Manufacturing Accuracy, Intaglio Surface Adaptation, and Survival of Additively and Subtractively Manufactured Definitive Resin Crowns After Cyclic Loading: An In Vitro Study

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Purpose: To assess the manufacturing accuracy, intaglio surface adaptation, and survival of resin-based CAD/CAM definitive crowns created via additive manufacturing (AM) or subtractive manufacturing (SM). ***Materials and Methods:*** A maxillary right first molar crown was digitally designed and manufactured using AM hybrid resin composite (VarseoSmile Crown Plus, Bego [AM-HRC]), AM glass filler–reinforced resin composite (Crowntec, Saremco Dental [AM-RC]), and SM polymer-infiltrated ceramic (Vita Enamic, VITA Zahnfabrik [SM-PICN]). Manufacturing accuracy (trueness and precision) was assessed by computing the root mean square (RMS) error (in µm; n = 15 per material). Intaglio surface adaptation was assessed by calculating the average gap distance (µm). Ten crowns from each group were cemented on fiberglass-reinforced epoxy resin dies and cyclically loaded to simulate 5 years of functional loading. One-way ANOVA, post hoc Bonferroni comparison tests, and Levene's test were used to analyze the data ($\alpha = .05$). ***Results:*** AM-RC had higher overall trueness than AM-HRC and SM-PICN ($P \leq .05$), whereas the trueness of AM-RC on the external surface was similar to that of SM-PICN ($P = .99$) and higher than AM-HRC ($P = .001$). SM-PICN had lower precision than AM-RC and AM-HRC overall and at internal occlusal surfaces ($P \leq .05$). Overall intaglio surface adaptation was similar between all groups ($P = .531$). However, for the axial intaglio surface, AM-RC and AM-HRC had higher adaptation than SM-PICN ($P \leq .05$). All tested crowns survived the cyclic loading simulation of 5 years clinical use. ***Conclusions:*** AM-RC showed high manufacturing accuracy and adaptation. The tested resin-based CAD/CAM materials demonstrated clinically acceptable manufacturing accuracy and simulated medium-term durability, justifying the initiation of clinical investigations to determine their potential implementation in daily clinical practice. *Int J Prosthodont 2024;37(suppl):s175–s185. doi: 10.11607/ijp.8976*

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Additive manufacturing (AM) has experienced a significant surge in popularity for the production of definitive dental restorations. This has been driven by factors such as cost-effectiveness, faster production, less material waste, and the ability to produce complex shapes compared with subtractive manufacturing (SM).[1] Recently, 3D-printed resin-based materials intended for definitive restorations have been introduced.[2] These resins vary in composition[3,4] and include hybrid resin composite (VarseoSmile Crown Plus, Bego),[5,6] glass filler–reinforced resin composite (Crowntec, Saremco Dental), and urethane acrylate–based resins (Tera Harz TC-80DP, Graphy; C&B Permanent, ODS). Their use is increasing in parallel with research showing that they provide results comparable to those found with SM resin composites and hybrid resin composites.[3,4] The SM polymer-infiltrated ceramic network is still commonly used for the fabrication of tooth- and implant-supported restorations because it combines the advantages of ceramics and resin composites.[7–9] Nevertheless, not enough evidence has been amassed to definitively establish the acceptable medium-term durability, manufacturing accuracy, and intaglio surface adaptation of AM for definitive dental restorations.

Manufacturing accuracy and intaglio surface adaptation play a pivotal role in the clinical success of tooth-supported fixed dental prostheses. Intaglio surface adaptation refers to the precise fitting of the inner surface of a dental crown to the surfaces of the prepared tooth structure. This adaptation is essential for proper seating of the crown, which in turn promotes stability, retention, and resistance. A well-adapted intaglio surface minimizes the risk of open margins (marginal gaps), thus contributing to the overall success and longevity of the dental restoration.[10–12] Misfit at the crown margin can increase the risk of cement washout at the margin and axial walls, leading to issues like microleakage, plaque accumulation, and associated complications, such as secondary caries, pulpitis, and periodontal diseases.[10–12] Furthermore, a larger internal gap may increase the risk of restoration fracture and limit long-term survival.[13] Traditionally, the survival of dental materials in vitro is studied via cyclic loading. This technique allows for the simulation of repetitive forces or stress patterns that occur in real-life situations within the mouth. This involves applying loads to a dental material repeatedly over a period of time to mimic conditions induced by normal chewing.

While some previous studies reported on the marginal gap and/or fracture resistance of AM implant–supported crowns[4,14] or tooth-supported crowns,[15–19] others reported on the manufacturing accuracy and/or intaglio surface adaptation of only one type of AM restorative material.[11,20,21] Thus, despite AM's growing popularity, there is insufficient comparative research on AM and subtractive manufacturing (SM), and studies are needed that compare the manufacturing accuracy, intaglio surface adaptation, and mid- or long-term survival of AM crowns to those of SM crowns under identical study conditions.

Therefore, this study aimed to evaluate the manufacturing accuracy, intaglio surface adaptation, and survival of AM resin-based definitive crowns fabricated from hybrid resin composite and glass filler–reinforced resin composites compared with SM crowns made of polymer-infiltrated ceramic network material. The null hypotheses were that *(1)* material type would not affect the manufacturing accuracy or the intaglio surface adaptation of resin-based definitive crowns, and *(2)* the survival of the AM and SM resin-based definitive crowns would not be different after cyclic loading.

MATERIALS AND METHODS

Specimen Preparation

A maxillary right first molar typodont tooth with a 1-mm-wide chamfer finish line was digitized using a tactile scanner (Procera Forte, Nobel BioCare). The standard tessellation (STL) file of this scan was imported into a dental design software (Zirkonzahn.Modellier, Zirkonzahn), and a virtual die of the typodont tooth was generated (reference STL file for the die [RD-STL]). A complete coverage crown for resin composite was designed with the following parameters: a 30-µm cement gap starting 1 mm from the margin, additional spaces of 20 µm for the axial and radial surfaces, 1.5-mm minimal thickness, and a 0.1-mm horizontal and vertical crown margin.[3,22] This design was saved and exported to manufacture crowns and to further use as a reference STL file for the trueness analysis (RC-STL). With this reference STL file, a total of 45 crowns were fabricated either additively or subtractively from three different materials: AM hybrid resin composite (VarseoSmile Crown Plus [AM-HRC]), AM glass filler–reinforced resin composite (Crowntec [AM-RC]), and an SM polymer-infiltrated ceramic network material (Vita Enamic, Vita Zahnfabrik [SM-PICN]) (Fig 1). One experienced operator (G.C.) performed all crown manufacturing processes.

Sample Size Calculation

The sample size for the trueness and intaglio surface adaptation test (n = 15 per material) was determined based on a priori power analysis (95% statistical power, 95% CI, and effect size of 0.623).[22] The sample size for the survival test (n = 9 per material) was determined based on a priori power analysis (95% statistical power, 95% CI, and effect size of 0.524).[23] However, 10 crowns were tested per material for the survival analysis, and 15 crowns were tested for the trueness and intaglio surface adaptation.

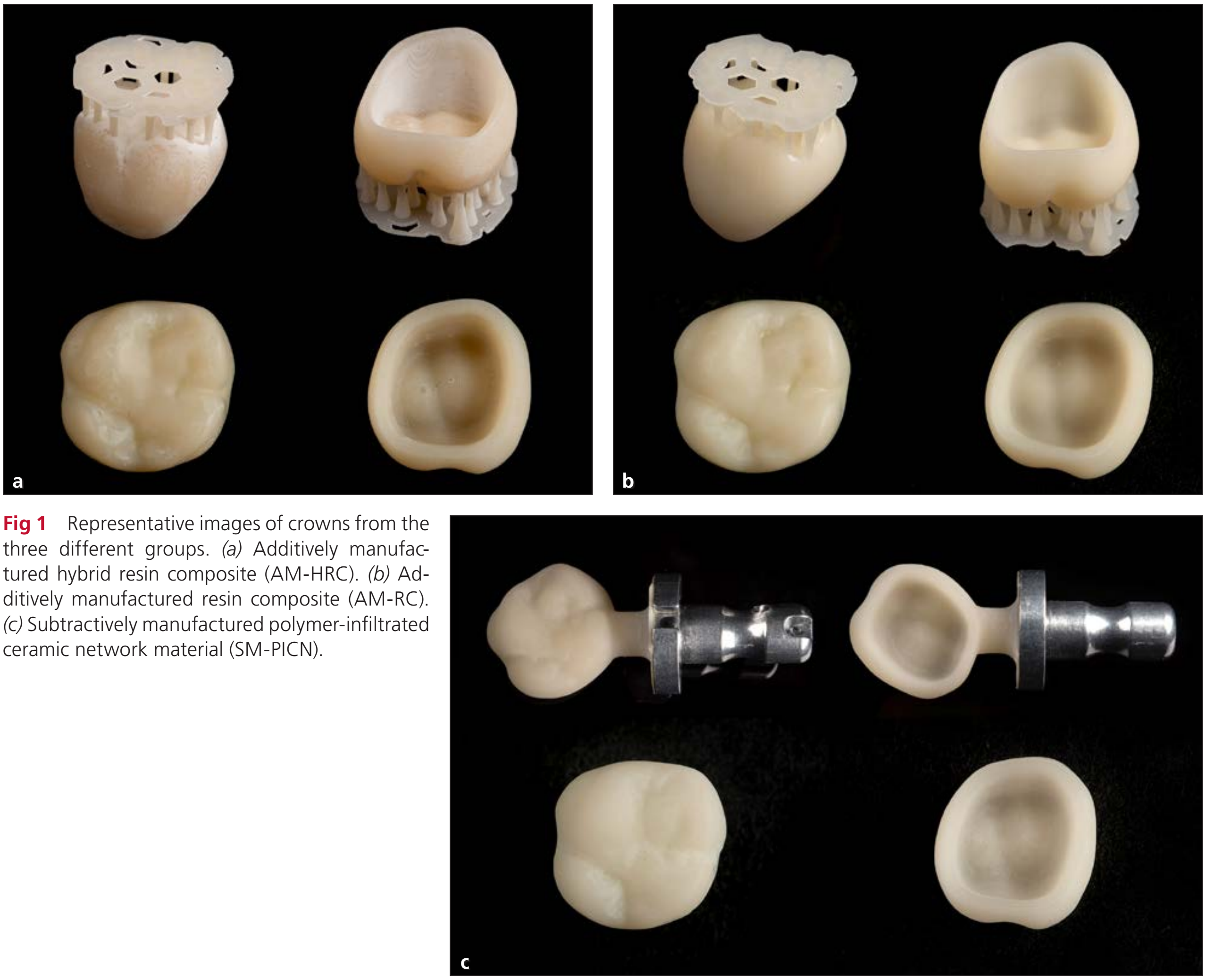

Fig 1 Representative images of crowns from the three different groups. *(a)* Additively manufactured hybrid resin composite (AM-HRC). *(b)* Additively manufactured resin composite (AM-RC). *(c)* Subtractively manufactured polymer-infiltrated ceramic network material (SM-PICN).

Additive Manufacturing Protocol

To fabricate the AM crowns (AM-HRC and AM-RC), RC-STL was imported into the nesting software of a digital light processing (DLP) 3D printer (Composer v1.3, Asiga). The crowns were positioned vertically, with the occlusal surface facing the build platform. The support structures were created automatically and controlled to be removed or added as needed. This adjusted structure was duplicated 15 times per material for standardization. Then, AM crowns were printed using a DLP printer (MAX UV, Asiga) with the relevant resin. After manufacturing, the printed crowns were post-processed. AM-HRC crowns were ultrasonically cleaned with ethanol solution (95% Ethanol Absolut, Grogg Chemie) for 3 minutes followed by an additional 2 minutes of cleaning using a fresh ethanol solution. To remove any remaining unpolymerized resin, ethanol solution was sprayed on the crowns. After washing, the crowns were allowed to air dry, and the support structures were removed using a carbide instrument (CX78MF, Jota) under magnification loupes (EyeMag Pro ×3.5, Carl Zeiss). Then, airborne particle abrasion was performed on the crowns with 50-µm glass beads (Rolloblast, Renfert) at 1.5-bar pressure to remove the whitish coating layer that had formed after cleaning. AM-RC crowns were first cleaned using a cloth soaked in the same ethanol solution (95% Ethanol Absolut). Then, any unpolymerized residual resin was removed using a cotton swab, and the crowns were dried using an air syringe. The support structures were cut, as done for the AM-HRC crowns. The crowns were polymerized with the presence of nitrogen oxide gas in the polymerization unit (Otoflash G171, NK Optik): two exposures of 1,500 flashes for AM-HRC[14] and 2,000 flashes for AM-RC[4,24] on each surface.

Subtractive Manufacturing Protocol

SM-PICN crowns were wet-milled using a five-axis milling machine (PrograMill PM7, Ivoclar) after importing and nesting the RC-STL file in the relevant nesting software (PrograMill CAM v.4.2, Ivoclar). After milling, the support structures were cut with a green wheel abrasive (622.GRN, Jota) under the magnification loupes. The

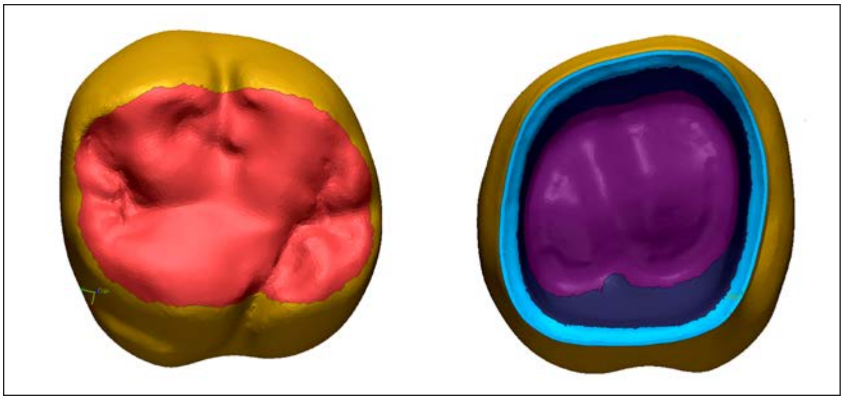

Fig 2 Digitally segmented reference STL file (RC-STL) for manufacturing trueness analysis of the external *(yellow)*, external occlusal *(red)*, intaglio axial wall *(navy blue)*, internal occlusal *(purple)*, and marginal *(turquoise)* surfaces.

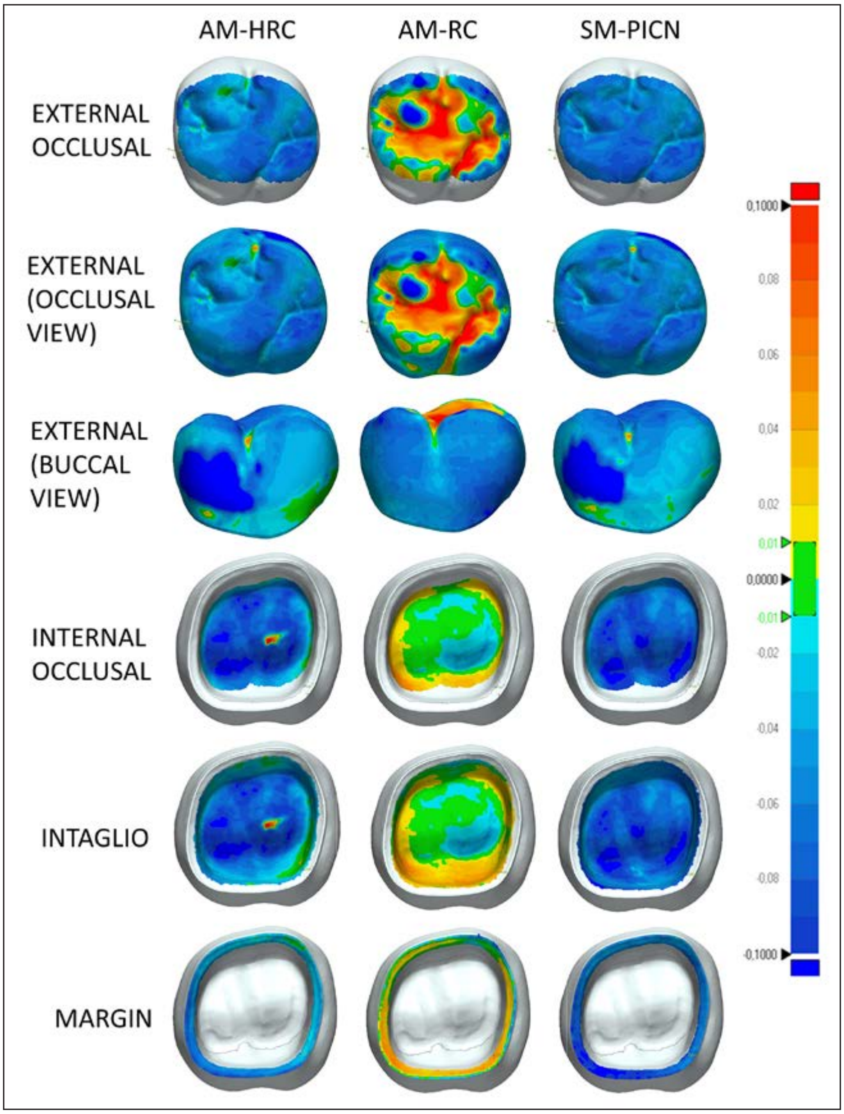

Fig 3 Color deviation maps for the manufacturing trueness. When the deviation values fall outside the range of ±100 µm, a red color indicates areas that are overcontoured and a blue color indicates areas that are undercontoured. A nominal deviation of ±10 µm is considered within the acceptable tolerance threshold, which is shown by the color green.

crowns were then steam cleaned, dried, and stored in a lightproof box and scanned within 48 hours of being manufactured.

Manufacturing Accuracy Analysis

For the manufacturing accuracy analysis, the entire surface of the crowns (both intaglio and external) was scanned using an intraoral scanner (Trios 3, 3 Shape) under ambient light conditions. The scanner was calibrated before each scanning, and a single operator (P.M.) performed the scans. After checking for any errors, the scans were saved as test scan STL files (TC-STLs). To analyze the manufacturing accuracy (trueness and precision), a 3D inspection software program (Geomagic Control X 2022.3, 3D Systems) was used. Manufacturing trueness was defined by the average root mean square (RMS) error variation (mean) between the reference file and the digitized specimens, and manufacturing precision was identified as the RMS error discrepancy within each group (SD). The reference STL file (RC-STL) was imported into this software, moved to the reference data, and digitally segmented into five regions to further analyze deviations at the external occlusal, external, internal occlusal, intaglio, and marginal surfaces (Fig 2) with the software's "region" tool. This file was saved as a reference template to further inspect 3D deviations of all crowns by superimposing with this file. Then, the test scan STL file (TC-STL) of each crown was imported as measured data and an initial alignment was done followed by a best-fit alignment. After superimposition, the software's "3D compare" tool was used to generate color difference maps (± 100 µm maximum/minimum deviation values and 10-µm tolerance range) for the quantitative (mean ± SD) evaluation of the 3D deviations (Fig 3). The 3D deviation was analyzed using the RMS method.[8] A low RMS value indicates a high level of trueness between the reference and test scans.[25] For each crown, RMS values were calculated for six different surfaces: overall, external occlusal, external, internal occlusal, intaglio, and marginal surfaces. For these surfaces, previously segmented regions were selected using the "use selected data only" tool while 3D comparison was done. This 3D analysis was repeated for all crowns, and absolute values of the calculated RMS values (μm) were used for the statistical analyses.

Intaglio Surface Adaptation Analysis

For the intaglio surface adaptation analysis, first a modified triple scan procedure (TSP) was used. For this, an additional scan was made. After seating the crowns on the prepared tooth, the crown and die were inserted into the center of a brass rod by placing the tip on the central fossa to apply 2 N of pressure.[26] All tooth surfaces were scanned, the tip was removed, and the occlusal surface was recaptured. STL files of these scans were saved as crown-on-tooth STLs (test crown-on-die STL [TCD-STL]). Then, as the first step, RD-STL was imported as the reference data, and TCD-STL was superimposed over the RD-STL using the software's initial alignment and overall best-fit alignment algorithms (Fig 4). The TCD-STL was then exported as "mesh 1," which allowed the exact position of the TCD-STL relative to RD-STL to be recorded in the spatial coordinate system. In the second step, the "mesh 1" file was imported as the reference data, and the TC-STL file was superimposed over "mesh 1" in the same manner as described in the first step. After this superimposition, TC-STL was exported as "mesh 2." In the third and final step, the software program automatically superimposed "mesh 2" over the RD-STL with its actual spatial position, after RD-STL was imported as the reference and the "mesh 2" file was imported as the measured data. This process was repeated for each crown. Following the triple scan alignment procedure, a total of 32 "sections" were created on the RD-STL using the software's "multiple 2D compare" tool to measure the distance between the crown and the die to evaluate intaglio surface adaptation (average gap distance, μm). These sections were created with a 0.5-mm interval in the buccolingual and mesiodistal directions, resulting in 17 and 15 sections, respectively. The software automatically calculated the average distance between the manufactured crown and die per section. The top 2-mm portion of these sections was defined as "occlusal 2D distance," the portion from this point to the margin was defined "axial 2D distance," and the sum of these measurements was defined as "overall 2D distance" (Fig 5). A total of 6,400 measurements were made, with an average of nearly 200 measurement points in each section, allowing for the calculation of the intaglio surface adaptation between each RC-STL file and RD-STL file. Standardization and calibration of repeated measurements were achieved by replacing different measured data onto the same measurement pathway. All measurements were conducted by a single experienced operator (M.E.G.).

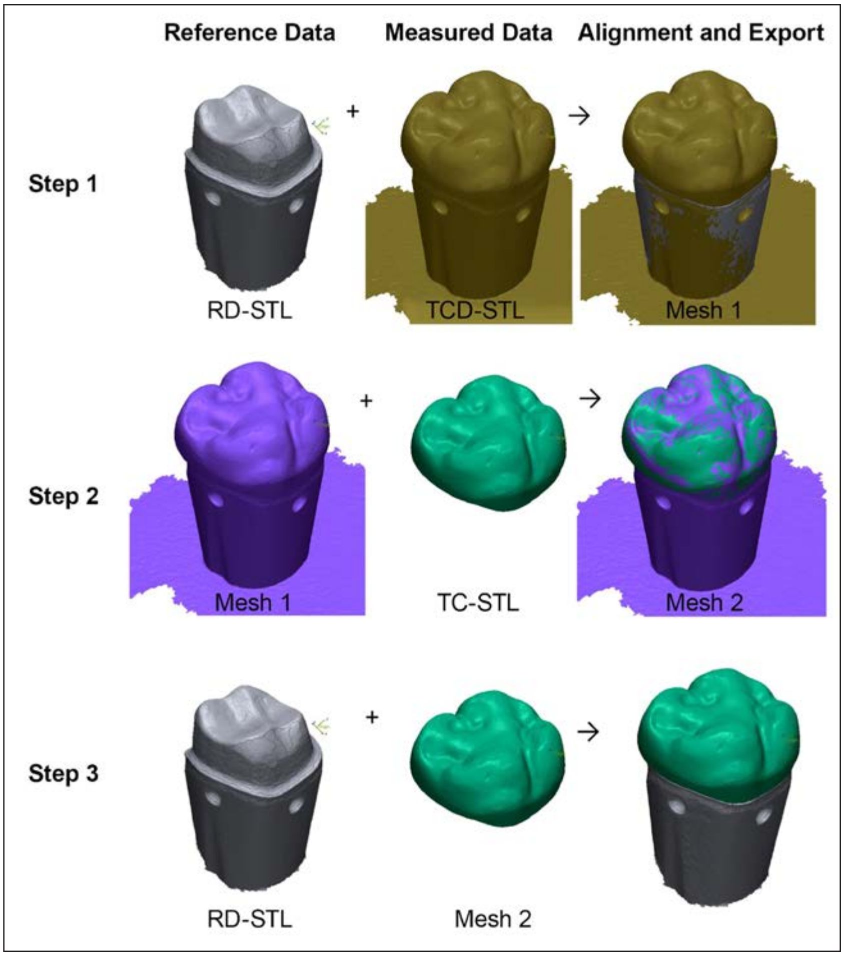

Fig 4 Steps of the TSP for crown restoration intaglio surface adaptation analysis.

Survival Analysis

For cyclic loading and survival analysis, RD-STL was used to fabricate fiberglass-reinforced epoxy resin dies (G10, McMaster-Carr).[27] A total of

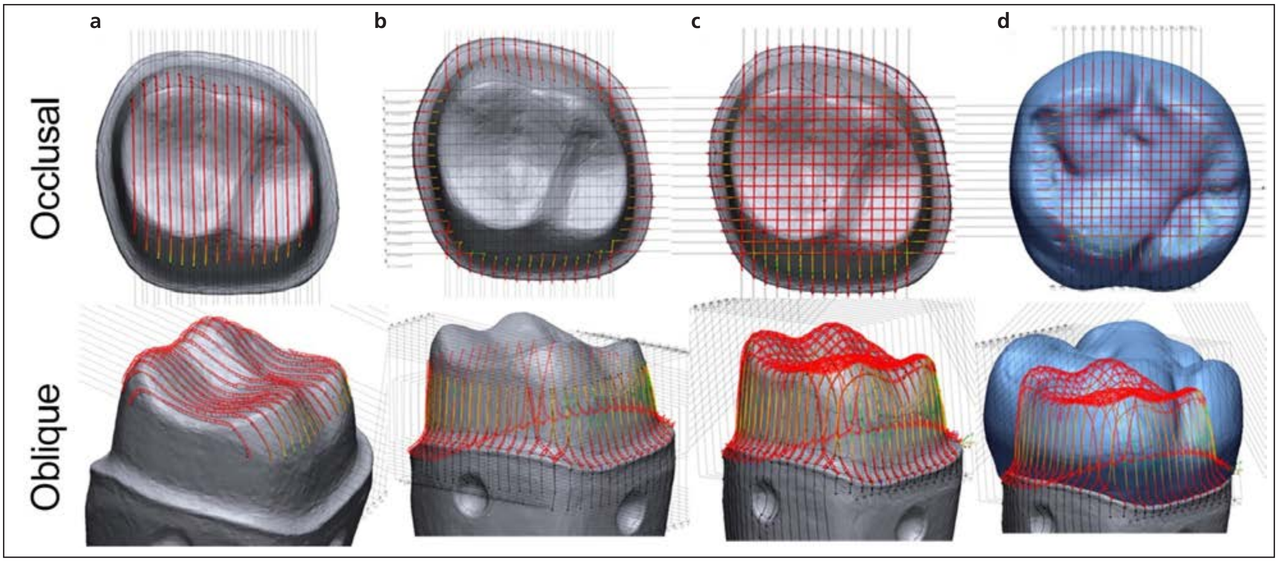

Fig 5 Intaglio surface adaptation analysis by measuring the distance between the crown and the abutment tooth die. The average distance between the crown's intaglio surface and the abutment tooth die was measured at 17 buccolingual sectioned planes and 15 mesiodistally sectioned planes with 0.5-mm intervals. *(a)* The top 2 mm of these sections was defined as "occlusal 2D distance." *(b)* The portion from this point to the margin was defined as "axial 2D distance." *(c and d)* The sum of these measurements was defined as "overall 2D distance."

Fig 6 *(a to c)* Representative images of crowns before *(left)* and after *(right)* cyclic loading.

30 epoxy resin dies were milled using the same milling machine, and 10 crowns from each group were randomly selected (Excel, Microsoft). The crowns were cemented onto the epoxy resin dies using a dual-polymerized resin cement (Panavia V5, Kuraray Noritake). For the surface preparation, epoxy resin dies were airborne particle abraded (110-μm Al_2O_3 for 10 seconds under 2-bar pressure; Cobra, Renfert), steam-cleaned, and dried. A ceramic primer (Clearfil Ceramic Primer Plus, Kuraray Noritake) was applied to the surface and air-dried for 5 seconds, followed by application of an adhesive (Panavia V5 Tooth Primer, Kuraray Noritake) for 20 seconds and gentle air-drying for 5 seconds.

For the cementation of SM-PICN crowns, the intaglio surfaces were etched using hydrofluoric acid (IPS Ceramic Etching Gel, Ivoclar) for 60 seconds, steam-cleaned, and air-dried. For the AM-HRC and AM-RC crowns, intaglio surfaces were airborne-particle abraded (50-μm Al_2O_3 for 10 seconds under 2-bar pressure; Cobra), steam-cleaned, and dried. The same ceramic primer was then applied to all crown intaglio surfaces and gently air-dried for 5 seconds. Then, resin cement was mixed and applied, and the crowns were seated on an epoxy resin die, which was placed under a brass holder for constant load application (2 N) during resin cement polymerization.[28] The resin cement was light polymerized (Bluephase, Ivoclar) for 40 seconds and left under the brass holder for 10 minutes from the start of mixing the resin cement. The crowns were then kept in tap water (37°C) for 24 hours and subjected to cyclic loading (1.2 million cycles, 49-N load, 1.7 Hz) for the simulation of functional loading of 5 years with a built-in-house chewing machine filled with distilled-water (Fig 6).[18,29,30] Following cyclic loading, the crowns were evaluated for any failure using a microscope (M420, Leica) equipped with a light source (CLS 150X, Leica) and a fiber optic illuminator (Intralux150H, Volpi).

Statistical Analysis

The results of Shapiro–Wilk tests indicated that the RMS and the intaglio surface adaptation results were normally distributed ($P > .05$). A one-way ANOVA model was performed to evaluate the effect of the material type on manufacturing trueness and intaglio surface adaptation.

Table 1 Manufacturing Trueness and Precision Values for Each Material and Surface

	AM-HRC		AM-RC		SM-PICN	
	Mean ± SD	Median (Min–Max)	Mean ± SD	Median (Min–Max)	Mean ± SD	Median (Min–Max)
Overall	$81.7^{c} \pm 5.3^{A}$	81.0 (78.1–85.2)	$45.1^{a} \pm 3.2^{A}$	45.8 (41.9–47.7)	$55.7^{b} \pm 14.4^{B}$	52.3 (42.3–67.3)
External occlusal	$110.9^{b} \pm 12.7^{AB}$	112.7 (99.8–118.2)	$61.0^{a} \pm 7.8^{A}$	62.5 (55.2–67.6)	$60.4^{a} \pm 26.6^{B}$	54.6 (41.5–71.3)
External	$84.9^{b} \pm 7.7^{AB}$	83.2 (78.1–90.2)	$53.6^{a} \pm 5.7^{A}$	55.3 (49.2–57.3)	$53.4^{a} \pm 16.5^{B}$	51.1 (41.0–59.1)
Internal occlusal	$97.0^{c} \pm 11.2^{A}$	96.2 (89.4–101.4)	$26.5^{a} \pm 6.4^{A}$	25.8 (21.9–30.4)	$62.9^{b} \pm 23.9^{B}$	60.1 (46.5–77.1)
Intaglio	$72.7^{c} \pm 8.2^{AB}$	72.8 (66.3–76.2)	$25.9^{a} \pm 6.0^{A}$	24.8 (23.1–28.7)	$56.5^{b} \pm 14.8^{B}$	56.1 (47.1–68.5)
Marginal	$90.4^{c} \pm 10.4^{AB}$	95.6 (83.1–98.7)	$29.3^{a} \pm 8.2^{A}$	26.8 (24.6–29.9)	$67.1^{b} \pm 18.5^{B}$	64.2 (55.0–82.0)

Data are shown as RMS error values (µm).
Mean ± SD values are shown as trueness ± precision. For trueness, different lowercase superscript letters indicate significant differences in rows ($P < .05$). For precision, different superscript uppercase letters indicate significant differences in rows ($P < .05$).

Table 2 Intaglio Surface Adaptation

	AM-HRC		AM-RC		SM-PICN	
	Mean ± SD	Median (Min–Max)	Mean ± SD	Median (Min–Max)	Mean ± SD	Median (Min–Max)
Overall	77.5 ± 42.4	92.2 (2.12 to 155)	77.7 ± 43.0	82.3 (11.3 to 134)	91.0 ± 22.8	89.2 (50.9 to 131)
Occlusal	91.5 ± 52.8	100.7 (7.87 to 213)	92.3 ± 51.6	93.6 (1.28 to 158.9)	84.3 ± 30.3	80.9 (33.3 to 138)
Axial	$67.0^{a} \pm 31.7$	74.6 (9.91 to 124)	$60.8^{a} \pm 36.6$	71.6 (–3.79 to 112)	$96.9^{b} \pm 14.3$	95.8 (70.8 to 122)

Values are shown as the average gap distance (µm). Different superscript lowercase letters indicate significate differences in rows ($P < .05$).

Bonferroni post hoc test was used to specifically compare pairs of groups. For precision evaluation, Levene's test was used to assess the homogeneity of the SD of the RMS values in each group. Pearson's correlation analysis was conducted to examine the relationships between manufacturing trueness at intaglio surfaces and 2D distance measurements. Two primary comparisons were derived from the dataset: one between intaglio RMS and overall 2D distance, and the other between internal occlusal RMS and occlusal 2D distance. The level of significance used in the analyses was 5% ($\alpha = .05$). The statistical analyses were performed using SPSS for Windows (version 26.0, IBM).

RESULTS

Table 1 summarizes the descriptive statistics for the manufacturing accuracy of each material and surface. Descriptive statistics related to intaglio surface adaptation between the crowns' intaglio surfaces and the abutment tooth die surfaces are presented in Table 2. Figures 7 and 8 display the box-plot graphs of the manufacturing trueness (RMS, µm) and intaglio surface adaptation (average gap distance, µm), respectively.

One-way ANOVA indicated significant differences in manufacturing trueness among the groups ($P < .05$). AM-RC had higher trueness overall and at the internal occlusal, intaglio, and marginal surfaces compared to AM-HRC and SM-PICN ($P \leq .05$); its trueness at the external and external occlusal surfaces was similar to that of SM-PICN ($P = 0.99$). AM-HRC had the lowest trueness, with significantly higher deviations at all surfaces compared to other materials ($P \leq .05$) (Fig 7). Levene's test revealed significant differences in manufacturing precision among the groups ($P < .05$). SM-PICN had lower precision compared to AM-RC and AM-HRC overall and at internal occlusal surfaces ($P \leq .05$), whereas AM-RC and AM-HRC had similar precision. Moreover, SM-PICN had lower precision compared to AM-RC at the external occlusal, external, intaglio, and marginal surfaces ($P \leq .05$). Therefore, the type of CAD/CAM resin-based material affected manufacturing accuracy of the crowns.

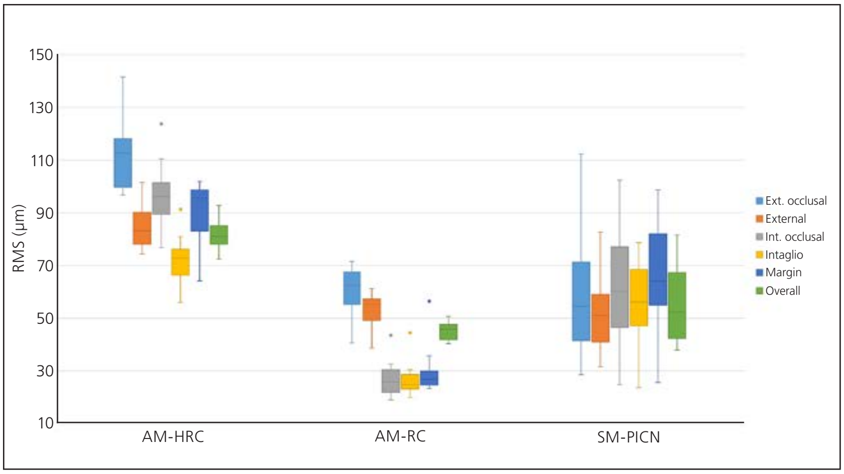

Fig 7 Box-plot graph of the manufacturing trueness (RMS, µm) of the three groups.

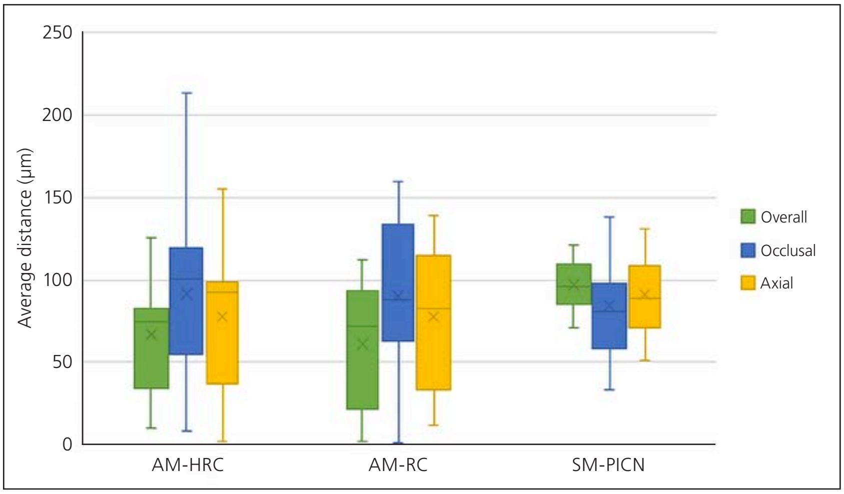

Fig 8 Box-plot graph of the intaglio surface adaptation (average gap distance, µm) of the three groups.

Table 3 Pearson's Correlation Analysis

	Internal occlusal surface RMS vs Occlusal 2D distance	Intaglio surface RMS vs Overall 2D distance
Pearson's *r*	0.057	0.066
df	43	43
P	.354	.667

Regarding the intaglio surface adaptation, average gap distance values were statistically similar between the groups overall (P = .531) and at the occlusal surfaces (P = .873). However, on the axial walls, AM-RC and AM-HRC demonstrated higher adaptation, showing lower average gap distances compared to SM-PICN (P = .003) (Fig 8). Therefore, the type of CAD/CAM resin-based material affected intaglio surface adaptation of the crowns.

Pearson's correlation analysis found no significant correlations between internal occlusal surface RMS and occlusal 2D distance, or between intaglio surface RMS and overall 2D distance (Table 3).

None of the crowns failed during cyclic loading, and there were no microcracks or chipping. Therefore, crowns of all three types of CAD/CAM resin-based material demonstrated medium-term durability.

DISCUSSION

The present study aimed to evaluate the manufacturing accuracy, intaglio surface adaptation, and survival of AM resin-based definitive crowns fabricated from two different resin composites and of SM crowns made from a polymer-infiltrated ceramic network material. The fact that significant differences were found in manufacturing accuracy (trueness and precision) and intaglio surface adaptation on the axial walls not only between AM and SM crowns but also between the two AM materials suggests that the observed differences were attributable not to the manufacturing technique but rather to the inherent properties of the resin materials. Consequently, the first null hypothesis was rejected. In contrast, the type of material did not affect the survival of the crowns, as none of the tested crowns failed during cyclic loading, and therefore, the second null hypothesis was accepted.

Crowns fabricated from AM-RC exhibited the highest manufacturing trueness across all tested materials and assessed surfaces, except for at the external and external occlusal surfaces. Moreover, AM-RC crowns showed higher intaglio surface adaptation at the axial walls compared to SM-PICN crowns. At the external and external occlusal surfaces, AM-RC and SM-PICN crowns showed similar trueness values that were higher than that of AM-HRC. The difference in mean deviation values (RMS) between AM-RC and SM-PICN, compared to AM-HRC crowns, was 31 µm at the external surface and 50 µm at the external occlusal surface. AM-HRC crowns had the lowest trueness at all surfaces, with deviations ranging between 72.7

and 110.9 μm (visually supported with the color maps). The AM-RC crowns showed predominantly green areas with some yellow parts at the margin and internal occlusal surfaces. This can be interpreted as acceptable deviation and high trueness which would be expected to result in higher intaglio surface adaptation.

Although AM-RC crowns showed more green areas at the cusp tips, they had prominent red color on the external occlusal surface, including central fossae and fissures, indicating overcontoured surfaces. This could be attributed to the occlusal placement of printing supports. Despite diligent efforts in support removal, the potential presence of residue poses a disadvantage compared to SM crowns. Although AM-RC and SM-PICN had similar external occlusal surface trueness, the red parts in the color map of AM-RC may require further clinical adjustments, which could potentially increase the chairside time. This result confirms the findings of a previous study, which reported increased deviation on the occlusal surface of AM crowns due to the presence of supports.[7]

AM-HRC and SM-PICN showed predominantly blue color on most of the tooth surfaces, which indicates undercontoured crowns. Clinically, undercontouring may result in lighter occlusal and interproximal contacts and may require either a remake or additional veneering,[7] which is prone to chipping complications. Moreover, varying shades of blue at the intaglio surface may be interpreted as an increased cement gap during manufacturing. The dark blue color was more prominent at the intaglio surface of SM-PICN crowns. This is consistent with the intaglio surface adaptation results of the axial wall, which showed that SM-PICN crowns had a higher average gap distance between the crown and the prepared abutment tooth than the AM-HRC and AM-RC crowns. However, no significant difference was observed in the intaglio surface adaptation results of the overall and occlusal surfaces of tested materials. The mean average gap distance for overall intaglio surface adaptation ranged between 77 and 91 μm. These gap distance values are above the set cement space of 50 μm, which includes 30 μm for the cement (considering reduced friction due to surface roughness) and an additional 20 μm to accommodate potential distortion in the manufacturing process. However, the gap distance remained below the threshold of 120 μm, which is considered the maximum clinically acceptable marginal gap size.[31,32] A study conducted with AM resin definitive posterior single fixed dental prostheses with varying build angles concluded that the RMS error discrepancies of the intaglio surface were 37 μm when the printing angle was 0 degrees.[20] Similar results were obtained with tested AM-RC with the same printing angle, which is lower than the deviations obtained with AM-HRC. Therefore, it could be interpreted that CAD/CAM resin material selection affects the manufacturing accuracy.

Many previous studies have evaluated only intaglio surface trueness[3,22,24]; however, they interpreted lower intaglio surface trueness as an indicator of lower intaglio surface adaptation. One study[33] reported a partial correlation between intaglio surface RMS values and marginal adaptation. However, the authors[33] used a silicone replica technique to assess marginal adaptation and conducted measurements at only 14 points for each tooth. In contrast, in the present study, the intaglio surface adaptation was digitally evaluated at over 6,500 points, and there was no correlation between manufacturing accuracy of the internal surface and intaglio surface adaptation. This could be attributed to the fact that RMS values represent an absolute measure of the whole deviation and do not provide clear information about the direction of the deviation.[34,35] However, changes in the inward or outward direction may result in early contact during seating or an increased cement gap that may affect the intaglio surface adaptation. Therefore, in addition to the evaluation of intaglio surface manufacturing accuracy, intaglio surface adaptation should be evaluated. In the present study, the TSP was used, as it has been commonly used in recent years for the evaluation of the restoration adaptation.[25,36,37]

SM-PICN crowns showed the lowest manufacturing precision overall and at the internal occlusal surfaces, displaying a variability of up to 14 μm. In contrast, AM-RC and AM-HRC demonstrated negligible variation at these surfaces. Moreover, SM-PICN showed lower precision compared to AM-RC at other tested surfaces: external occlusal, external, intaglio, and marginal. The same milling machine and strategy were used for the fabrication of SM-PICN crowns, so this result may be due to the abrasive wear of milling burs with time.[38,39] In contrast, higher precision with AM crowns may be attributed to layer-by-layer manufacturing. In the present study, a DLP printer with a pixel resolution of 62 μm was used. However, different results may be obtained with different printers and printing technologies.

Regarding survival results, none of the tested crowns failed. This finding indicates that the tested crowns may be promising in terms of no micro-crack or chipping complications for potentially up to 5 years. Similarly, Rosentritt et al evaluated the in vitro performance (5-year simulation) of AM and SM definitive crowns; one of the materials tested in that study was also tested in the present study (AM-HRC).[15] The authors reported that the materials showed acceptable in vitro performance, fracture force, and wear for clinical mid-term application. However, the present study findings do not allow for any conclusions to be drawn on wear performance and fracture strength, which could be regarded as a limitation. Restoration and opposing dentition wear, and fracture tests for restorations made of tested materials should be performed in the future to better understand their overall performance during and after aging. Nevertheless, considering that all restorations survived the fatigue tests and their manufacturing accuracy was high overall, the material and manufacturing technique with other collateral benefits can be considered when making decisions for the choice of material. This could include ecologic aspects of the material and manufacturing process; in this respect, additive manufacturing may be considered advantageous for minimizing material waste, fabrication time, and costs.[2]

This study has some limitations that should be considered when interpreting its findings. The use of a single operator in the present study may introduce operator bias. The findings of the present study may not be applicable to all resin-based materials used in AM. Because AM's performance heavily relies on the specific resin material chosen, the external validity of these results is limited when extrapolating to other new resin materials. Therefore, each new AM resin-based material should undergo comprehensive in vitro and in vivo evaluations before being considered suitable for clinical application.[40]

CONCLUSIONS

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

- AM-RC had the highest overall manufacturing trueness and the highest trueness at the internal occlusal, intaglio, and marginal surfaces, whereas AM-HRC had the lowest overall trueness and the lowest trueness at all surfaces.
- SM-PICN had the lowest overall precision and the lowest precision at the internal occlusal surface.
- Intaglio surface adaptation of the tested materials was overall similar and similar at the occlusal surfaces. However, AM exhibited better adaptation at the axial surface when compared to SM.
- All crowns survived cyclic loading that simulated 5 years of clinical use.
- The fact that the resin-based CAD/CAM crowns exhibited medium-term durability and manufacturing accuracies within a clinically acceptable range supports the rationale for conducting clinical investigations to assess their suitability for routine patient care.

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