Fabrication Trueness, Intaglio Surface Adaptation, and Marginal Integrity of Resin-Based Onlay Restorations Fabricated by Additive and Subtractive Manufacturing

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Purpose: To evaluate the fabrication trueness, intaglio surface adaptation, and marginal integrity of resin-based onlay restorations made via additive manufacturing (AM) or subtractive manufacturing (SM). ***Materials and Methods:*** An onlay restoration was designed (DentalCAD Galway 3.0) and saved as an STL file to generate a design STL file (DO-STL). Using this design, 45 onlays were fabricated either with AM (3D-printed resin for definitive [AM-D; Tera Harz TC-80DP] and interim [AM-I; Freeprint temp] restorations) or SM (composite resin, Tetric CAD) technologies. Onlays were scanned with an intraoral scanner (CEREC Primescan SW 5.2), and the scans were saved as test STL files (TO-STLs). For trueness evaluation, TO-STLs were superimposed over the DO-STL, and root mean square (RMS) values of overall and intaglio surfaces were measured (Geomagic Control X). For the intaglio surface adaptation and marginal integrity, a triple-scan protocol was performed. Kolmogorov-Smirnov, one-way ANOVA, and post-hoc Tukey honestly significant difference tests were used to analyze data (α = .05). ***Results:*** RMS values of intaglio and overall surfaces, intaglio adaptation, and marginal integrity varied among test groups ($P < .001$). AM-D had the greatest overall surface RMS ($P < .001$), while SM had the greatest intaglio surface RMS ($P < .001$). SM had the highest average distance deviations for intaglio surface adaptation and marginal integrity, whereas AM-D had the lowest ($P < .001$). ***Conclusions:*** AM-D onlays showed lower overall trueness than AM-I onlays and SM definitive onlays. However, AM-D onlays presented high intaglio surface trueness, intaglio surface adaptation, and marginal integrity. *Int J Prosthodont 2024;37(suppl):s99–s107. doi: 10.11607/ijp.8802*

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Along with computer-aided design (CAD) processes, computer-aided manufacturing (CAM)—including subtractive manufacturing (SM) and additive manufacturing (AM) technologies—has revolutionized the implementation of restorative dentistry.[1–8] SM refers to the production of dental restoration by milling a block or disk with the help of a numerically controlled machine and milling burs.[1,7,9]

Fig 1 Cavity preparation on a mandibular right molar for resin-based onlay restoration.

Although SM has been in use for many years,[1,7] it has been reported that milling tools can be susceptible to abrasive wear, and the process itself can lead to microsized cracks within the restorations due to vibration, also producing a substantial amount of nonreusable material waste.[9,10] In recent years, the AM approach has been introduced in the field of dentistry, which refers to a layer-by-layer building of an object.[2,4,5,8,11] AM enables unrestricted fabrication of small, hollow spaces and undercuts, useful for producing complex geometric shapes.[2,4,5,8,11] Further, it helps fabricate several objects at the same time with minimal waste and at a reasonable cost.[2,4,5,8]

Digital light processing (DLP) is a commonly used AM technique that utilizes ultraviolet structured light[2,11] and can be used to fabricate resin-based interim or definitive restorations such as crowns, veneers, and onlays.[2,11–14] To achieve clinically acceptable mechanical strength, structural durability, and surface properties, it is important to achieve strong adhesion between the building layers during DLP process to prevent interlayer pores and structural inhomogeneity.[11–16] Previous studies have evaluated the trueness, marginal gap, production time, and fracture resistance of 3D-printed definitive resin crowns.[17–19] However, the feasibility of DLP for the fabrication of veneers or onlays is not extensively studied.

Whether the restoration is printed or milled, its dimensional accuracy is important for the optimal fit of its intaglio surface.[20] A marginal discrepancy can lead to microleakage by cement dissolution, secondary caries on the cavity surface, pulpitis of the abutment, and periodontal inflammation.[21–24] So far, the trueness or dimensional accuracy of onlay restorations has not been extensively evaluated, considering the effect of different milling procedures or different restorative materials, such as composite resin, leucite glass-ceramic, and lithium disilicate glass-ceramic.[20,25] Ahlholm et al reported that the accuracy of 3D printing is at least at the same level as the milling technique in the fabrication of dental inlay/onlay restorations.[14] In addition, definitive 3D-printed resins showed similar results for marginal adaptation both before and after fatigue loading, suggesting possible advantages in cost and production time over milled restorative materials[19]; however, that study did not evaluate the fabrication trueness, which affects internal and marginal adaptation. With the development of digital technologies, the clinician can efficiently evaluate trueness and adaptation of indirect restorations using the triple-scan protocol (TSP) with high reliability.[26–28] To the present authors' knowledge, no study has compared the fabrication trueness, intaglio surface adaptation, and marginal integrity of resin-based onlay restorations manufactured using either AM or SM.

Therefore, the purpose of this in vitro study was to evaluate the trueness, intaglio surface adaptation, and marginal integrity of CAD/CAM onlay restorations made of 3D-printed (definitive and interim use) or milled resins intended for definitive or interim restorations. The null hypotheses were that there would be no difference in terms of *(1)* fabrication trueness, *(2)* intaglio surface adaptation, and *(3)* marginal integrity of resin-based onlay restorations manufactured via AM and SM.

MATERIALS AND METHODS

An onlay cavity was prepared on a mandibular typodont molar tooth (Frasaco) with an isthmus width of 2 to 2.5 mm, slightly divergent buccal and lingual axial walls (6 to 10 degrees), functional and nonfunctional 2-mm cusp reductions with a 90-degree butt joint margin, 1-mm fissure width, and 1.5-mm step width[29] (Fig 1).The prepared cavity was scanned using an intraoral scanner (IOS; CEREC Primescan SW 5.2, Dentsply Sirona; 5- to 10-µm resolution) and converted to STL (standard tessellation language) file format. Using a design software program (DentalCAD Galway 3.0, Exocad), an onlay indirect restoration for resin composite was designed with the following parameters: 80-µm cementation space (starting 1 mm from the margin), 3-mm border taper, 1.5-mm minimal thickness, 0.8-mm starting cement gap, additional 20-µm spaces for axial and radial surfaces, 0-degree angle, 0-mm angled crown margin, 0.1-mm horizontal crown margin, 0-mm

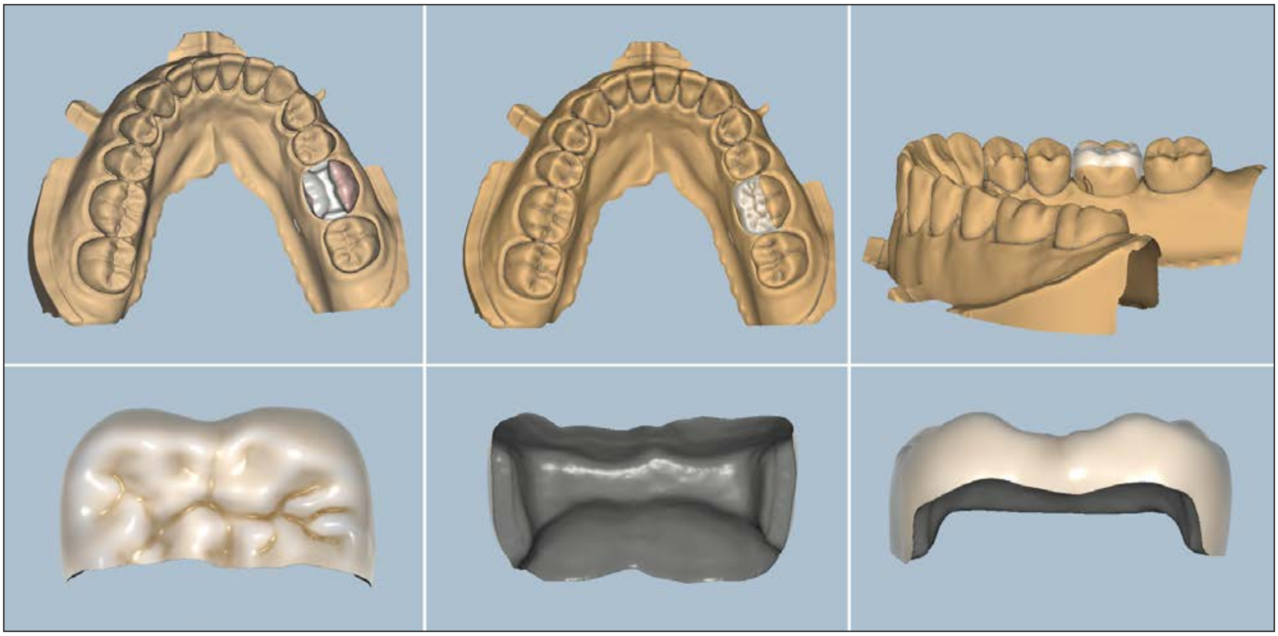

Fig 2 External and internal surfaces of the virtual design on a mandibular right molar for onlay restoration.

vertical crown margin, 0.1-mm distance to the antagonist tooth, 0-mm distance to the neighboring tooth. The design was exported, stored as a design STL file (DO-STL; Fig 2), and used to fabricate the specimens for this study to ensure standardization and consistency.

A total of 45 onlay restorations were fabricated from the DO-STL using either AM or SM with three different materials (n = 15 restorations per material group): *(1)* an acrylate resin for definitive AM restorations (AM-Ds; Tera Harz TC-80DP, Graphy); *(2)* an acrylate resin for interim AM restorations (AM-Is; Freeprint temp, Detax); and *(3)* a composite resin for definitive SM restorations (Tetric CAD, Ivoclar Vivadent) (Fig 3). The sample size for this study was determined based on a priori power analysis (80% statistical power, 95% CI, and effect size of 0.623).[11]

For the AM groups, the DO-STL was imported and positioned perpendicular to the build platform using a nesting software (Composer, Asiga). The supports were automatically attached to the virtual restoration by the software, except those placed on the margin or in the intaglio surface of the onlay, which were manually eliminated before further processing. The adjusted configuration was duplicated 15 times per resin group. A DLP-based printer (MAX UV, Asiga) with a 405-nm wavelength was used to fabricate the specimens with a layer thickness of 50 µm. The printing and postprocessing stages were performed according to the manufacturer's information. For each printing process, the printed specimen remained on the platform for a 10-minute drain time before removal. For postprocessing, AM-D specimens were ultrasonically cleansed for 40 seconds in 96% ethanol (Ethanol absolut, Grogg Chemie) followed by carefully removing unpolymerized residual resin with a cotton swab and drying with an air syringe. AM-I specimens were ultrasonically precleansed for 3 minutes in 98% isopropyl alcohol (Isopropanolum rein, Christoffel-Apotheke), cleansed for an additional 3 minutes in fresh 98% isopropyl alcohol, and dried with an air syringe. After ensuring that the specimens were completely dry and free of alcohol residue, they were postpolymerized using a xenon lamp-based polymerizing device (Otoflash G171, NK-Optik) under nitrogen oxide gas atmosphere for 4,000 lighting exposures. The support structures were ground and gently smoothed under magnification loupes (EyeMag Pro, Zeiss). For the fabrication of SM onlays, the DO-STL file was imported into a nesting CAM software (PrograMill CAM version 4, Ivoclar Vivadent), and onlay specimens were wet-milled from composite resin blocks (Tetric CAD HT A1, Ivoclar Vivadent) using the "High Finish Tetric CAD Milling Strategy for Inlays" milling strategy with a five-axis milling unit (PrograMill PM7, Ivoclar Vivadent) with a milling time of 1 hour and 15 minutes. The support structures were cut, and the surface was gently smoothed under the same magnification loupes.

In summary, a total of 45 resin-based onlay specimens were fabricated using either AM or SM and were steam-cleaned, dried, and stored in a lightproof box. After calibrating the IOS before each scan, the external and internal surfaces of the onlay restorations were digitized under ambient light conditions by a single operator (D.S.).

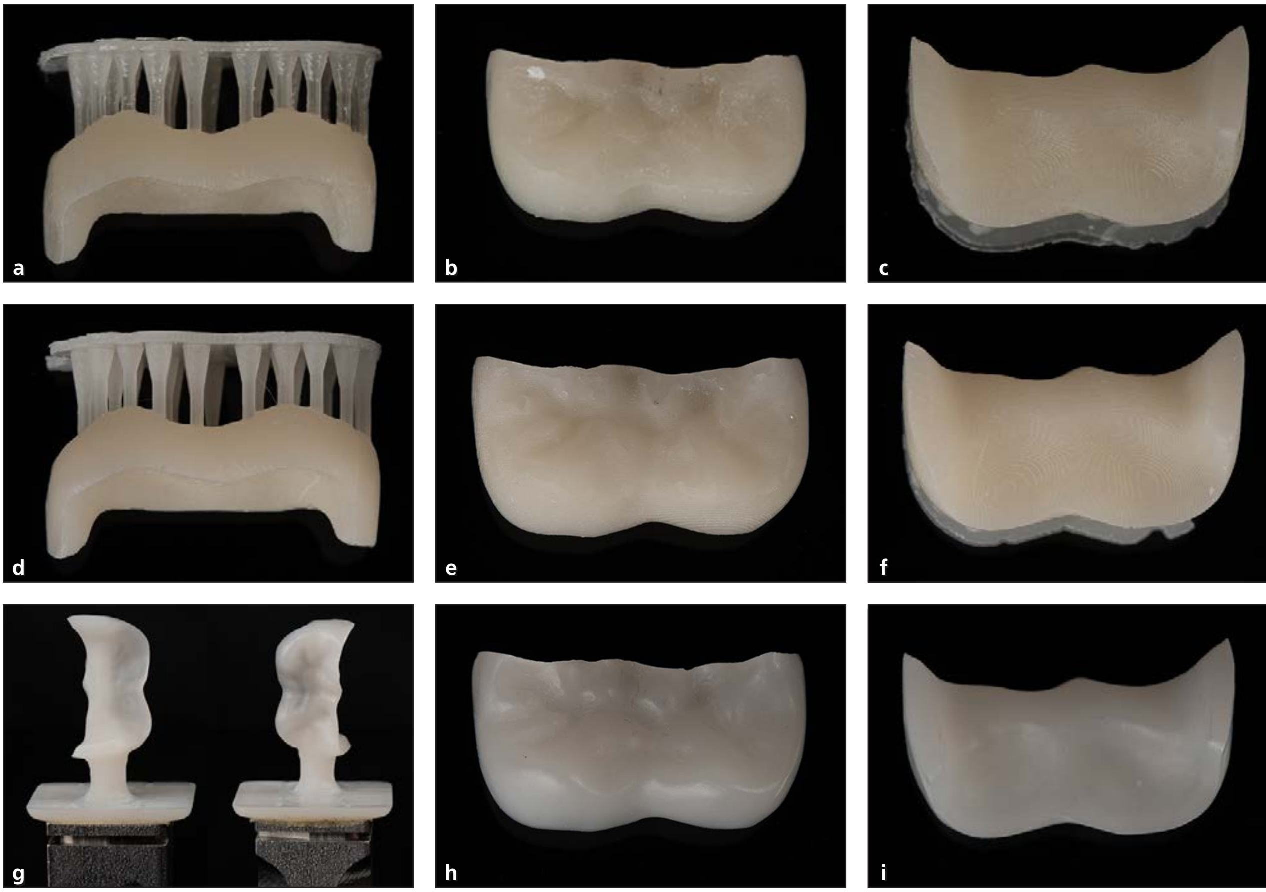

Fig 3 Representative images of resin-based onlay restorations for three different groups: *(a to c)* AM-D, *(d to f)*, AM-I, and *(g to i)* SM for a definitive restoration.

Scans were done using the following protocols (Fig 4): A stick with an adhesive on its tip (OptraStick, Ivoclar Vivadent) was used to handle and fix the onlay restorations while scanning. The stick was fixed to the intaglio surface. Then, as recommended by the scanner manufacturer, the outer occlusal surfaces were scanned first. Then, the scanner wand was rotated to a maximum of 20 degrees toward the intaglio and aproximal surfaces to capture the proximal surfaces and fine margins. After scanning these surfaces, the stick was placed on the occlusal surface to further scan the whole intaglio surface. While scanning, the distance between the coated sapphire glass of the scanner and the scanned surface was nearly 20 mm, as recommended by the manufacturer. The scans were checked for any errors and, if no errors were present, converted to test-scan STL files (TO-STLs).

To analyze fabrication trueness, the DO-STL file was imported into an inspection software (Geomagic Control X, 3D Systems). The DO-STL was separated into two regions, intaglio and external surfaces, using the software's "Region" tool. This file was used as a reference template to further align with TO-STL files for analysis. After best-fit alignment between the DO-STL and TO-STL files, each onlay restoration had the root mean square (RMS) values calculated for two different surfaces: overall and intaglio surface. The *overall surface* was defined as all external and intaglio surfaces, including the marginal area, while the *intaglio surface* was defined as the axial and occlusal area of internal surface and the marginal area, excluding external surfaces.[11,13] A color-difference map with critical deviation values of ±100 μm and a nominal deviation (tolerance) of ± 0 μm was created for surface deviations between the STL files.[30–32] According to the International Organization for Standardization 5725-233 standards, accuracy is defined by trueness and precision. *Trueness* refers to the distance between an object's measurements and its real dimensions, whereas *precision* is defined as the proximity of repeated measurements. A low RMS value indicates high fabrication trueness.[33]

To assess the intaglio surface adaptation of the onlays, TSP was used[27] (Fig 5). For this method, an additional scan of onlay restorations was performed when the restorations were seated on the prepared tooth. Scans were performed under 2 N pressure using a brass rod, as follows: Onlays were placed on the master die, the fit was checked, and the master die was placed in a

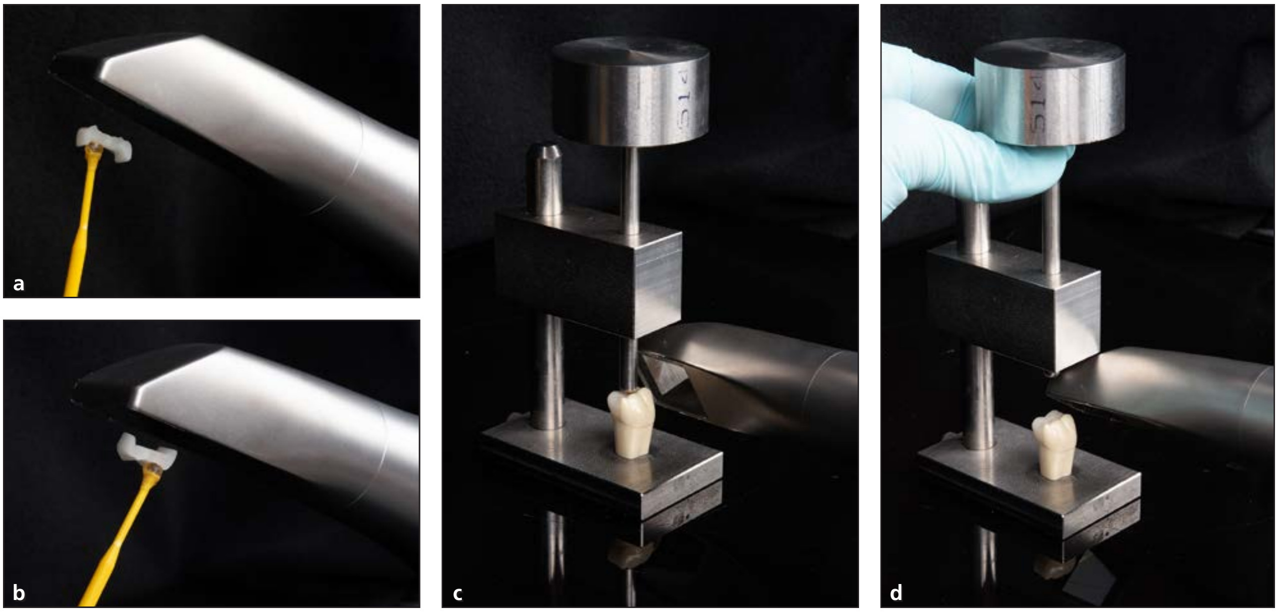

Fig 4 *(a to d)* Representative images of the scanning protocol for the fabrication trueness and TSP.

brass rod. The tip of the brass rod was placed on the central fossa. The scan was then completed by capturing all tooth surfaces. The tip was then removed, and the occlusal surface was recaptured, allowing the scanner to automatically erase the brass rod's tip. These scans were then converted to STL files (onlay-on-tooth STL).

For the first stage of TSP analysis, the STL of the prepared tooth was imported into the same analysis software and moved to the reference data. Then, the onlay-on-tooth STL was imported as measured data and best-fit aligned with the prepared-tooth STL. The measured data had the same x, y, and z coordinates of the prepared tooth after this alignment, and the file was exported as Mesh 1. For the second stage, Mesh 1 was imported as reference data, and onlay scans (TO-STLs) were imported as measured data and best-fit aligned with Mesh 1. Then, onlay scans (TO-STLs) were exported as Mesh 2. For the third stage, the STL of the prepared tooth was imported into the software and moved to the reference data, and Mesh 2 was imported as measured data. With this last stage, the software automatically

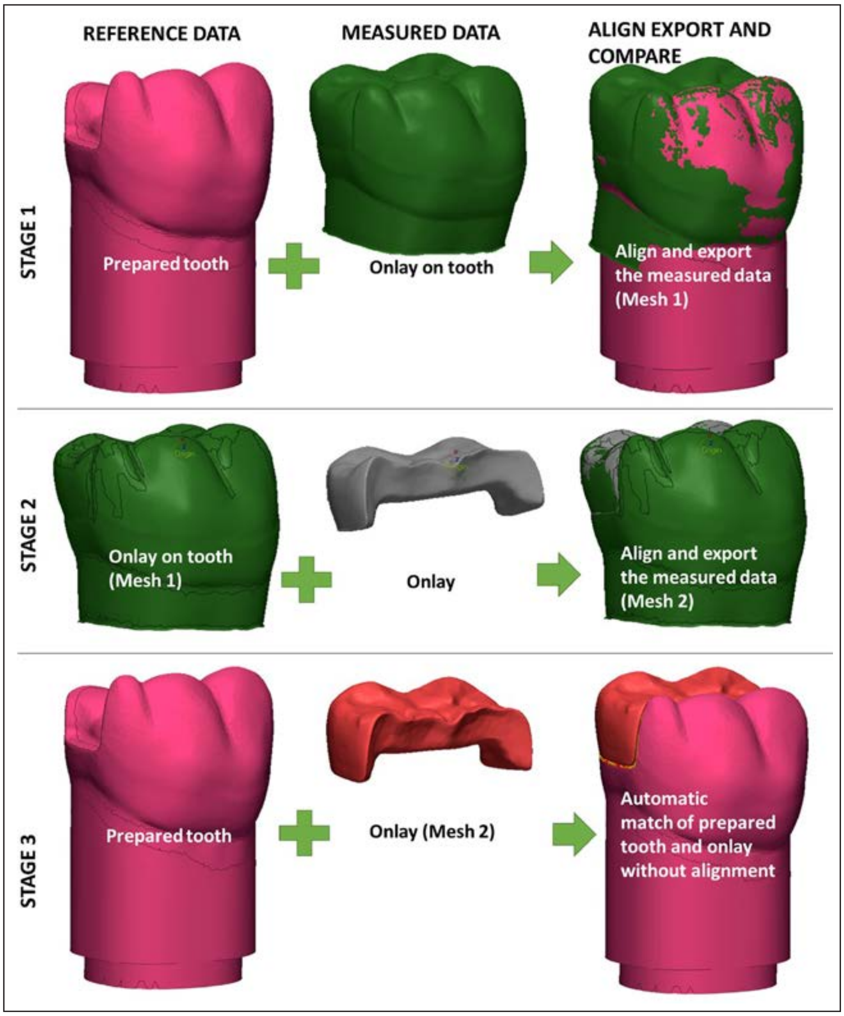

Fig 5 Stages of TSP for analyzing the intaglio surface adaptation of onlay restorations.

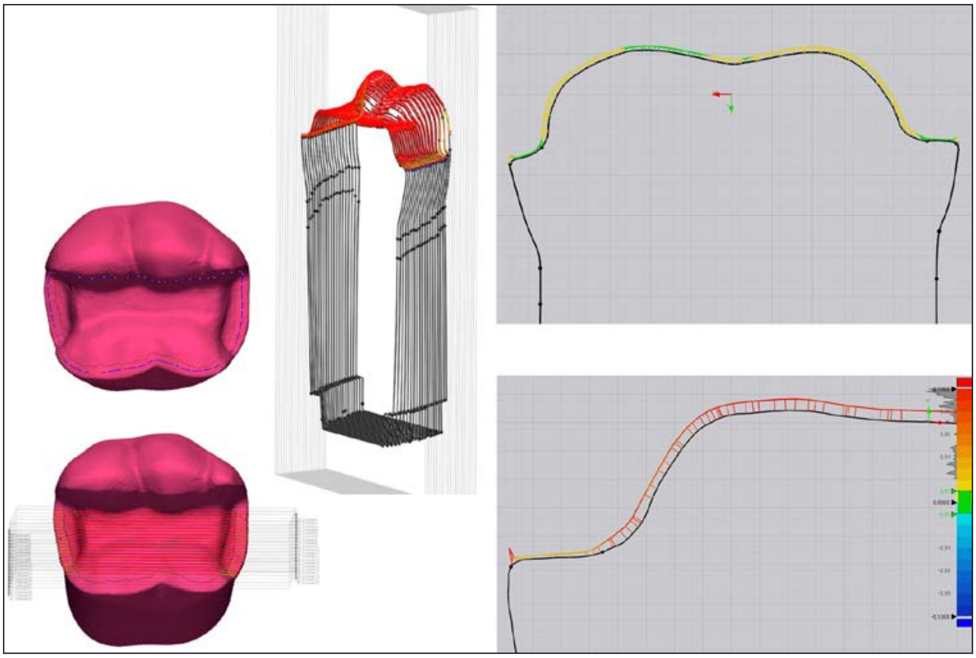

Fig 6 TSP was used to evaluate the intaglio surface adaptation and marginal integrity. The average distance between the cavity and intaglio surface of the restoration was measured at the mesiodistally sectioned plane and repeated for 20 parallel planes with 0.25-mm intervals to assess the adaptation. The average distance between the cavity and restoration was measured on the curve that passes through the entire margin line (0.4 mm inside from the outer surface) to analyze the marginal integrity.

Table 1 RMS Values for Fabrication Trueness of Overall and Intaglio Surfaces, Intaglio Surface Adaptation, and Marginal Integrity for Each Group

	Trueness		Intaglio surface adaptation	
Group	Overall surface	Intaglio surface		Marginal integrity
AM-D	82.5 ± 12.42 μm^{A}	17.7 ± 4.71 μm^{B}	87.3 ± 8.1 μm^{A}	42.6 ± 9.49 μm^{A}
AM-I	51.2 ± 2.58 μm^{B}	19.7 ± 1.85 μm^{B}	127 ± 14.16 μm^{B}	65 ± 13.55 μm^{B}
SM	55.6 ± 2.12 μm^{B}	62.0 ± 3.11 μm^{A}	159.3 ± 5.56 μm^{C}	101.9 ± 11.11 μm^{C}

Different superscript letters show significant differences among tested materials ($P < .05$). Data are presented as mean ± SD.

aligned Mesh 2 over the STL of the prepared tooth without additional alignment. Then, 20 parallel planes (0.25-mm intervals) were created in the mesiodistal direction, and 2D comparison was done to measure the average distance between the cavity and restoration. The adaptation was evaluated from the discrepancy results (see Fig 5). For the marginal integrity evaluation, a curve that passes through the entire margin line (0.4 mm inside from the outer surface) of the tooth and restoration was created using with "Curves > Spline tools" in the software. Then, the deviation between both curves was calculated, which provided data for marginal integrity (Fig 6).

Descriptive statistics were calculated, including means and SDs for the RMS values and average distance measurements. Based on the data normality tested by Kolmogorov-Smirnov method, one-way ANOVA and post hoc Tukey honestly significant difference tests were performed using a statistical software program (SPSS version 22.0, IBM), with a significance level (α) of .05.

RESULTS

Table 1 and Fig 7 list the means and SDs of the RMS values for all regions of the onlay restorations. The mean RMS values of the fabrication trueness of overall and intaglio surfaces, intaglio surface adaptation, and marginal integrity of the onlay specimens varied significantly among the groups (all $P < .001$). When the overall surface trueness was considered, the AM-D group had higher RMS values than SM and AM-I groups (both $P < .001$), whereas SM and AM-I groups showed similar trueness ($P = .255$). In terms of intaglio surface trueness, the SM group had higher RMS values than AM groups (both $P < .001$), whereas there was no statistical difference between the two AM groups ($P = .284$). The SM group also had the highest deviation of average distance measurements for intaglio, surface adaptation, and marginal integrity (both $P < .001$), whereas the AM-D group had the lowest deviation among the groups ($P < .001$).

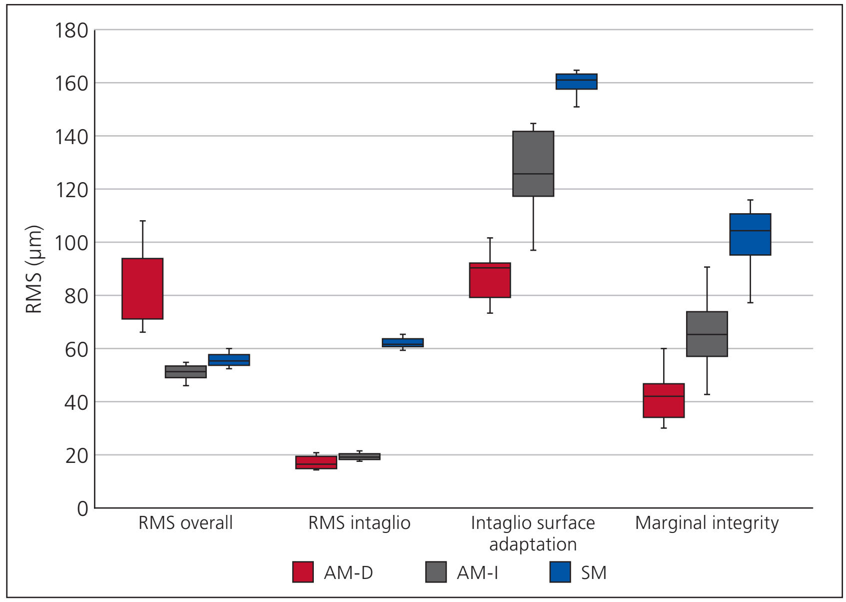

Fig 7 Box-plot of the RMS values (µm) measured at overall and intaglio surfaces, average distance deviations for intaglio surface adaptation, and marginal integrity.

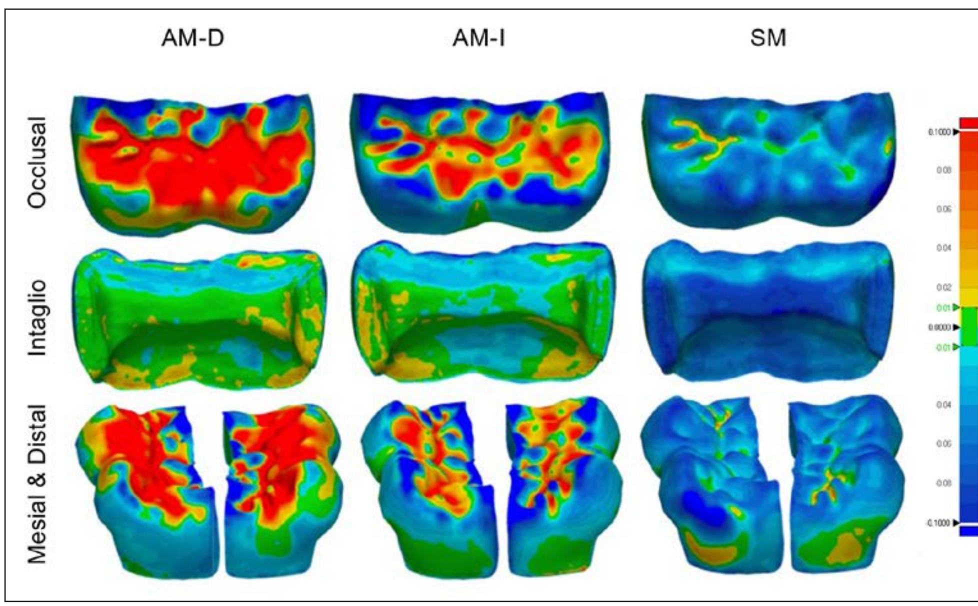

Fig 8 Color deviation maps presented by superimposing TO-STL files over the DO-STL files. Using +100 µm and –100 µm as critical deviation values, the red color shows overcontoured areas, while the blue color shows undercontoured areas. A nominal deviation of +10 to –10 µm was the tolerance level, shown as the color green, indicating acceptable areas.

A color-deviation map (Fig 8) confirmed that the external surfaces of AM groups were overcontoured (red) in the grooves or fissures and undercontoured (blue) in the cuspal region. On the contrary, the grooves and fissures of SM group were within the nominal deviation (green) or slightly overcontoured (light yellow). The cuspal region of the SM group was slightly undercontoured (light blue). In terms of intaglio surface trueness, the AM groups were within the nominal deviation in most of the area, with some overcontoured (yellow) or undercontoured (light blue) areas near the restoration margins. However, the SM group onlays were undercontoured (blue) in most of the tested region.

DISCUSSION

Based on the present findings, the AM-D group showed the highest intaglio surface trueness, intaglio surface adaptation, and marginal integrity among the three groups. The SM group had the highest external surface trueness. The AM-I group was comparable to AM-D group in terms of intaglio surface trueness but had worse adaptation and marginal integrity than AM-D. Therefore, all three null hypotheses were rejected. Color-deviation maps confirmed that the intaglio surface adaptation of AM groups was within the nominal deviation (< 10 µm in most regions). The SM onlays had undercontoured intaglio surfaces, which may increase the cement layer from the original design.

In clinical situations, the dimensional accuracy and marginal fit are crucial for the success of a restoration.[20–24] The dimensional accuracy is affected by different factors, such as the restorative material, fabrication method, and tooth preparation quality.[21,34,35] Any factor responsible for low dimensional accuracy may lead to a higher risk of microleakage, secondary caries, and pulp inflammation.[21,22] The literature lists an acceptable clinical gap range of 50 to 120 mm.[22,24] Therefore, the AM-D and AM-I onlay results were in an acceptable range, but the SM onlay results exceed this range. When intaglio surface adaptation and marginal integrity were considered, the SM group showed the highest average distance measurement, whereas the AM-D group had the lowest. An increased marginal discrepancy in the SM group may lead to an increase of cement layer, which may be associated with higher change of cement layer dissolution in the oral cavity, secondary caries, hypersensitivity, and pulpal or periodontal inflammation.[21,34,35] In addition, a poor intaglio surface adaptation can lead to lack of restoration retention.[21–23]

In the present study, the AM-D group had significantly higher overall surface RMS values than the SM group. The reason for this difference may be the external surface; compared with SM onlays, the external surface of AM onlays were covered with supports. As shown on the color map, removal of supports can lead to over- or undercontoured areas, which can affect the trueness of the external surface. This may also explain the higher deviation in AM-D onlays and lower deviation in AM-I onlays. Higher deviations may lead to tighter or open interproximal or occlusal contacts, which would lead to chairside adjustments for an optimal fit. Therefore, it can be speculated that AM-D onlays may require more chairside time for occlusal adjustments. Contrarily, undercontouring was significantly dominant on the occlusal surface of SM onlays, except for sites with grooves and fissures, which may lead to open occlusal contacts. AM onlays had significantly lower RMS values at intaglio surfaces than SM onlays, whereas AM-D and AM-I had similar values. Therefore, AM onlays showed higher intaglio surface trueness. Those differences could be considered small and may lead to a similar clinical fit.

A limitation of the present study was the use of only one type of 3D-printing and milling unit; different units may lead to other results. Another limitation of this study is the use of only one type of onlay cavity preparation. Testing other cavity preparations may lead to different accuracy and adaptation results. This in vitro study only tested the accuracy and the fit of manufactured onlays and did not evaluate the mechanical properties of the materials in the form of indirect restorations. To validate the clinical fit and the dimensional accuracy of the onlays, further randomized and controlled clinical trials should be performed.

CONCLUSIONS

Additively manufactured definitive onlays showed lower overall trueness than additively manufactured interim onlays and subtractively manufactured definitive onlays. However, additively manufactured definitive onlays presented high intaglio surface trueness, intaglio surface adaptation, and marginal integrity.

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G.Ç., D.Y and B.Y. conceptualized the study; G.Ç., D.Y., D.S., and B.Y. performed the methodology; software, M.E.G. worked on software; G.Ç. and B.Y. validated data; M.E.G performed formal analysis; G.Ç., M.E.G., D.S, D.Y. performed investigations; M.E.G and H.Y curated data; D.S, G.Ç, M.E.G., and H.Y prepared the original draft; H.Y., M.S., and B.Y. reviewed and edited the article; G.Ç. worked on visualization; M.S. and B.Y. supervised; G.Ç. and B.Y. were project administrators, G.Ç acquired funding. All authors read and agreed to the published version of the manuscript.

The data that support the findings of this study are available from the corresponding author upon reasonable request. The authors declare no conflicts of interest.

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