan accuracy can vary significantly depending on the system used and the design of the scanned object [15]. Conversely, the design conditions were similar for all groups and should not have affected the scanning accuracy between groups. The accuracy discrepancies in this study ranged from 119.8 to 141.8 μm in the mean of the trueness and from 74.8 to 98.4 μm in the mean of the precision, with trueness being slightly more than 100 μm, which is the clinically acceptable range of the surgical splint [16]. This could be attributed to manufacturing errors, scanning procedures, or other factors. Furthermore, an antireflective spray was used to aid optical scanning. Powder spray, even if sprayed by a single operator, can make it difficult to maintain consistent powder thickness and increase surgical splint dimensions. However, the discrepancies in this study are lower than in previous studies, which reported that the errors of rapid prototype surgical wafers are 1.0 [21], 0.18–1.04 [22], and 0.04–1.73 mm [18]. The surgical splint was the most accurate in the 6-min curing group, according to the manufacturer's recommended post-polymerization time. The RMS value of trueness in this study was greater than 100 μm. However, we performed a final trial of printed stents with the prototype dentoform, and all had clinically acceptable results. Accuracy analysis can be influenced by the printing technology, printing direction, layer thickness, and material composition [11]. The printer parameters have a significant impact on the 3D printing output. Printing parameters such as LCD intensity and printer-software calibration, which can affect the printing accuracy and precision, must be optimized.

Future research could be extended to test larger sample sizes to enhance statistical power. Because all other printing parameters were held constant in this study, future research could test various build angles, layer thicknesses, and rinsing times to determine the accuracy of 3D printing. There is no distinct consensus on the post-processing rinsing protocol for 3D printed parts regarding the solvent, time, and method (i.e., hand wash versus ultrasonic). This essential step in the 3D printing process requires additional research and protocol development [6,17].

5. Limitation and future perspectives

This study had several limitations. The post-polymerization temperature was not determined because of its unavailability on the LCD printer used in this study. The post-processing procedure was performed according to the manufacturer's recommendations; however, because each manufacturer provides different post-processing condition recommendations, further research should be conducted to evaluate the accuracy of various 3D printers or different 3D printing methods. In addition, biocompatibility should be considered in future studies, considering that post-polymerization can affect biological stability, resulting in monomer elution and cytotoxicity. Orthognathic splints could have a vital impact on the stability of the final occlusion; thus, further investigation from the clinical point of view of utilizing 3D printing splints should also be evaluated at the clinical level.

6. Conclusion

This study found that post-rinsing solvents influenced the dimensional accuracy of LCD-printed surgical splints. The trueness and precision of the IPA rinsing solvent were higher than those of 70 % ethanol and water rinsing groups. Furthermore, the post-polymerization time influenced the dimensional accuracy of LCD-printed surgical splints. The 6-min post-polymerization time showed the highest dimensional accuracy in terms of trueness and precision.

CRediT authorship contribution statement

Siripatra Patchanee: Writing – review & editing, Writing – original draft, Software, Formal analysis. **Pokpong Amornvit:** Writing – review & editing, Resources, Conceptualization. **Maneethip Mortin:** Writing – original draft, Validation, Data curation. **Narissaporn Chaiprakit:** Writing – review & editing, Supervision, Formal analysis, Conceptualization.

Availability of data and materials

The datasets supporting the conclusions of this study are included in this article. The datasets used and/or analyzed in the current study are available from the corresponding author upon reasonable request.

Ethics approval and consent to participate

Experiments on both animals and humans were not conducted.

Consent for publication

We consent to the publication of the manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] F.S.R. Carvalho, et al., The use of surgical splints in orthognathic surgery: a bibliometric study, Indian J. Plast. Surg. 55 (1) (2022) 26–30, https://doi.org/10.1055/s-0041-1734570.
[2] S. Aboul-Hosn Centenero, F. Hernández-Alfaro, 3D planning in orthognathic surgery: CAD/CAM surgical splints and prediction of the soft and hard tissues results - our experience in 16 cases, J. Cranio-Maxillo-Fac. Surg. 40 (2) (2012) 162–168, https://doi.org/10.1016/j.jcms.2011.03.014.
[3] A. Dawood, et al., 3D printing in dentistry, Br. Dent. J. 219 (11) (2015) 521–529, https://doi.org/10.1038/sj.bdj.2015.914.
[4] D. Khorsandi, et al., 3D and 4D printing in dentistry and maxillofacial surgery: printing techniques, materials, and applications, Acta Biomater. 122 (2021) 26–49, https://doi.org/10.1016/j.actbio.2020.12.044.
[5] I.A. Tsolakis, et al., Three-dimensional printing technology in orthodontics for dental models: a systematic review, Children 9 (8) (2022) 1106, https://doi.org/10.3390/children9081106.
[6] D. Mostafavi, et al., Influence of the rinsing postprocessing procedures on the manufacturing accuracy of vat-polymerized dental model material, J. Prosthodont. 30 (7) (2021) 610–616, https://doi.org/10.1111/jopr.13288.
[7] M.D. Scherer, et al., Influence of postprocessing rinsing solutions and duration on flexural strength of aged and nonaged additively manufactured interim dental material, J. Prosthet. Dent 131 (5) (2024) 959–968, https://doi.org/10.1016/j.prosdent.2022.03.034.
[8] J.R.C. Dizon, et al., Post-processing of 3D-printed polymers, Technologies 9 (3) (2021) 61, https://doi.org/10.3390/technologies9030061.
[9] R. Chaudhary, et al., Additive manufacturing by digital light processing: a review, Progress in Additive Manufacturing 8 (2) (2023) 331–351, https://doi.org/10.1007/s40964-022-00336-0.
[10] Y. Tian, et al., A review of 3D printing in dentistry: technologies, affecting factors, and applications, Scanning 2021 (2021) 9950131, https://doi.org/10.1155/2021/9950131.
[11] A. Katheng, et al., Evaluation of dimensional accuracy and degree of polymerization of stereolithography photopolymer resin under different postpolymerization conditions: an in vitro study, J. Prosthet. Dent 125 (4) (2021) 695–702, https://doi.org/10.1016/j.prosdent.2020.02.023.
[12] F. Rouzé l'Alzit, et al., Accuracy of commercial 3D printers for the fabrication of surgical guides in dental implantology, J. Dent. 117 (2022) 103909, https://doi.org/10.1016/j.jdent.2021.103909.
[13] A. Unkovskiy, et al., Objects build orientation, positioning, and curing influence dimensional accuracy and flexural properties of stereolithographically printed resin, Dent. Mater. 34 (12) (2018) e324–e333, https://doi.org/10.1016/j.dental.2018.09.011.
[14] B.I. Lee, et al., Evaluating the accuracy (trueness and precision) of interim crowns manufactured using digital light processing according to post-curing time: an in vitro study, J Adv Prosthodont 13 (2) (2021) 89–99, https://doi.org/10.4047/jap.2021.13.2.89.
[15] C. Kirsch, et al., Trueness of four different milling procedures used in dental CAD/CAM systems, Clin. Oral Invest. 21 (2) (2017) 551–558, https://doi.org/10.1007/s00784-016-1916-y.
[16] P. Phudphong, P. Amornvit, N. Sirintawat, Comparison of accuracy of alginate impression and intraoral scanner in model with and without orthodontic brackets, Appl. Sci. 11 (13) (2021) 6037, https://doi.org/10.3390/app11136037.
[17] L. Yoojin, Influence of Different Post Processing Rinsing Agents on the Manufacturing Accuracy of Dental Models Printed by LCD Resin 3D Printer. Master's Thesis, Texas A&M University, 2022, https://doi.org/10.3390/polym16192795.
[18] A. Shqaidef, A.F. Ayoub, B.S. Khambay, How accurate are rapid prototyped (RP) final orthognathic surgical wafers? A pilot study, Br. J. Oral Maxillofac. Surg. 52 (7) (2014) 609–614, https://doi.org/10.1016/j.bjoms.2014.04.010.
[19] S. Kirby, et al., Effect of different post-curing methods on the degree of conversion of 3D-printed resin for models in dentistry, Polymers 16 (4) (2024) 549, https://doi.org/10.3390/polym16040549.
[20] M.S. Yang, et al., Investigation of the marginal fit of a 3D-printed three-unit resin prosthesis with different build orientations and layer thicknesses, J Adv Prosthodont 14 (4) (2022) 250–261, https://doi.org/10.4047/jap.2022.14.4.250.
[21] K.G. Song, S.H. Baek, Comparison of the accuracy of the three-dimensional virtual method and the conventional manual method for model surgery and intermediate wafer fabrication, Oral Surg. Oral Med. Oral Pathol. Oral Radiol. Endod. 107 (1) (2009) 13–21, https://doi.org/10.1016/j.tripleo.2008.06.002.
[22] B.C. Kim, et al., Clinical experiences of digital model surgery and the rapid-prototyped wafer for maxillary orthognathic surgery, Oral Surg. Oral Med. Oral Pathol. Oral Radiol. Endod. 111 (3) (2011), https://doi.org/10.1016/j.tripleo.2010.04.038, 278-85.e1.