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RESEARCH AND EDUCATION

Effect of printing layer thickness on the trueness of 3-unit interim fixed partial dentures

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ABSTRACT

Statement of problem. Three-dimensional printing has facilitated the fabrication processes in dentistry. However, knowledge on the effect of layer thickness on the trueness of 3D-printed fixed partial dentures (FPDs) is lacking.

Purpose. The purpose of this in vitro study was to compare the effect of printing layer thickness on the trueness of 3-unit interim FPDs fabricated by using additive manufacturing with that of those fabricated by subtractive manufacturing.

Material and methods. The right first premolar and first molar teeth of a dentate mandibular model were prepared for a 3-unit restoration and then digitized by using an intraoral scanner. A 3-unit interim FPD was designed to fabricate 40 restorations by using either the additive (NextDent C&B MFH) with layer thicknesses of 20 μm (n=10), 50 μm (n=10), and 100 μm (n=10) or subtractive manufacturing technique (Upcera) (milled, n=10). After fabrication, the interim FPDs were digitized by using the same intraoral scanner and were superimposed over the design data by using a 3D analysis software program. Root mean square (RMS) was used to analyze the trueness of the restorations at 4 different surfaces (external, intaglio, marginal area, and intaglio occlusal) and as a complete unit (overall). Data were analyzed with the Kruskal-Wallis and Wilcoxon tests with Bonferroni correction (α=.05).

Results. The 100-μm-layer thickness interim FPDs showed the greatest overall ($P\leq.015$), external ($P\leq.021$), and intaglio occlusal ($P\leq.021$) deviations, whereas the milled interim FPDs showed the lowest (P=.001). No significant differences were found among the test groups for marginal RMS ($P\geq.108$). The differences between the 50-μm-layer thickness and 100-μm-layer thickness interim FPDs for the intaglio surface deviations (P=.064) and between the 20-μm-layer thickness and 50-μm-layer thickness interim FPDs for each surface tested were not statistically significant ($P\geq.108$).

Conclusions. The printing layer thickness had a significant effect on the trueness of the additively manufactured interim FPDs. However, subtractively manufactured interim FPDs presented higher trueness than those additively manufactured, regardless of the printing layer thickness. (J Prosthet Dent 2022;■:■-■)

Computer-aided design and computer-aided manufacturing (CAD-CAM) systems operate in 3 stages: data acquisition by using a scanner, processing the acquired data to form a standard tessellation language (STL) file, and manufacturing either via subtractive or additive method.[1-4] Subtractive manufacturing (SM) is the fabrication of an object from a block or disk with various processes such as milling, grinding, drilling, turning, and polishing.[5-7] Even though SM has been synonymous with CAM,[5] additive manufacturing (AM) or 3-dimensional (3D) printing has become increasingly popular in dentistry, with a number of applications for fabricating casts, surgical guides, crown or partial denture frameworks, implant-supported prostheses, and

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Clinical Implications

For the tested 3D-printed resin, 20- and 50-µm-layer thickness interim fixed partial dentures presented lower deviations. Therefore, these FPDs may require less chairside adjustment and have better marginal adaptation than when a 100-µm-layer thickness is used.

orthodontic appliances.[2,8] AM is the process of combining 3D data in consecutive layers[9] and has advantages over SM in terms of passive and vertical manufacturing, recycling of the unused material, and the possibility of producing larger and more complex objects and of increasing the number of products to be manufactured at a time.[10,11] The American Section of the International Association for Testing Materials (ASTM) International Standard Organization has categorized AM into 7 methods[12] with stereolithography (SLA), in which a liquid resin is polymerized by an ultraviolet laser, being the most commonly used method for dentistry.[5] An alternative to SLA is digital light processing (DLP), a method based on the activation of light-sensitive monomers by the projection of a laser. The laser beam is directed by a digital micromirror device (DMD), which consists of a vast number of micromirrors that control the reflection path of the light.[13,14]

Interim restorations are pivotal for the success of a prosthetic rehabilitation as they replace the missing tooth structure and thereby provide biological and mechanical protection as well as positional stability.[15,16] Currently methacrylate polymers and composite resins are typically used for interim restorations.[17] Polymethyl methacrylate (PMMA) is the leading alternative among these materials because of its low cost, ease of fabrication, and reliability.[15] However, polymerization shrinkage, marginal discrepancies, and that the polymerization reaction of this material is exothermic are problems associated with the direct use of PMMA.[15] It is also possible to manufacture these restorations by using either SM or AM,[6,16,18,19] and compared with the conventional method, these CAD-CAM technologies lead to more rapid production with a final product that has higher precision and adaptation.[17]

The accuracy of a printed object can be affected by the technology and software program used, laser speed, laser intensity, printing orientation, number of layers, printing angle, layer thickness, and postprocessing methods.[7,10,11,18,20] Printing orientation has been the main subject of interest of previous studies on 3D-printed interim materials.[7,11,13,18,21] However, setting the ideal thickness, which is a controllable parameter,[22] is also essential for optimal restoration properties.[23] Studies on the effects of layer thickness on the accuracy of 3D-printed interim restorations are sparse.[14,17] Dikova1[17] did not compare 3D-printed and milled interim fixed partial dentures (FPDs), while Park et al[14] focused on the marginal fit and internal gaps of interim FPDs. Therefore, the purpose of this in vitro study was to evaluate the effect of printing layer thickness on the trueness of 3-unit PMMA interim FPDs and to compare them with milled PMMA interim FPDs. The null hypotheses were that the layer thickness or fabrication technique would not affect the trueness of 3-unit interim FPDs.

MATERIAL AND METHODS

The right mandibular second premolar was removed from a dentate typodont model (ANA-4; frasaco GmbH), and the right first premolar and first molar were prepared with a 1-mm-wide chamfer finish line to receive 3-unit FPDs. The maxillary and mandibular models and the occlusion were scanned with an intraoral scanner (i500; Medit) (Fig. 1). The digital scan data were converted to a standard tessellation language (STL) file that was exported to a software program (DentalCAD 2.2; exocad GmbH) to design a 3-unit interim FPD. The cement space was set at 30 µm, and the connector sizes to 9 mm^2 with a modified-ridge lap pontic design.[18] This design was converted to an STL file to generate a reference interim FPD scan STL file (RIFPD-STL) to fabricate the study groups (Fig. 2). By using this design, 40 interim FPDs were fabricated by using 2 techniques: AM (n=30) and SM (n=10). SM served as the control group.

In the AM technique, 3 different layer thicknesses (20, 50, and 100 µm) were used to print the interim FPDs (n=10/layer thickness). The STL file of the designed interim FPD was imported to a DLP software program (SprintRay; SprintRay Inc). The support and build angle settings were determined by following the resin manufacturer's (NextDent C&B MFH; 3D Systems) recommendation. The angle was set at 45 degrees to obtain details on the occlusal surface. The generated supports were evaluated, and any support on the margin of the interim FPD or intaglio surface was removed. To print identical interim FPDs, this configuration was duplicated 10 times and arranged on the printer's build platform. This standard arrangement was used to fabricate each 3D-printed group. The resin (NextDent C&B MFH; 3D Systems) was mixed according to the manufacturers' recommendations and poured into the printing material tank of the DLP printer (MoonRay S100; SprintRay Inc). Interim FPDs were then printed in 20-µm, 50-µm, and 100-µm layer thicknesses (n=10). The properties of the resin material and the printer have been previously reported.[24] The printed interim FPDs were removed from the platform, rinsed 5 minutes in 96% clean alcohol solution ultrasonically (alcohol isopropilico; QuimiKlean) according to the manufacturers' recommendations, and

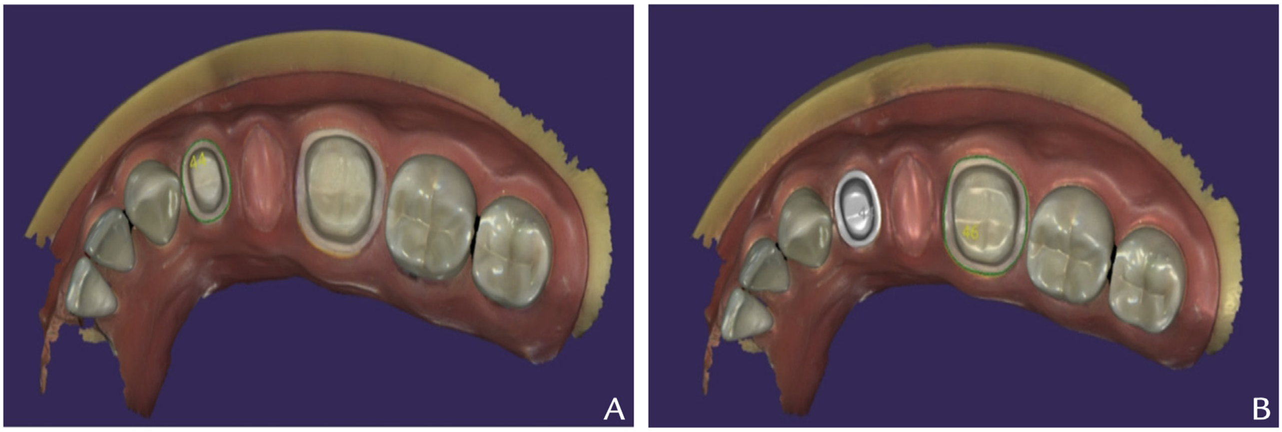

Figure 1. Preparations for interim FPD. A, Margin of mandibular right first premolar. B, Margin of mandibular right first molar.

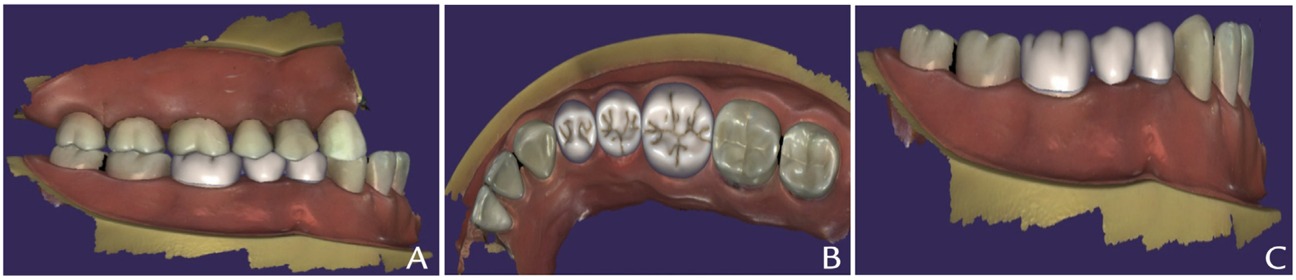

Figure 2. STL file of interim FPD. A, In contact with maxillary model. B, Occlusal aspect. C, Buccal aspect. FPD, fixed partial denture; STL, standard tessellation language.

then postpolymerized (ProCure; SprintRay Inc) (405-nm LED arrays) (Fig. 3). The supports were removed with a cutoff wheel (Keystone Cut-off Wheels; Keystone Industries), and the cut surfaces smoothed with a small tungsten carbide bur (Lab Carbide #71G; Keystone Industries) to prevent alignment errors.

For SM, the designed STL file was inserted in the same angulation and support structures onto a PMMA block (Upcera; Shenzhen Upcera Dental Technology Corp) to mill 10 identical interim FPDs (Zenotec mini; Wieland Dental+Technik GmbH & Co KG). After milling, the supports were removed by using a cutoff wheel (Keystone Cut-off Wheels; Keystone Industries), and the sectioned areas adjusted with a small tungsten carbide bur (Lab Carbide #71G; Keystone Industries) to minimize or prevent alignment errors. The specimens were fabricated by 1 operator (G.Ç.). All AM and SM interim FPDs were evaluated under ×3.5 magnification (EyeMag Pro; Carl Zeiss) during and after adjustments to detect defects (concavities or convexities). No concavities were detected on the specimens, and all surfaces were smoothed until no convexities were observed or detected with an explorer. No intaglio surface adjustments were made.[18]

The interim FPDs were kept in lightproof boxes before scanning with an intraoral scanner. First, the intraoral scanner (i500; Medit) was calibrated, and then interim FPDs were sprayed with a thin layer of antireflective scan powder (IP Scan-Spray; IP-Division) to facilitate scanning. Then, AM, SM, and milled interim FPDs were scanned, and the scan files were converted to test-scan STL files by 1 operator (G.Ç.). The scanner had 5.3 ±0.34-µm trueness and 3.2 ±0.49-µm precision for crowns as specified by the manufacturer.

For trueness measurements, root mean square (RMS), which indicates how far deviations are from zero between the 2 different data sets, was used.[25] Low RMS values indicated increased 3D matching between superimposed scans and accordingly high trueness.[26] The RIFPD-STL and test-scan STL files were uploaded to a 3D analysis software program (Medit Link; Medit). The STL files of test scans were superimposed to the RIFPD-STL file by using the comparison application of the software program (Medit Compare v1.1.1.61; Medit). The superimposition was performed by selecting 3 reference points on the central fossa of each tooth for both RIFPD-STL and the test-scan STL (Fig. 4). To visualize and then quantify the 3D deviations, ±50 µm was used as the maximum and minimum critical (nominal) values with a ±10-µm tolerance range,[27] and color-difference maps were generated. The test scan STL file and the RIFPD-STL were compared

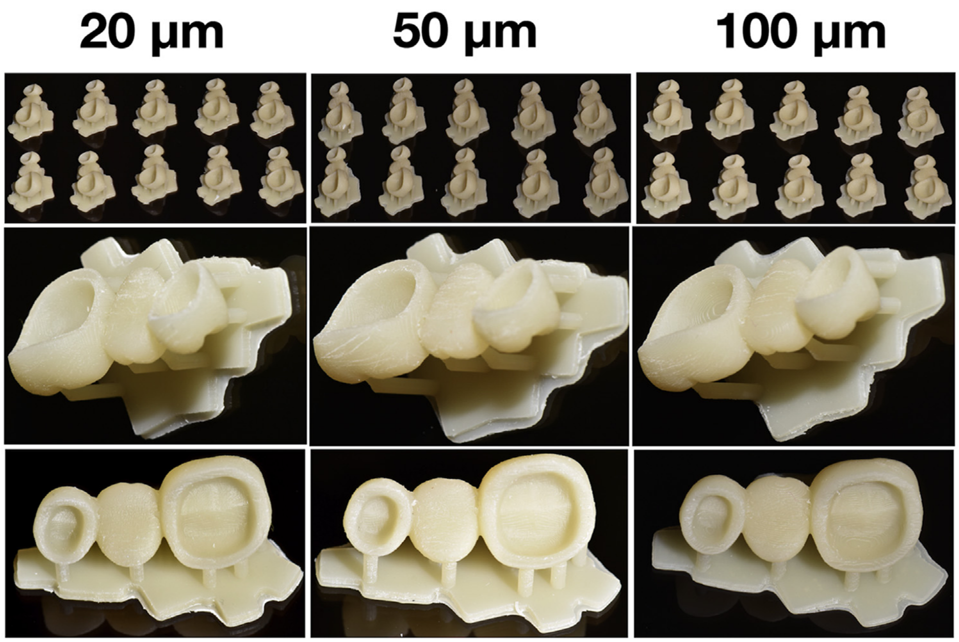

Figure 3. Three-dimensionally printed interim FPDs. FPD, fixed partial denture.

for the overall RMS that involves all interim FPD surfaces. The 3D analysis software program calculated the RMS from the color-difference maps. Therefore, no additional formula was used. For external, marginal, intaglio, and intaglio occlusal surface RMS values for premolar and molar teeth, test-scan STL files, and RIFPD-STL were reimported. These surfaces were separated into test-scan STL files and RIFPD-STL virtually, dividing crowns into 4 parts as reported in a previous study.[26] After separating, superimposition was performed again for each surface of the premolar and molar teeth at the same time. The color-difference maps were also generated for these surfaces to calculate the RMS values (Fig. 5). The areas showing greater deviations than the scale used were represented with gray and were included in the calculation.

Statistical evaluation of the data was performed by using a software program (R 3.6.1; The R Foundation). RMS values, depending on the layer thickness, were analyzed by using the Kruskal-Wallis tests. Any significant interactions were further resolved with Wilcoxon tests with Bonferroni correction (α=.05).

RESULTS

The results of the Kruskal-Wallis test are summarized in Table 1. Figure 6 displays the RMS values of the tested surfaces for the control and different layer thickness groups. According to the results of the Wilcoxon tests with Bonferroni correction (Table 2), significant differences were found among the test groups for overall, external, and intaglio occlusal RM, in all pairwise comparisons except for the differences between the 20- and 50-μm-layer thickness interim FPDs. Interim FPDs fabricated by using a100-μm-layer thickness had the highest overall ($P\leq$.015), external ($P\leq$.021), and intaglio occlusal ($P\leq$.021) RMS values, and the milled IFPDs had the lowest (P=.001). For marginal ($P\geq$.108) and intaglio ($P\geq$.064) RMS values, the differences among the test groups were not statistically significant.

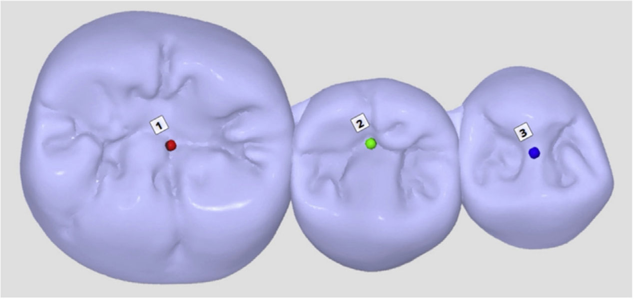

Figure 4. Reference points selected for superimposition of RIFPD-STL and test-scan STL files. RIFPD, reference interim fixed partial denture; STL, standard tessellation language.

DISCUSSION

The printing layer thickness significantly affected the trueness of AM crowns, and SM interim FPDs had higher trueness than AM FPDs. Therefore, the null hypotheses were rejected.

Among the 3D-printed interim FPDs, the 20- and 50-μm-layer thickness groups showed no difference in trueness, but differences were found when those were compared with the 100-μm-layer thickness group in terms of overall, external, and intaglio occlusal trueness. Furthermore, a tendency for higher trueness of the

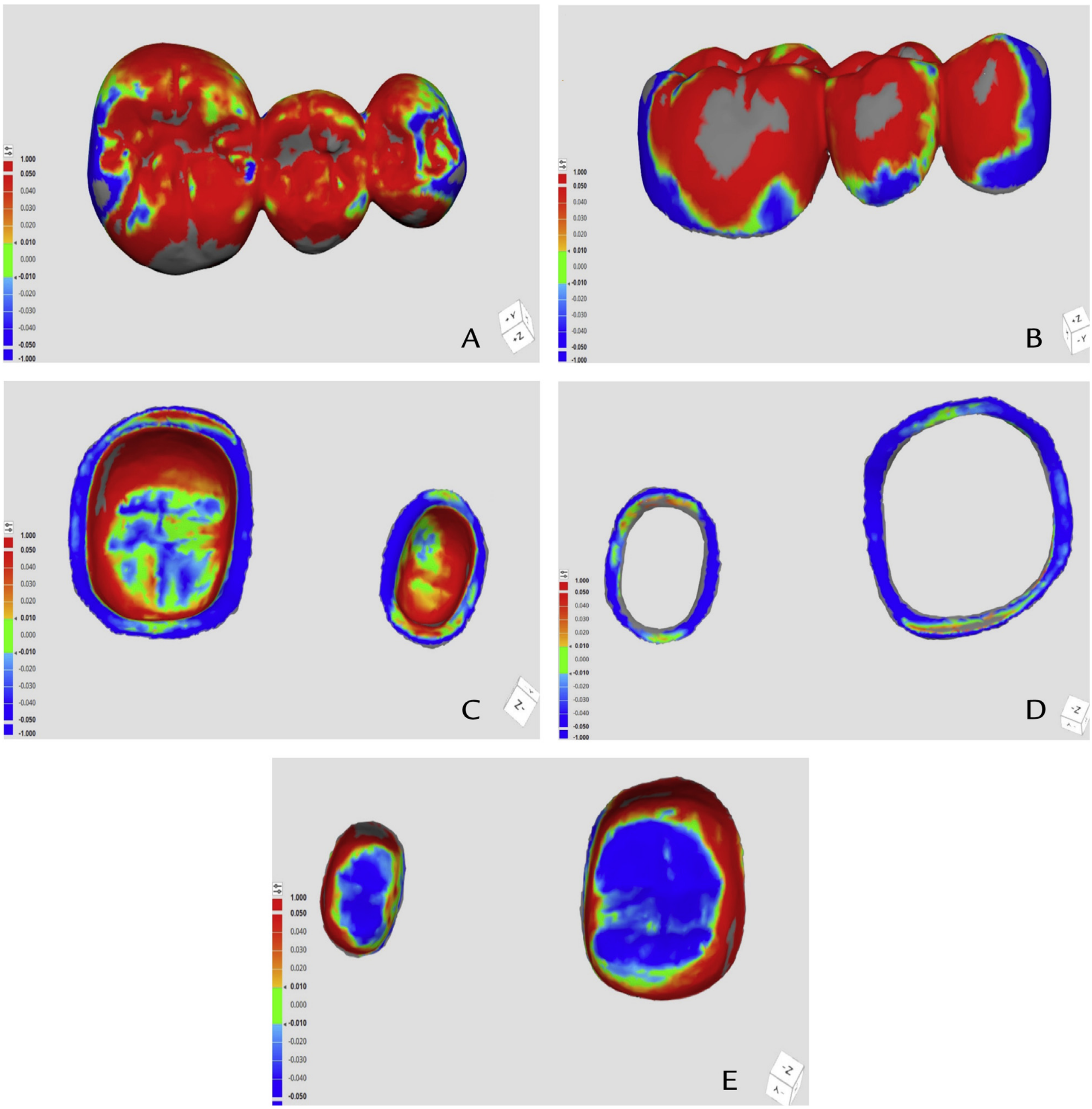

Figure 5. Color maps generated by superimposition of RIFPD-STL and test-scan STL files. A, Overall. B, External. C, Intaglio. D, Marginal. E, Intaglio occlusal. RIFPD, reference interim fixed partial denture; STL, standard tessellation language.

Table 1. Median and mean ±standard deviation RMS values (μm) for printed or milled interim FPDs

Layer Thickness (Fabrication Technique)	Overall (n=10)	External (n=10)	Intaglio (n=10)	Marginal (n=10)	Intaglio Occlusal (n=10)
Control (milled)	5^{a} (6.1 ±2.38)	9.5^{a} (9.6 ±2.41)	18.5^{a} (18.8 ±7.89)	3^{a} (4 ±2.26)	3^{a} (2.9 ±0.74)
20 μm	65^{b} (66.4 ±10.09)	55.5^{b} (56 ±8.88)	16.5^{a} (17 ±3.13)	4.5^{a} (4.7 ±1.42)	32.5^{b} (30.7 ±5.31)
50 μm	62.5^{b} (63.7 ±9.68)	50^{b} (52.6 ±8.68)	13.5^{a} (15.1 ±4.09)	3^{a} (3.1 ±1.1)	31.5^{b} (31.1 ±4.2)
100 μm	82.5^{c} (85.1 ±9.11)	66^{c} (68.1 ±7.85)	20^{a} (22 ±6.77)	3^{a} (3.1 ±1.1)	37.5^{c} (38.2 ±4.54)

Significant differences among groups are indicated with different superscript lowercase letters in same column (*P*<.05).

intaglio surface of the 50-μm-layer thickness group was observed compared with the 100-μm-layer thickness group (*P*=.064 after Bonferroni correction, a rather conservative analysis approach[28]). Therefore, the intaglio surface of the 100-μm-layer thickness group may have had lower trueness. Previous studies on casts or complete

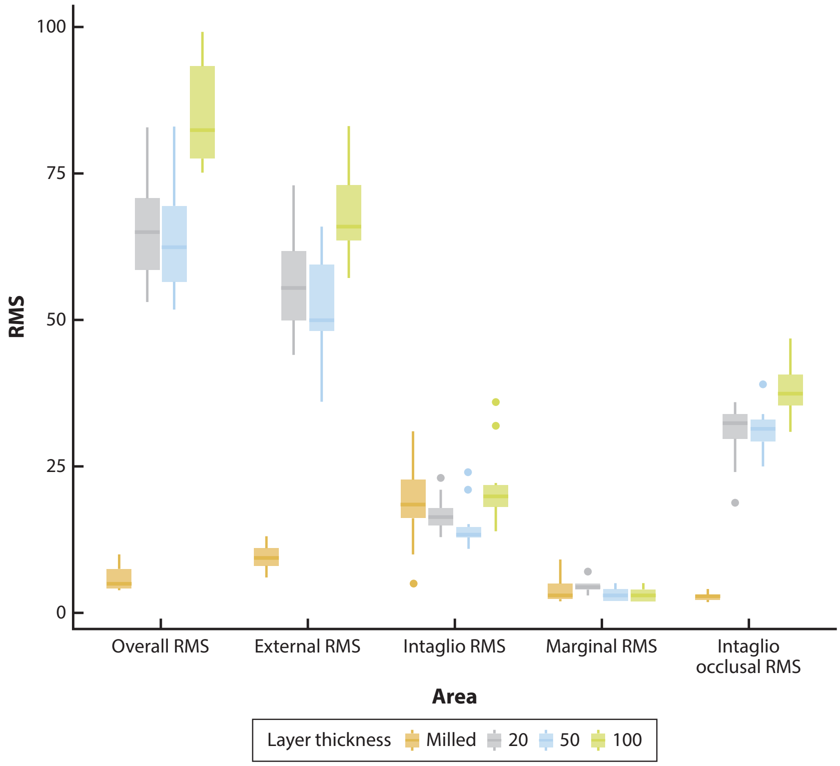

Figure 6. RMS values of each surface according to layer thickness when compared with control (milled). RMS, root mean square.

Table 2. Adjusted *P* values and estimated differences (μm) for pairwise comparisons of RMS values for printed and milled interim FPDs

Surface	Control vs 20 μm	Control vs 50 μm	Control vs 100 μm	20 μm vs 50 μm	20 μm vs 100 μm	50 μm vs 100 μm
Overall RMS	.001 (-60.3)	.001 (-57.6)	.001 (-79)	>.05 (2.7)	.015 (-18.7)	.001 (-21.4)
External RMS	.001 (-46.4)	.001 (-43)	.001 (-58.5)	>.05 (3.4)	.021 (-12.1)	.01 (-15.5)
Intaglio RMS	>.05 (1.8)	.894 (3.7)	>.05 (-3.2)	.472 (1.9)	.24 (-5)	.064 (-6.9)
Marginal RMS	>.05 (1.8)	>.05 (3.7)	>.05 (-3.2)	.108 (1.9)	.108 (-5)	>.05 (-6.9)
Intaglio Occlusal RMS	.001 (-27.8)	.001 (-28.2)	.001 (-35.3)	>.05 (-0.4)	.018 (-7.5)	.021 (-7.1)

**P*<.05 indicates significant differences between different layer thicknesses within each surface.

dentures reported no significant influence of layer thickness on the trueness of the finished object.[29-31]

The most difficult areas to reproduce in FPDs are likely to be the thin complex structures. Therefore, a small printing layer thickness could be advantageous, particularly at thin areas with complex structures. Considering that the fissures present on the occlusal fossa are among the thinnest areas of an FPD, this phenomenon might have led to higher trueness with 20- and 50-μm-layer thickness groups than with the 100-μm-layer thickness group at the intaglio occlusal surface. When compared with the results of a study that investigated the occlusal fit of 3D-printed FPDs, among other factors, it can be seen that the smallest gap was also found in the 50-μm-layer thickness group compared with the 100-μm-layer thickness group in the present study.[14]

AM of interim restorations has been increasingly used in dentistry. However, the 3D printing of single crowns has been studied most often.[6,15,16,21,32] Studies comparing the accuracy of 3D-printed or milled single crowns have reported that 3D-printing could achieve similar accuracy to milling and may therefore be clinically applicable.[6,27] In the present study, which may be the first focusing on the effect of layer thickness on the trueness of 3D-printed interim FPDs, the milled group performed significantly better in terms of overall, external, intaglio, and intaglio occlusal trueness. Therefore, milling may still be preferred over the 3D printing of interim FPDs, even though all analyzed aspects of the printed groups, especially for the 20- and 50-μm-layer thickness groups, were well below the 120-μm marginal gap value generally described as the clinically acceptability threshold for marginal fit.[33] A study focusing on interim FPDs fabricated by using different 3D printing methods reported that DLP is a valid method of fabrication.[8] Another study, which investigated the influence of layer thickness on the trueness of interim FPDs also achieved the best results when using a small layer thickness.[17] However, in this study,[17] the trueness of the 35-μm-layer thickness group was higher than that of the

50-μm-layer thickness group, whereas in the present study, no difference was seen between the 20- and 50-μm-layer thickness groups.

Intraoral scanners have been used to scan the preparations on the cast for the fabrication of interim FPDs.[34-36] Earlier studies have described that the most accurate ways to obtain surface data are tactile or optical industrial-grade scanners.[37,38] The effect of scanning the preparation with the intraoral scanner is likely to be negligible, as this scan was only used to generate the STL data set of the interim FPDs and not for further analysis. Thus, the same STL data set was always used to fabricate the interim FPDs, which was then also used as a reference for the subsequent comparisons. The situation was different, however, for scanning the interim FPDs with the intraoral scanner. Theoretically, it would have made more sense to scan the interim FPDs with a more precise laboratory- or industrial-grade scanner in order to obtain the most accurate data sets possible for comparisons with the CAD data set. In practice, scanning with the laboratory scanner repeatedly resulted in data gaps in the areas that were difficult for the light to access, a known problem of stationary optical scanning systems.[39] In addition, scanning 40 interim FPDs with an industrial-grade scanner was not possible for financial reasons. Therefore, an intraoral scanner was used to scan the interim FPDs, and the scans were straightforward as the movable wand of the scanner enabled the light to access the details of the interim FPDs. Despite the high trueness and precision described by the manufacturer of the applied intraoral scanner, a recent study demonstrated a precision of 13.6 ±2.5 μm for single-tooth preparation scans of this scanner.[40] Although the accuracy of laboratory scanners is generally higher, the difference does not seem to be large; thus, the use of the intraoral scanner might be considered as a minor limitation.[39,41,42] For all AM interim FPDs, a build angle of 45 degrees was used, based on the recommendations of the manufacturer. The effect of printing orientation on accuracy has been demonstrated in previous studies[7,11,13,18,21] which have shown the best results with a printing orientation of 135 degrees (interim crowns) and 45 degrees (interim FPDs).[7,14] Consequently, the methodology used followed the recommendations in the literature, especially considering the similarity of the 45-degree and 135-degree printing orientation. The analysis of trueness by means of a best-fit algorithm and subsequent calculation of RMS deviations also followed the recommendations in the literature, which described this analysis method as the standard.[43] In the current study, a landmark-based superimposition was executed instead of the most commonly applied best-fit alignment. When using the best-fit algorithm, it must be assumed that the actual deviations of specific points can be underestimated, since the best possible superposition of corresponding data sets is calculated.[43,44] However, the quality of the landmark-based superimposition directly depends on the operator selecting the points.[43] Therefore, the superimposition in the present study was executed by a single operator with extensive knowledge in the field of digital analyses to minimize the risk of underestimating the deviations between the corresponding data sets.

Limitations of the present study included that only one material, one 3D printer, and one intraoral scanner were used, factors that have been reported to have a significant influence on accuracy.[23,40,45] Therefore, the results should not be generalized. However, the materials tested have been used in previous studies.[24,40,46] A sample size calculation was not performed as the present study was considered to be a pilot study. Nevertheless, the sample size was determined according to previous studies focusing on the trueness of the AM techniques,[11,21,24,47] and statistically significant differences in terms of trueness were demonstrated. A similar design and instruments were used in a previous study, which was considered when determining the sample size.[24] In addition, the thickness of the powder used might be a limitation. Another limitation was the manual removal of support structures for all interim FPDs. Although this step was performed by the same practitioner for all reconstructions, manual rework always includes a subjective nonstandardizable component.

CONCLUSIONS

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

1. The trueness of the 3D-printed interim FPDs was affected by the printing layer thickness.
2. Layer thicknesses of 20 or 50 μm may result in higher trueness than a 100-μm-layer thickness for the printing resin, 3D printer, and settings used in the present study.
3. The milled interim FPDs presented higher trueness than those fabricated by 3D printing, regardless of the layer thickness.

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Gülce Çakmak: Design, Conceptualization, Investigation, Writing – original draft. **Alfonso Rodriguez Cuellar:** Conceptualization, Investigation, Resources. **Mustafa Borga Donmez:** Writing – original draft, Writing – review & editing. **Samir Abou-Ayash:** Writing – original draft. **Wei-En Lu:** Formal analysis. **Martin Schimmel:** Visualization, Supervision. **Burak Yilmaz:** Supervision, Writing – review & editing.

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