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RESEARCH AND EDUCATION

Trueness of crowns fabricated by using additively and subtractively manufactured resin-based CAD-CAM materials

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ABSTRACT

Statement of problem. Advancements in digital dental technologies have enabled the use of different resin-based materials that can be fabricated either additively or subtractively. However, knowledge on the fabrication trueness of these materials is scarce.

Purpose. The purpose of this in vitro study was to investigate the trueness of crowns fabricated by using different resin-based computer-aided design and computer-aided manufacturing (CAD-CAM) materials.

Material and methods. A complete crown for a mandibular right first molar with a 30-µm cement space was designed in standard tessellation language (STL) format. This master STL (MC-STL) was used to fabricate 40 complete crowns with 4 different resin-based CAD-CAM materials and either additive (Crowntec [MS]) or subtractive techniques (Brilliant Crios [BC], breCAM.monoCOM [PMMA], and G-CAM [GR]; n=10). All crowns were digitized with an intraoral scanner (CEREC Primescan SW 5.2) to generate their STL files (TC-STLs). MC-STL and TC-STLs were transferred into a 3-dimensional analysis software program (Medit Link v2.4.4), and a trueness (overall, external, occlusal, intaglio occlusal, and marginal) analysis was performed by using the root mean square (RMS) method. The Kruskal-Wallis and Dunn tests were performed to analyze data (α=.05).

Results. The test groups had significantly different deviations on all surfaces ($P\leq.001$). MS crowns had higher overall ($P\leq.007$) and external surface ($P\leq.001$) deviations than GR and PMMA crowns, while the differences between GR and PMMA crowns were not significant ($P\geq.441$). BC crowns had higher external surface deviations than GR crowns (P=.005), higher occlusal deviations than GR and MS crowns ($P\leq.007$), and higher intaglio occlusal deviations than GR and MS crowns ($P\leq.009$). However, BC crowns had lower marginal deviations than MS and GR crowns ($P\leq.018$).

Conclusions. The brand of resin-based CAD-CAM materials affected the trueness of crowns. Additively manufactured crowns (MS) mostly had lower overall and external surface trueness than the other groups. Nevertheless, the deviation values of occlusal, intaglio occlusal, and marginal trueness were generally small; thus, the effect of the tested materials on clinical crown fit may be negligible. (J Prosthet Dent 2022;■:■-■)

Digital technologies have revolutionized prosthodontics,[1-3] and computer-aided design and computer-aided manufacturing (CAD-CAM) systems have been integrated into daily practice by means of subtractive manufacturing[4,5] and, more recently, additive manufacturing.[6,7] Of many available additive manufacturing technologies,[8] digital light processing (DLP) has been commonly used for dental procedures.[9,10] Regardless of the technology, additive manufacturing improved the manufacturing processes by enabling cost-efficient fabrication with less waste and the fabrication of products with more complex geometries.[11-13]

Advancements in CAD-CAM technologies have also diversified the materials that

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Clinical Implications

The clinical fit of complete crowns fabricated by using the tested materials was similar. However, crowns fabricated by using the tested additively manufactured resin might require more chairside adjustments.

can be used either with subtractive manufacturing or additive manufacturing.[14-17] One of the recent advancements in subtractively manufactured restorative materials was the integration of graphene as a reinforcement phase in polymers, including polymethyl methacrylate (PMMA), through nanotechnology.[18] Graphene is a crystalline form of carbon[19] that has favorable mechanical properties[20] which have been reported to improve the properties of PMMA,[16,19,21] and a nanographene-reinforced PMMA, indicated for veneers, inlays, onlays, tooth- or implant-supported crowns, and 3-unit tooth-supported fixed partial dentures, has been marketed.[22] The additive manufacturing of dental products has become more popular given the advantages of this technology over subtractive manufacturing,[8] and additively manufactured composite resins that can be used for definitive prostheses have been recently introduced.[23]

Even though these materials have been indicated for use in definitive prostheses by their manufacturers, the properties of prostheses fabricated by using materials that could affect their clinical success should be broadly investigated. The studies focusing on different properties of nanographene-reinforced PMMA[16,18-21] or additively manufactured composite resins[17,24-28] were not based on the trueness of the manufactured products. Considering that the optimal fit of a prosthesis is correlated with its dimensional accuracy,[29] studies focusing on the trueness of prostheses fabricated with different types of CAD-CAM materials could benefit clinicians. Advancements in digital technologies have also facilitated these analyses, and it is possible to compare a product with its CAD file.[3] Therefore, the aim of the present study was to evaluate the trueness of CAD-CAM crowns made of 4 different resin-based materials that are either additively (1 additively manufactured composite resin) or subtractively manufactured (1 reinforced composite resin, 1 PMMA, and 1 nanographene-reinforced PMMA) by using digital comparison tools. The null hypothesis was that material type would not affect the trueness of crowns fabricated by using different CAD-CAM technologies.

MATERIAL AND METHODS

Figure 1 illustrates the methodology of the present study. A prefabricated titanium abutment with a 1.5-mm-wide chamfer finish line was digitized by using an intraoral scanner (CEREC Primescan SW 5.2; Dentsply Sirona). A complete crown for a mandibular right first molar with a 30-µm cement gap,[7,9,10] 3-mm-thick axial walls, 1.5-mm-thick margins, and 1 mm of minimum occlusal thickness was designed on the standard tessellation language (STL) file of the abutment by using a dental design software program (exocad DentalCAD; exocad GmbH).

The number of specimens in each group was determined based on previous studies investigating the trueness of additively manufactured prostheses that reported significant differences.[8-10,13] This master crown STL (MC-STL) was used to fabricate 40 complete-coverage crowns by using 4 different CAD-CAM materials (Brilliant Crios; Coltène AG [BC], breCAM.monoCOM; bredent [PMMA], Crowntec; Saremco Dental AG [MS], and G-CAM; Graphenano DENTAL SL [GR]). For the fabrication of subtractively manufactured crowns (BC, PMMA, and GR), MC-STL was transferred into a nesting software program (PrograMill CAM V4; Ivoclar AG) and milled with a 5-axis milling unit (PrograMill PM7; Ivoclar AG) (n=10).

For the fabrication of additively manufactured crowns (MS), MC-STL was imported into a nesting software program (Composer; ASIGA) and positioned with their occlusal surface facing toward the build platform. Support structures were generated automatically, and any support on the margin or in the intaglio surface was eliminated manually. This configuration was duplicated 10 times, and the layer thickness was set at 50 µm according to the manufacturer's recommendations.[28] MS crowns were printed by using the proprietary DLP-based 3-dimensional (3D) printer (MAX UV; ASIGA). After printing, the crowns were removed from the build platform, cleaned with an alcohol-soaked (96% Alcohol isopropilico; Quinei Klean) cloth until all unpolymerized resin had been removed, and dried with an air syringe. Crowns were then placed in a xenon polymerization device (Otoflash G171; NK Optik) in an atmosphere of nitrogen oxide gas for 4000 light exposures.[28] After the fabrication of additively and subtractively manufactured crowns had been completed, the support structures were removed with a cut-off-wheel (Keystone Cut-off Wheels; Keystone Industries), and the surface was gently smoothed under optical magnification loupes (EyeMag Pro; Carl Zeiss) at ×3.5 magnification to prevent errors during the alignment procedure. No adjustments were made on the intaglio surfaces (Fig. 2).[7]

A single operator (A.M.R.) digitized all crowns by using the same intraoral scanner to generate the STL files of the crowns (TC-STLs). The intraoral scanner was calibrated before starting the scan of each group, and fatigue-related deviations were minimized as the operator took 5-minute breaks between each group.[30] All scans were performed in

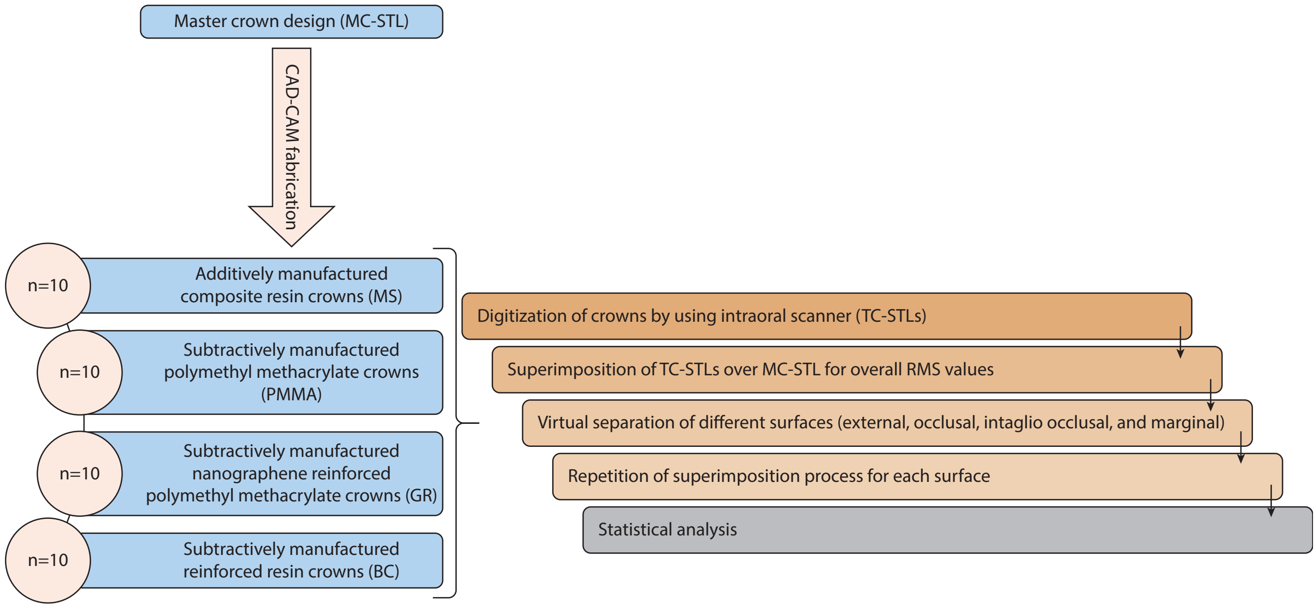

Figure 1. Overview of study. CAD-CAM, computer-aided design and computer-aided manufacturing. BC, Brilliant Crios; CAD-CAM, computer-aided design and computer-aided manufacturing; GR, G-CAM; MS, Crowntec; PMMA, breCAM.monoCOM.

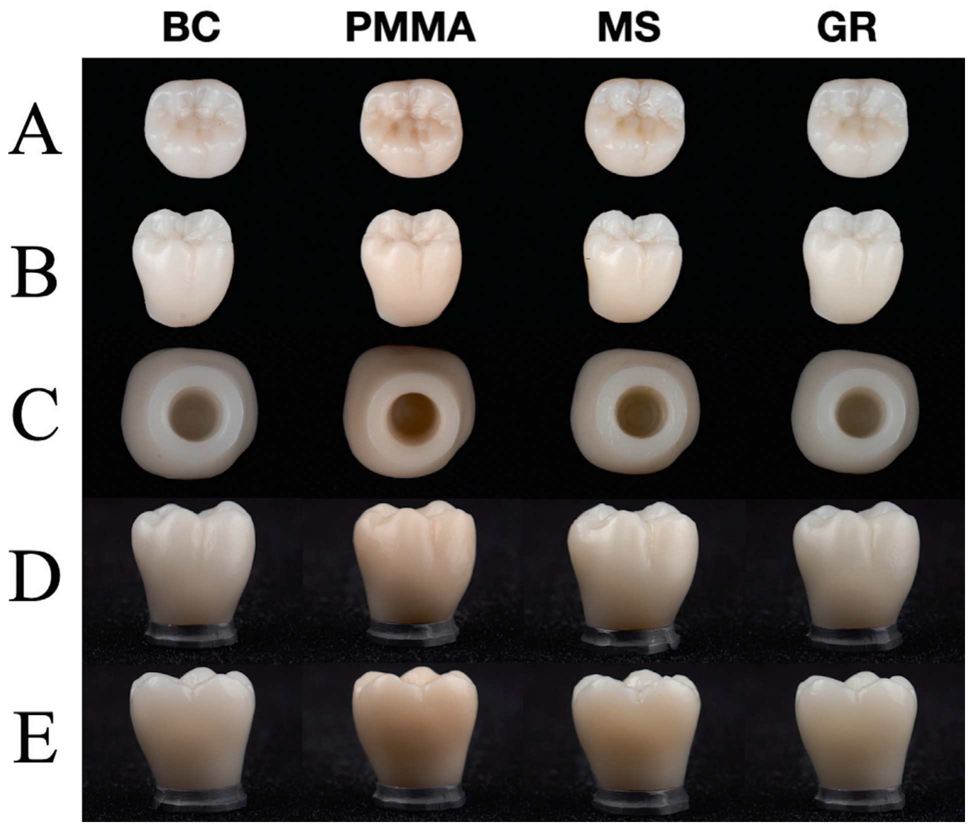

Figure 2. CAD-CAM fabricated crowns. A, Occlusal surface. B, Buccal surface. C, Intaglio surface and margin. D, Buccal view on die. E, Lingual view on die. CAD-CAM, computer-aided design and computer-aided manufacturing. BC, Brilliant Crios; CAD-CAM, computer-aided design and computer-aided manufacturing; GR, G-CAM; MS, Crowntec; PMMA, breCAM.monoCOM.

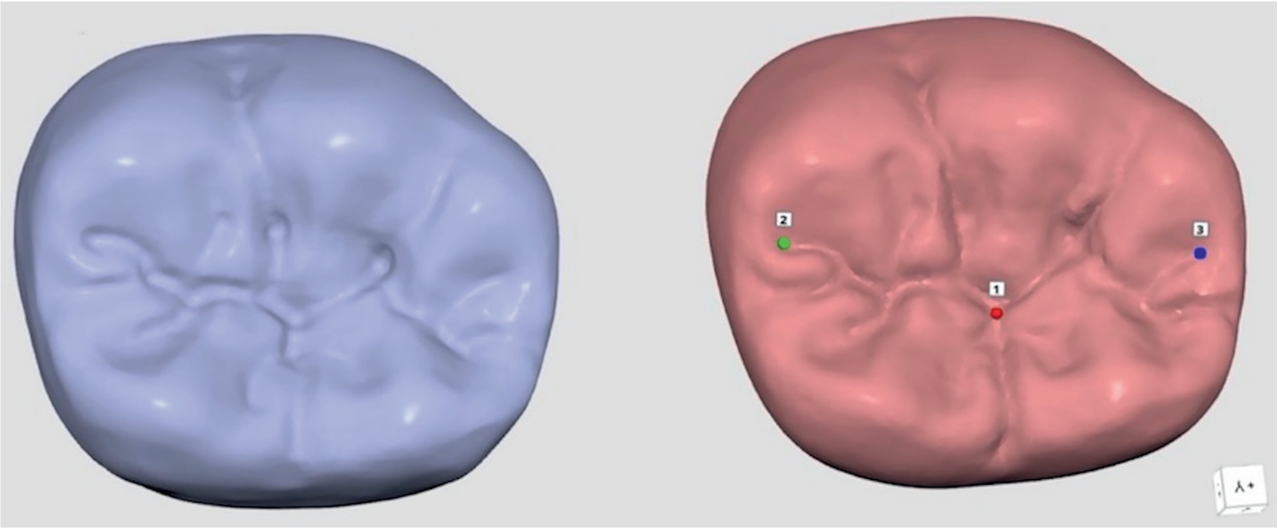

Figure 3. Points selected for superimposition process.

the same temperature and humidity-controlled room as the scan of the titanium abutment.

All STL files (1 MC-STL and 40 TC-STLs) were imported into a 3D analysis software program (Medit Link v2.4.4; Medit).[3,31] MC-STL was selected as the reference, and the comparison tool of the software program was used to superimpose TC-STL over the MC-STL by simultaneously selecting 3 points (1 point on the occlusal, mesial triangular, and distal triangular fossae) on each file (Fig. 3). After superimposition, color maps that represented 3D deviations were generated with the maximum/minimum critical (nominal) values set at +50 μm and -50 μm and the tolerance range set at +10 μm and -10 μm.[9,31,32] The deviation was analyzed by using the root mean square (RMS) method, the square root of the mean square of a set of numbers.[9,31] STL files were imported again for the evaluation of other surfaces (external, occlusal, intaglio occlusal, and marginal). These surfaces were virtually separated, which divided the patterns into 4.[9,32] This superimposition process was repeated for each surface, and RMS values were automatically calculated from the color maps and given either as a positive (overcontoured areas) or a negative (undercontoured areas) value in the software program (Fig. 4). However, absolute values of the calculated RMS values were used for the statistical analyses.

The normality of the data was analyzed by using the Kolmogorov-Smirnov test. Because of the nonnormal distribution, the Kruskal-Wallis and Dunn tests were performed by using a software program (IBM SPSS Statistics v22.0; IBM Corp) (α=.05).

RESULTS

The Kruskal-Wallis tests revealed significant differences among the test groups for all surfaces analyzed (overall P<.001; external P<.001; occlusal P=.001; intaglio occlusal P<.001; marginal P<.001). Table 1 summarizes the descriptive statistics of each material-surface pair. Figure 5 illustrates the boxplot for RMS values (deviations). GR and PMMA crowns had similar overall (P=.441) and external (P=.541) deviations that were lower than those of MS crowns ($P\leq$.007 for overall RMS and $P\leq$.001 for external surface RMS). In addition, BC crowns had deviations similar to those of PMMA (P=.609) and MS (P=.178) when the external surface was concerned and to all groups when the overall RMS values were considered ($P\geq$.052). However, BC crowns had higher external surface deviations than GR crowns (P=.005). For occlusal deviations, MS and GR crowns showed similar results (P>.05) that were lower than those of BC crowns ($P\leq$.007). PMMA crowns had occlusal deviations similar to those of the other groups ($P\geq$.317). While GR crowns had lower intaglio occlusal deviations than BC (P=.001) and PMMA (P=.028) crowns, MS crowns had lower deviations than BC crowns (P=.009). The differences between GR and MS (P>.05), PMMA and MS (P=.198), and PMMA and BC (P>.05) were not significant (P>.05). MS and GR crowns had higher marginal deviations than BC crowns ($P\leq$.018), whereas PMMA crowns had deviations similar to those of the other groups ($P\geq$.119).

DISCUSSION

Significant differences were observed among the test groups for overall deviations and for each surface analyzed. Therefore, the null hypothesis was rejected.

Among the materials tested, MS crowns had significantly higher overall and external surface RMS values than GR and PMMA crowns. In addition, BC crowns had higher external surface RMS values than GR crowns. When color maps were further investigated (Fig. 4), MS

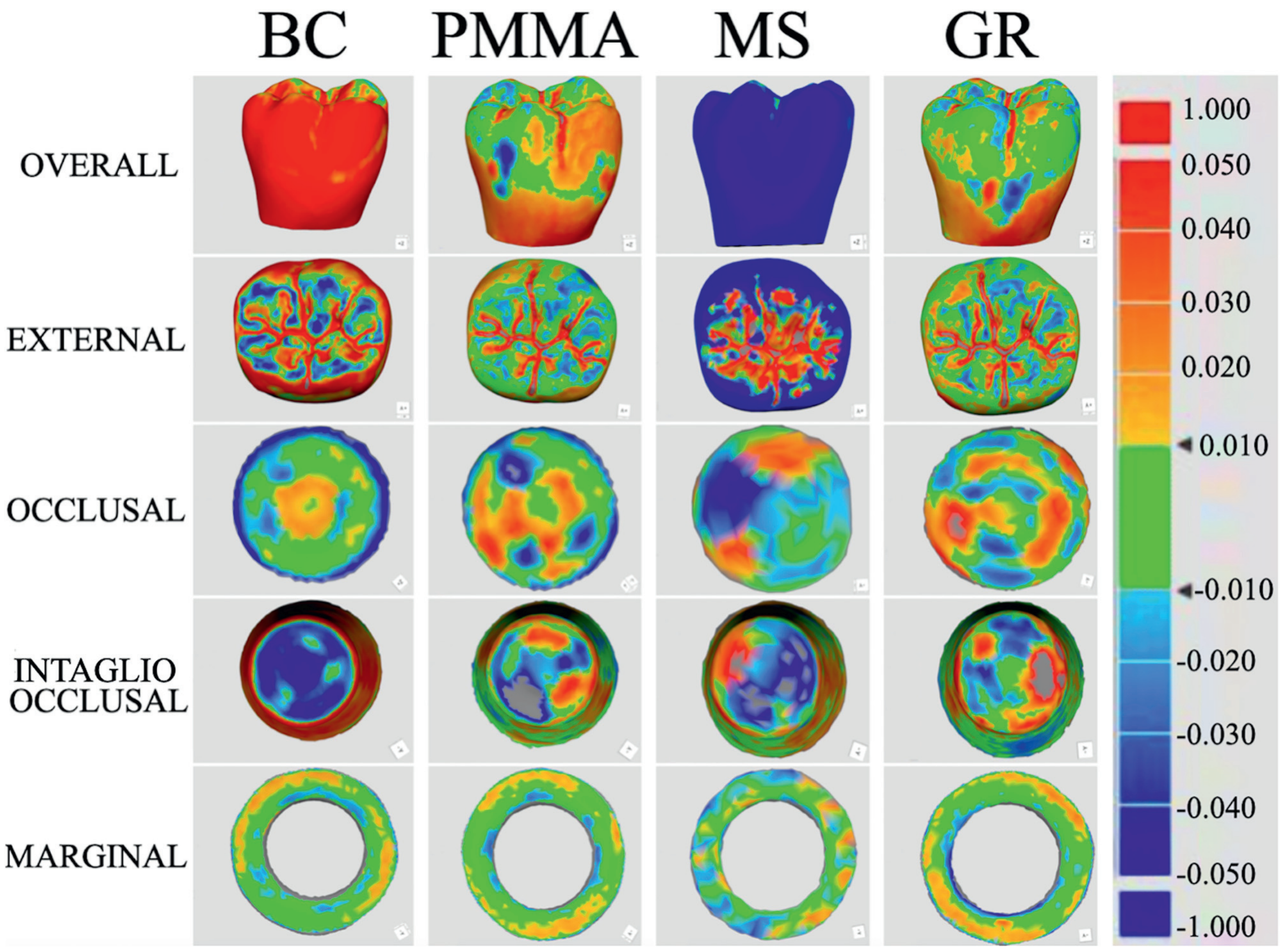

Figure 4. Color maps generated by superimposing TC-STLs over C-STL for each surface. *Red* color indicates overcontoured and *blue* color indicates undercontoured areas considering nominal values set at +50 μm and -50 μm. *Green* color indicates acceptable areas considering tolerance range set at +10 μm and -10 μm. BC, Brilliant Crios; GR, G-CAM; MS, Crowntec; PMMA, breCAM.monoCOM.

Table 1. Descriptive statistics of RMS values (μm) according to each material-surface pair

Material Type	Overall		External		Occlusal		Intaglio Occlusal		Marginal	
	Mean ±SD	Median (Min-Max)	Mean ±SD	Median (Min-Max)	Mean ±SD	Median (Min-Max)	Mean ±SD	Median (Min-Max)	Mean ±SD	Median (Min-Max)
BC	62 ±16	63^{ab} (42-86)	58 ±16	61^{bc} (34-78)	29 ±4	30^{b} (23-35)	31 ±9	33^{c} (15-41)	9 ±1	10^{a} (7-11)
PMMA	83 ±112	46^{a} (36-400)	39 ±12	34^{ab} (29-62)	25 ±5	25^{ab} (15-34)	22 ±6	20^{bc} (16-36)	11 ±1	11^{ab} (9-12)
MS	116 ±5	115^{b} (110-125)	93 ±4	93^{c} (87-98)	20 ±6	21^{a} (9-29)	17 ±2	17^{ab} (14-20)	12 ±1	12^{b} (11-12)
GR	38 ±6	35^{a} (32-50)	31 ±2	31^{a} (28-33)	20 ±5	20^{a} (12-29)	16 ±2	16^{a} (13-19)	14 ±2	14^{b} (10-17)

Surface Type spans all column groups.

BC, Brilliant Crios; GR, G-CAM; MS, Crowntec; PMMA, breCAM.monoCOM. Different superscript letters indicate significate differences in columns ($P<.05$).

differed noticeably from other materials as the blue color, which indicates undercontoured surfaces, was dominant. The undercontoured surfaces may be because of the difference in the manufacturing technique, as MS was the only additively manufactured material tested. Clinically, the undercontour can be interpreted as MS crowns having lighter interproximal contacts than other crowns, which might require a remake. The red color, which indicates overcontoured surfaces, was dominant on the occlusal surface of MS. The overcontouring found on the occlusal surfaces of MS may be because printing supports were positioned occlusally, and even though attention was paid when removing the supports, some support residue may have been left; this was not present with subtractively manufactured crowns. Considering that green was the primary color seen in GR and PMMA crowns and that BC crowns had predominantly blue on their occlusal surfaces, MS crowns may require more

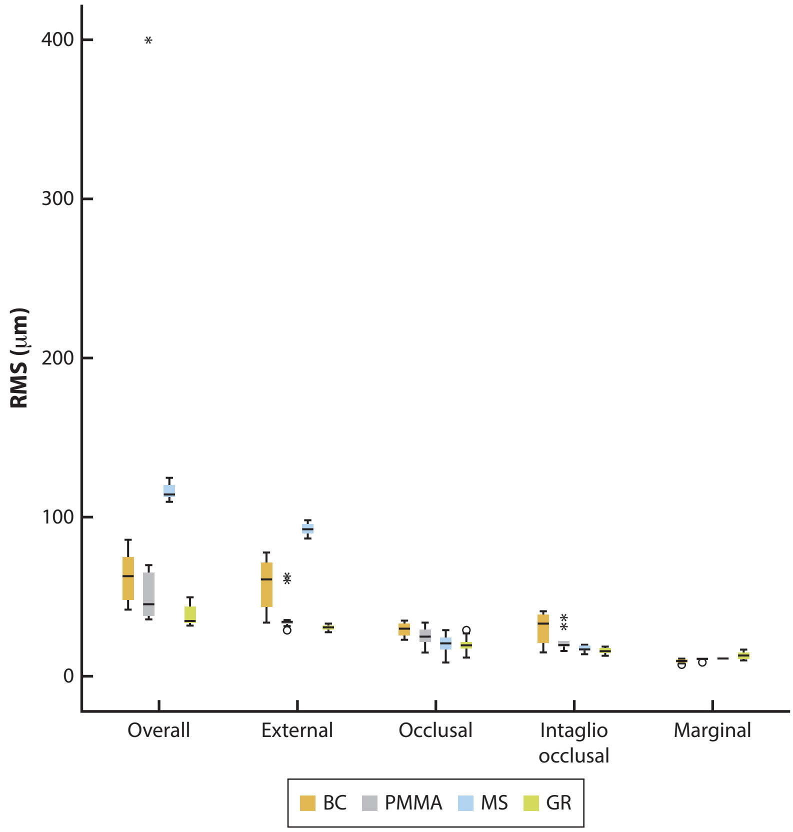

Figure 5. Box-plot graph RMS values (µm) for each material-surface pair. BC, Brilliant Crios; GR, G-CAM; MS, Crowntec; PMMA, breCAM.monoCOM.

chairside time for occlusal adjustments. As for BC crowns, red was the predominant color on the external surface, which may lead to tighter interproximal contacts, as well as poor esthetics because of overcontouring. The higher external surface RMS values of BC crowns compared with those of GR crowns may be associated with their inherent material properties. The manufacturers of these materials have reported their elastic moduli as 10.3 GPa for BC and 3.2 GPa for GR.[33,34] This difference might have led to the easier machinability of GR crowns. Nevertheless, considering that previous studies have reported better mechanical properties[16,18-20] and the fact that GR had deviations overall and on external surfaces similar to those of the PMMA tested in the present study, GR may provide longer clinical service. However, clinical studies are needed to substantiate this hypothesis.

When occlusal and intaglio occlusal surface deviations were evaluated, BC crowns had significantly higher deviations than MS and GR crowns. In addition, PMMA crowns had intaglio occlusal surface deviations similar to those of other crowns, except for GR crowns. Color maps showed that, except for BC crowns, intaglio axial walls of the crowns were predominantly green. However, red was dominant at the axial walls of BC crowns; thus, intaglio adjustments may be required for BC crowns. Nevertheless, the maximum difference in mean deviation values at the occlusal surface was only 9 µm, and the maximum difference in mean deviation values at the intaglio occlusal surface was 15 µm among the materials. In addition, mean marginal RMS values ranged from 9 to 14 µm. Because these differences could be considered clinically small and because the mean deviations of all materials at the occlusal and intaglio occlusal surfaces were generally smaller than the cement space of 30 µm, the clinical fit of the crowns fabricated by using these materials may be similar. However, this interpretation needs support from clinical trials. The intaglio surface trueness of interim crowns fabricated either with additive or subtractive manufacturing has been investigated previously,[5] and subtractively manufactured PMMA crowns had significantly higher deviations for all surfaces tested (overall intaglio, marginal, axial, and occlusal), an outcome that contradicts the results of the present study. Even though both studies used PMMA for subtractive manufacturing, the additively manufactured resin tested in the present study is marketed as a definitive and has a different chemical structure compared with the interim additively manufactured materials.

An IOS, which was reported to have a performance similar to that of a laboratory scanner,[30] was used in the present study to digitize the crowns, as these scanners enable data acquisition of both intaglio and outer surfaces in 1 continuous motion. Even though laboratory scanners have been reported to have a higher accuracy than IOSs,[35] these scanners digitally stitch separate scans of intaglio and outer surfaces with their algorithm, which may have led to amplified deviations.[10] Similar to previous studies on the trueness of additively manufactured prostheses,[8-10] 3-point alignment was used for the superimposition of STL files, while a freeware and the RMS method were used for the trueness analysis. However, different alignment algorithms,[36] 3D analysis software programs,[3] or deviation measurement methods[13] may lead to different results.

Even though significant differences were observed and the number of specimens in each group was based on the results of previous studies,[8-10,13] the absence of a power analysis is a limitation. A single operator performed test scans in the same room and under the same conditions for standardization; different operators[3] and ambient conditions[1,2] may affect the results. Only one 3D printer and resin were used; however, previous studies have reported significant differences between different additively manufacturing techniques[5] and various other parameters such as build angle, layer thickness, laser intensity, and laser speed; the geometry of the supporting structures may also affect the efficiency of additive manufacturing.[9] In addition, 1 type of prosthesis was investigated, and an increased number of retainers or pontics may lead to higher deviations.[6] The trueness of a prosthesis is only one of the parameters that affect clinical longevity. Therefore, in vitro and in vivo investigations of the other mechanical and optical properties of GR and MS, such as their wear resistance, fracture resistance, color stability, and translucency, would broaden the knowledge on the applicability of these materials in clinical situations given that they are relatively new when compared with the other tested materials.

CONCLUSIONS

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

1. Material type had a significant effect on the trueness of crowns.
2. The tested additively manufactured composite resin crowns had overall and external surface deviations that were either similar to or higher than those of subtractively manufactured crowns. Combined with the information obtained through color maps, these deviations may indicate more chairside occlusal adjustments and lighter interproximal contacts for tested additively manufactured composite resin crowns, which might even lead to a remake in clinical situations.
3. The clinical fit of the crowns fabricated from the tested materials may be similar, as deviations from the virtual design file at the occlusal, intaglio occlusal, and marginal surfaces can be considered small.

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CRediT authorship contribution statement
Gülce Çakmak: Conceptualization, Methodology, Investigation. **Ana Maria Rusa:** Methodology, Investigation. **Mustafa Borga Donmez:** Writing – original draft. **Canan Akay:** Resources, Formal analysis. **Martin Schimmel:** Conceptualization, Methodology, Supervision. **Burak Yilmaz:** Conceptualization, Methodology, Supervision, Writing – review & editing.

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