Journal of Dentistry 130 (2023) 104434

Contents lists available at ScienceDirect

Journal of Dentistry

journal homepage: www.elsevier.com/locate/jdent

Effect of computer-aided design and computer-aided manufacturing technique on the accuracy of fixed partial denture patterns used for casting or pressing

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A R T I C L E I N F O

Keywords:
3D-printing
Fixed partial denture
Milling
Resin pattern
Trueness

A B S T R A C T

Objectives: To evaluate the effect of additive and subtractive manufacturing on the accuracy (trueness and precision) of fixed partial denture patterns (FPDPs) used for casting or pressing.
Materials and Methods: A 3-unit complete coverage FPD on mandibular right first premolar and first molar teeth was virtually designed. Using the design data, FPD patterns were fabricated from an additively manufactured resin (PR, ProArt Print Wax) and 2 CAD-CAM wax discs (YW, ProArt CAD Wax Yellow and BW, ProArt CAD Wax Blue) ($n = 10$). Each pattern was then digitized with a scanner (CEREC Primescan) and evaluated for 3D surface deviation at 4 different surfaces (overall, external, marginal, and intaglio surfaces) by using a 3D analysis software (Medit Link). Root mean square (RMS) values were automatically calculated. Data were analyzed by using Kruskal-Wallis and Dunn's post hoc tests for trueness and precision ($\alpha = 0.05$).
Results: Significant differences were found among the RMS values for overall ($P<.001$) and each surface ($P\leq.040$) evaluated. PR had the highest overall ($P\leq.011$) and intaglio surface ($P\leq.01$) deviations, while the difference between YW and BW was not significant ($P\geq.199$). PR had the highest ($P\leq.027$) and BW had the lowest ($P\leq.042$) external surface mean RMS values. BW had higher mean marginal RMS value than YW ($P=.047$). For precision, significant differences were observed among test groups only for marginal RMS values ($P=.002$). PR had lower precision than BW ($P=.002$).
Conclusions: BW and YW FPDPs mostly had higher trueness compared with PR FPDPs. However, considering relatively smaller deviations at marginal and intaglio surfaces and the fact that patterns mostly had similar precision, clinical fit of FPDs fabricated by using tested patterns may be similar.
Clinical Significance: Definitive 3-unit fixed partial dentures fabricated by using tested patterns may be similar. However, FPDs fabricated with tested additively manufactured resin patterns might result in more chairside adjustments than those fabricated with tested subtractively manufactured wax patterns.

1. Introduction

Additive manufacturing has the advantage of passive and vertical manufacturing, recycling of unused material, possibility of producing larger and more complex objects, and increased number of products to be manufactured at a time [1]. In addition, a variety of materials including polymers, metals, waxes, and ceramics are applicable by using additive manufacturing technologies [2].

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https://doi.org/10.1016/j.jdent.2023.104434
Received 11 June 2022; Received in revised form 16 January 2023; Accepted 20 January 2023
Available online 21 January 2023

Wax pattern fabrication is a time-consuming process and outcomes are operator dependent [3,4]. Therefore, fabrication of patterns has shifted from conventional to digital technologies [4]. Patterns fabricated by using computer aided design-computer aided manufacturing (CAD-CAM) can be used to cast or press restorations. Considering that dental printers are generally more affordable than milling units and the fact that some dental laboratories continue using pressing technologies for ceramics, conventional lost-wax technique is still an indispensable part of manufacturing processes [5]. The integration of affordable and less human error-prone CAD-CAM fabrication techniques may enable efficient fabrication of patterns for the fabrication of commonly used restorations. However, fabrication trueness of patterns when new CAD-CAM technologies are used is not well-known.

Even though previous studies have focused on the accuracy [6–9] or fit [10] of additively manufactured fixed partial dentures (FPDs), those studies were based on interim restorations. Previous studies on the comparison of manufacturing techniques (additive, subtractive, and conventional) have reported conflicting results [11–15], and, accordingly, it can be considered that the type of CAD-CAM technique used for pattern fabrication could significantly affect the quality of a definitive restoration as clinical fit of a prosthetic restoration is directly related to its dimensional accuracy [16]. Any pattern related error may be amplified during casting or pressing, which makes the congruence between the design file of the restoration and the fabricated pattern critical. To the authors' knowledge, only 1 study has investigated the trueness of patterns fabricated by using different CAD-CAM technologies, which was based on crowns [5]. Therefore, a study on the accuracy of additively manufactured FPD patterns (FPDPs) would elaborate the knowledge on the effect of pattern fabrication technique on accuracy of multiple-unit restorations. Thus, the aim of the present study was to evaluate the accuracy of additively manufactured FPDPs, comparing with that of 2 subtractively manufactured (1 suitable for pressing and 1 suitable for casting) wax patterns. The null hypothesis was that there would be no difference in the accuracy (trueness and precision) of FPDPs fabricated with different CAD-CAM techniques.

2. Materials and methods

Mandibular right first premolar and first molar of a typodont model (ANA-4; Frasaco GmbH, Tettnang, Germany) were prepared with a 1-mm-wide chamfer finish line for a 3-unit FPD. Maxillary and mandibular models, and the occlusion were digitized by using an intraoral scanner (CEREC Primescan SW 5.2; Dentsply Sirona, Bensheim, Germany). A 3-unit complete coverage FPD was designed by using these standard tessellation language (STL) files and a software (Exocad Dental CAD2.2; Exocad GmbH, Darmstadt, Germany). Cement space was arranged to be 30 μm [17], and the connector sizes were 9 mm^2 with a modified-ridge lap pontic design. This design was saved in STL format (FPD-STL) and used for the fabrication of patterns from an additively manufactured resin (PR, ProArt Print Wax; Ivoclar Vivadent, Schaan, Liechtenstein) and 2 CAD-CAM wax discs (YW, ProArt CAD Wax Yellow and BW, ProArt CAD Wax Blue; Ivoclar Vivadent, Schaan, Liechtenstein) ($n = 10$). The number of specimens in each group was based on previous studies that investigated the trueness of additively manufactured patterns [5] or FPDs [18].

FPD-STL was transferred into a nesting software (3Shape CAMbridge; 3Shape, Copenhagen, Denmark) for the fabrication of additively manufactured resin patterns. The FPD-STL was positioned with its occlusal surface towards the build platform. After auto-generating the supports, this configuration was duplicated 10 times for standardization, and transferred into a digital light processing-based 3D printer (PrograPrint PR5; Ivoclar Vivadent, Schaan, Liechtenstein) with a software (PrograPrint Manager; Ivoclar Vivadent, Schaan, Liechtenstein). PR FPDPs were placed into an alcohol bath (PrograPrint Clean; Ivoclar Vivadent, Schaan, Liechtenstein) containing 96% isopropyl alcohol and cleaned for 4 min (2 min of rough cleaning and 2 min of fine cleaning at 850 rpm) and then left to dry for 1 h. Post-polymerization was performed by using a light-emitting diode curing unit (PrograPrint Cure; Ivoclar Vivadent, Schaan, Liechtenstein), which had a preset curing program for the resin used [19]. After removing the FPDPs from build platform by using a scraper, support structures were removed and surfaces were smoothened.

FPD-STL was transferred into a nesting software (PrograMill CAM V4.2; Ivoclar Vivadent, Schaan, Liechtenstein) and inserted in CAD-CAM wax discs for the fabrication of subtractively manufactured FPDPs. The wax discs were indicated either for pressing (YW) or casting (BW) technique. YW and BW FPDPs were subtractively manufactured with a 5-axis milling unit (PrograMill PM7; Ivoclar Vivadent, Schaan, Liechtenstein) and surfaces were smoothened after separating from discs. Same operator performed all fabrication processes (G.Ç.) and further evaluated the specimens under 3.5 × magnification to detect potential defects without making any adjustments on the intaglio surfaces [17,20] (Fig. 1).

An experienced operator (M.B.D.) scanned the FPDPs to generate test-STLs. All scans were performed in the same temperature and humidity-controlled room, by using the same intraoral scanner that was used to digitize the prepared teeth. Calibration was performed before starting the scans of each group and the operator took 5-minute breaks in between each group to prevent fatigue-related deviations [21].

A 3D analysis software (Medit Link v 2.4.4; Medit, Seoul, Korea) and root mean square (RMS) calculation method were used to evaluate the deviations of the FPDPs when compared with FPD-STL [5,20,22]. FPD-STL and test-STL files were imported into the software and the FPD-STL was selected as the reference. Test-STL was superimposed over FPD-STL by using the comparison tool of the software, which allows simultaneous selection of 3 points on both files (Fig. 2). Based on previous studies that investigated the trueness of additively manufactured restorations [5,18,20,22,23], maximum/minimum critical (nominal) values were set at +50/−50 μm and the tolerance range was set at +10/−10 μm for the color maps that represent 3D deviations. Software automatically calculated overall RMS values; thus, no additional formula was used. External, marginal, and intaglio surfaces without margins were also evaluated after virtually separating the FPDPs into 3 parts as reported in a previous study [23]. Each of these surfaces were superimposed over FPD-STL separately and color-difference maps were generated to calculate the RMS values (Fig. 3).

Precision was defined as the variances of deviations within each group for each surface. Distribution of data was evaluated by using Shapiro-Wilk tests. Non-parametric Kruskal-Wallis and Dunn's post hoc tests were used for the analyses. All statistical analyses were performed by using a statistical analysis software (SPSS v22.0; IBM, Chicago, IL, USA) at a significance level of α= 0.05.

3. Results

Measured RMS values of each material-surface pair are illustrated in Fig. 4. Table 1 summarizes descriptive statistics. Kruskal-Wallis tests

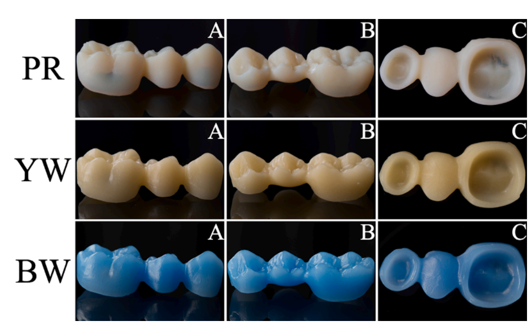

Fig. 1. Fixed partial denture patterns after fabrication (A: Buccal surface; B: Lingual surface; C: Marginal and intaglio surfaces).

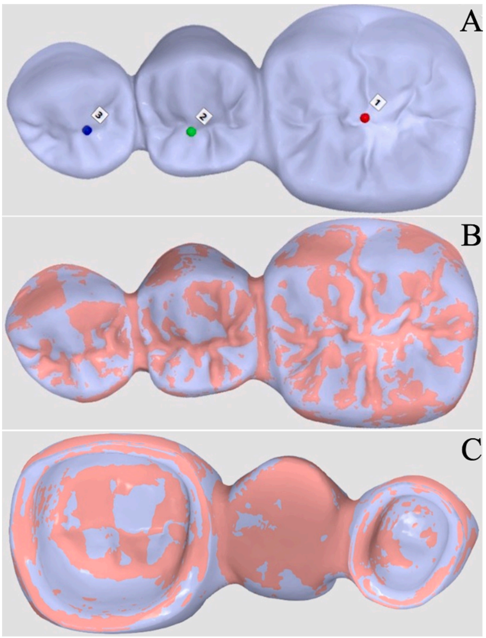

Fig. 2. Superimposition process (A: Points selected for superimposition; B: Superimposed files from occlusal surfaces; C: Superimposed files from intaglio surfaces).

revealed significant differences in RMS values among test groups for overall ($P<.001$) and each surface analyzed ($P<.001$ for external, $P=.04$ for marginal, and $P<.001$ for intaglio surface without margin). PR FPDPs had the highest overall ($P\leq.011$) and intaglio surface ($P\leq.01$) deviations, whereas the difference between YW and BW was nonsignificant ($P=.199$ for overall and $P=.22$ for intaglio without margin). When the external surfaces were concerned, BW FPDPs had the lowest RMS values ($P\leq.042$) and PR FPDPs had the highest ($P\leq.027$). For marginal RMS, only the difference between YW and BW was significant ($P=.047$), and BW had higher deviations. However, the difference in mean and median RMS values of BW and YW at margins was only 1 μm. Precision of patterns differed significantly only when marginal RMS values were considered ($P=.002$). While BW had higher precision than PR ($P=.002$), YW had similar precision to those of other groups ($P\geq.123$) (Table 2).

4. Discussion

Other than marginal surface, subtractively manufactured FPDPs had higher trueness than PR FPDPs for all surfaces evaluated. In addition, PR had lower precision than BW when marginal RMS values were considered. Therefore, the null hypothesis was rejected.

Higher deviations of additively manufactured FPDPs may lead to ill-fitting contours, particularly at external and intaglio surfaces of definitive restorations. Color maps revealed that blue areas (undercontour) may lead to open interproximal contacts or insufficient emergence profile, while red areas (overcontour) could result in heavy occlusal contacts or tighter internal fit. Areas with over or undercontoured surfaces were more frequently detected on PR FPDPs, which might indicate that the restorations fabricated by using these FPDPs would need more clinical chairside adjustments. BW and YW FPDPs had similar overall and intaglio RMS values, which is in line with color maps. Even though statistical analyses revealed significant differences between BW and YW at external and marginal surfaces, the authors believe that this difference is clinically negligible given the small differences between mean RMS values measured on those surfaces (3 μm at external surface and 1 μm at marginal surface). Nevertheless, regardless of CAD-CAM technique used, intaglio surface RMS values of all FPDPs were below 30 μm. In addition, marginal deviations, which are directly related to the clinical fit of an FPD, were below 20 μm for all test groups. Even though BW had higher precision than PR at the margins, the authors believe that this difference may be negligible considering that a mean difference of 2.3 μm is difficult to clinically quantify. Therefore, it may be considered that clinical fit of the FPDs fabricated by using tested FPDPs could be similar. Given the fact that successful outcomes have been reported on the clinical performance of posterior lithium disilicate-based FPDs [24–26], pattern fabrication techniques tested in the present study could be considered for future studies on ceramic FPDs with premolar and molar abutments. Such in vivo studies would also elaborate and corroborate the results of the present study. However, it should be noted that the interpretation on possible effects of wax or resin FPDP deviations on definitive restorations should be made carefully. Casting and pressing are technique-sensitive processes that are prone to operator-, process-, restoration type, and material-related errors, which should be considered when interpreting the results of the present study.

It has been reported that the size of an object might have an effect on additive manufacturing trueness [27]. Therefore, the results of the present study may be used to interpret the effect of printing a larger prosthesis compared with printing a smaller prosthesis, like a crown, on the fabrication trueness. Çakmak et al. [5] used methods and materials similar to those utilized in the present study to investigate the fabrication trueness of crown patterns, and reported similar results to those of the present study. Magnitude of deviations reported in these studies were very similar as the greatest difference between mean deviation values in the present study and in Çakmak et al's [5] study was 15 μm, which can be considered small given the fact that this difference was on the entire external surface. In addition, there is no clear trend on how a material affected measured deviations depending on the size of the prosthesis. Considering these findings, it can be speculated that the prosthesis size did not have a significant effect on the fabrication trueness of tested materials. However, this interpretation needs further support with studies on the fabrication accuracy of FPDPs with more units.

Several studies have investigated the effect of CAD-CAM technique on the marginal fit of fabricated patterns for dental prostheses [11–15]. Whether it was statistically significant or not, a tendency towards higher marginal gap was frequently reported for additively manufactured patterns compared with subtractively manufactured patterns [11–14]. Similarly, in the present study, PR FPDPs had nonsignificantly higher mean marginal RMS values. Several factors including the type of the restorative material, restoration, and its geometry have been reported to affect the marginal fit [11–15]. However, when additive manufacturing is concerned, additional factors such as build orientation and layer thickness may also affect the restoration accuracy [10]. Thus, future studies should focus on these factors to elaborate the effect of CAD-CAM fabrication technique, particularly of additive manufacturing on the clinical fit of dental restorations.

Deviation measurements by using RMS calculation have been preferred in dental accuracy studies [18,22,23]. However, for trueness analysis, alternative methods such as the use of average deviation, absolute average, or (90–10)/2 percentile could also be performed [28]. In the present study, RMS measurements of FPDPs were performed by using a 3D analysis software, which has been used in previous studies [22,29]. In addition, a previous study has concluded that the IOS used in the present study had similar results to that of a laboratory scanner when the congruence between a scan mesh and CAD file was evaluated [21]. Therefore, the digitization of FPDPs with the IOS used in present study can be considered straightforward and reliable, as the scan can be completed in at one attempt. If a laboratory scanner is to be used, separate scans of occlusal and intaglio surfaces need to be stitched, which may amplify deviations measured. Nevertheless, different methodologies, inspection software, and evaluation protocols may lead to different results [30].

Even though significant differences were found among test groups

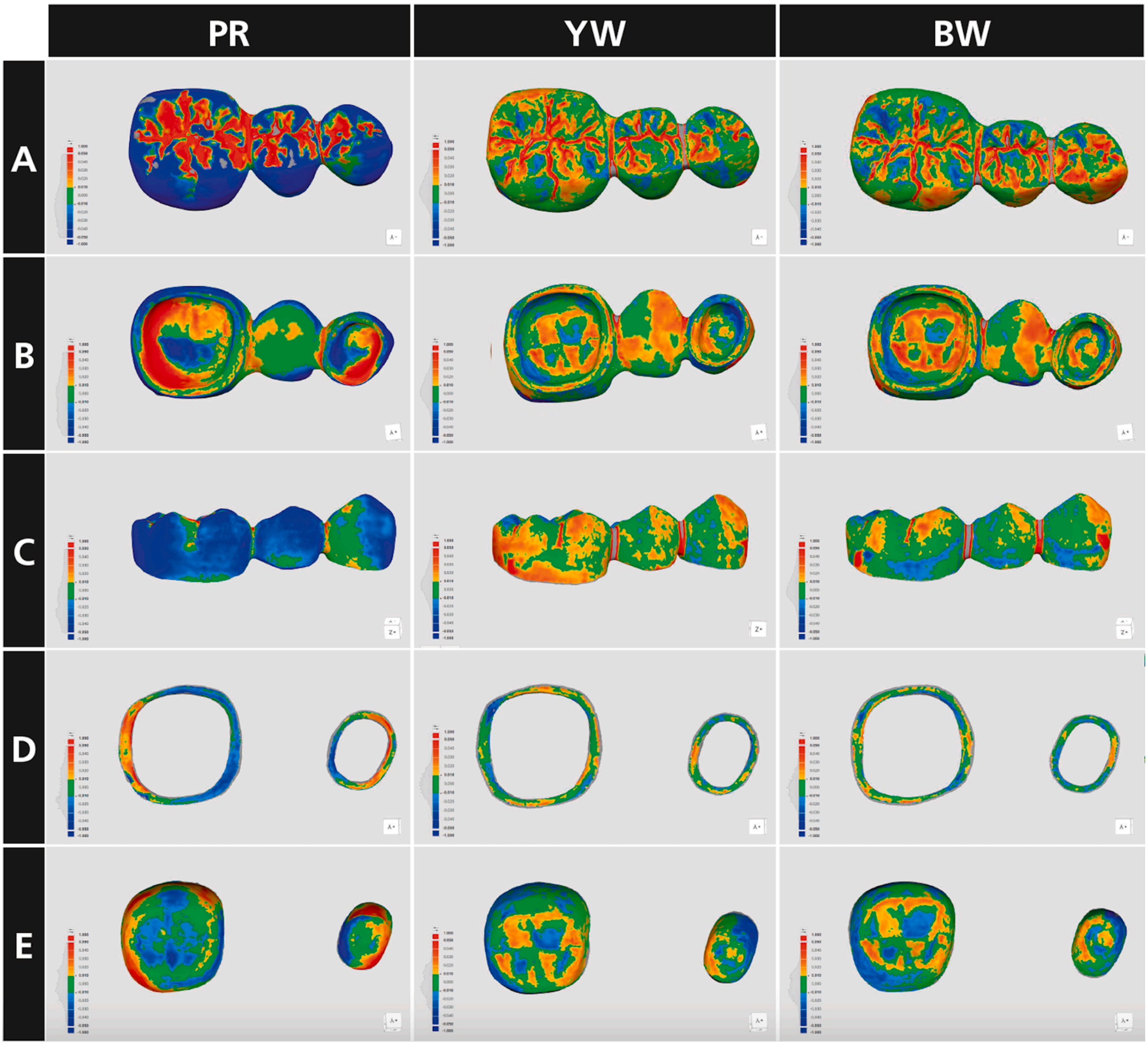

Fig. 3. Color maps generated for each material-surface pair (A and B: Overall; C: External; D: Marginal; E: Intaglio without margin).

and the number of specimens in each group was based on previous studies on the trueness of additively manufactured restorations that reported significant differences [5, 18], absence of a priori power analysis could be considered as a limitation. Another limitation of the present study was the absence of a control group. Differences in chemical composition of tested materials may have also affected the results as specimens may have undergone different dimensional changes until being digitized. In addition, all materials tested in the present study belong to a single brand, and one type of 3D-printer, milling unit, IOS, and 3D analysis software were used. Finally, standardized in vitro design of the present study might be a limitation considering that digital workflow is prone to human-related errors at different stages starting from data acquisition to definitive fabrication of restoration. Therefore, the results of the present study should be accounted as preliminary and substantiated with future studies that investigate how these deviations propagate and affect the definitive restoration, and how the restorations fabricated by using these techniques differ from clinically applied milled CAD-CAM materials.

5. Conclusions

Within the limitations of the present study, it can be concluded that tested FPDPs fabricated by subtractive manufacturing mostly had higher trueness than additively manufactured FPDPs. However, deviation values at marginal and intaglio surfaces were below 30 μm, regardless of the technique. In addition, patterns mostly had similar precision. Therefore, clinical fit of FPDs cast or pressed by using the patterns tested may be similar.

CRediT authorship contribution statement

The authors of the manuscript contributed in the following ways to the submitted manuscript:

Mustafa Borga Donmez: Writing-original draft and Writing-review& editing.

Burak Yilmaz: Critical revision of the article, Approval of the submitted and final versions.

Hyung-In Yoon: Drafting article.

Çiğdem Kahveci: Data analysis, Data interpretation, Statistical analysis.

Martin Schimmel: Design, Critical revision of the article.

Gülce Çakmak: Design, Methodology, Data collection.

Declaration of Competing Interests

The authors declare that they have no known competing financial

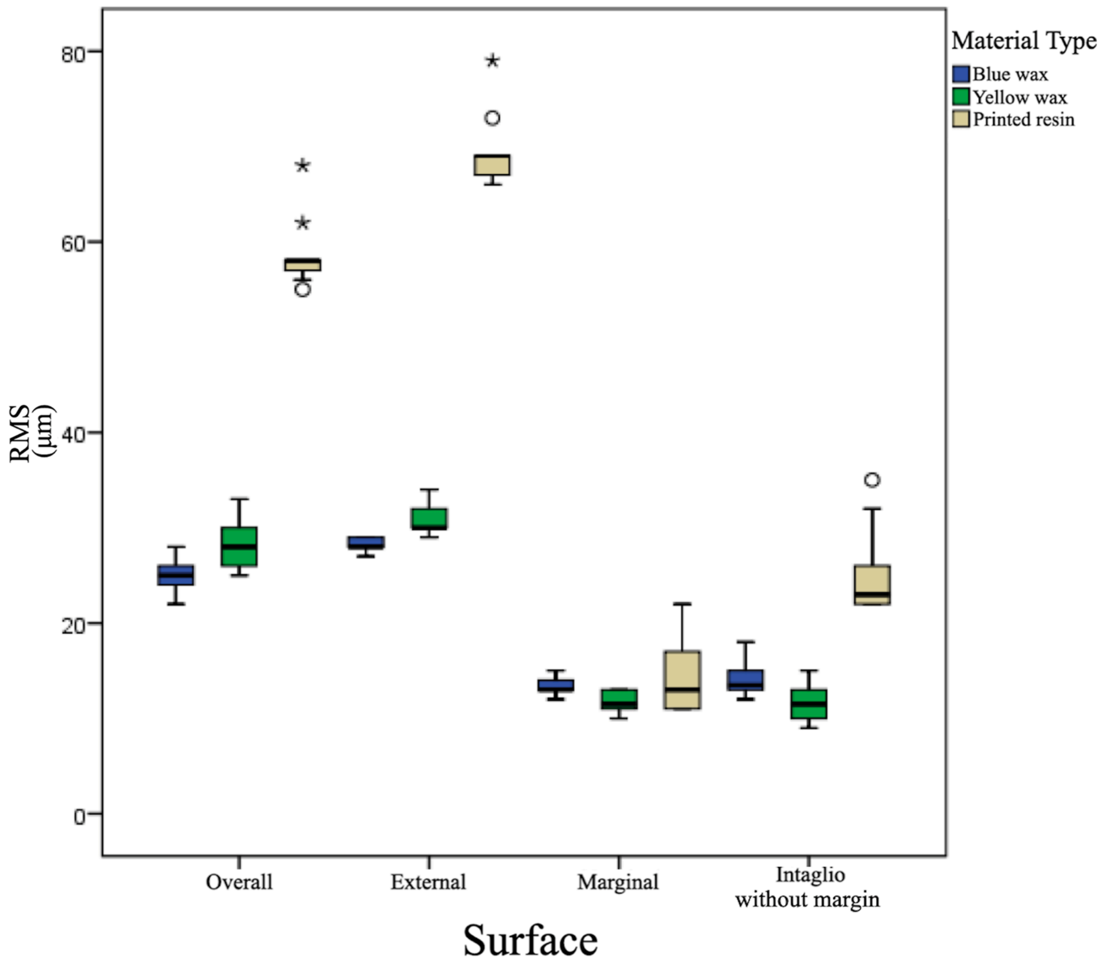

Fig. 4. Box-plot graph of RMS values for each material-surface pair.

Table 1
Descriptive statistics of RMS values (trueness) within test groups.

	Surfaces							
	Overall		External		Marginal		Intaglio without margin	
Material	Mean ±SD	Median (Min-Max)	Mean ±SD	Median (Min-Max)	Mean ±SD	Median (Min-Max)	Mean ±SD	Median (Min-Max)
PR	59 ± 4	58[b] (55 - 68)	69 ± 4	55[c] (66 - 79)	14 ± 4	13[ab] (11 - 22)	25 ± 5	23[b] (22 - 35)
YW	28 ± 3	28[a] (25 - 33)	31 ± 1	30[b] (29 - 34)	12 ± 1	12[a] (10 - 13)	12 ± 2	12[a] (9 - 15)
BW	25 ± 2	25[a] (22 - 28)	28 ± 1	28[a] (27 - 29)	13 ± 1	13[b] (12 - 15)	14 ± 2	14[a] (12 - 18)

*Different superscript letters indicate significate differences among columns ($P<.05$).

Table 2
Descriptive statistics of RMS values (precision) within test groups.

	Surfaces							
	Overall		External		Marginal		Intaglio without margin	
Material	Mean ±SD	Median (Min-Max)	Mean ±SD	Median (Min-Max)	Mean ±SD	Median (Min-Max)	Mean ±SD	Median (Min-Max)
PR	1.4 ± 1.1	1[a] (0 - 3)	0.6 ± 0.4	0.8[a] (0.2 - 1.2)	0.7 ± 0.4	0.5[a] (0.4 - 1.6)	1.2 ± 1.1	1[a] (0 - 4)
YW	2.1 ± 1.3	2[a] (0.7 - 4.7)	1.2 ± 0.8	0.8[a] (0.2 - 3.2)	1.1 ± 0.5	1.3[ab] (0.3 - 1.7)	1.5 ± 1.1	1.5[a] (0.5 - 3.5)
BW	2.5 ± 2.6	1.7[a] (0.7 - 9.3)	2.6 ± 2.8	2.4[a] (0.4 - 9.6)	3 ± 2	3.2[b] (0.2 - 7.8)	3.5 ± 2.9	3.2[a] (0.2 - 9.8)

*Different superscript letters indicate significate differences among columns ($P<.05$).

interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

Ivoclar Vivadent is gratefully acknowledged for supplying the materials used in this study. The authors also thank Marco Pannier for supplying the materials.

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