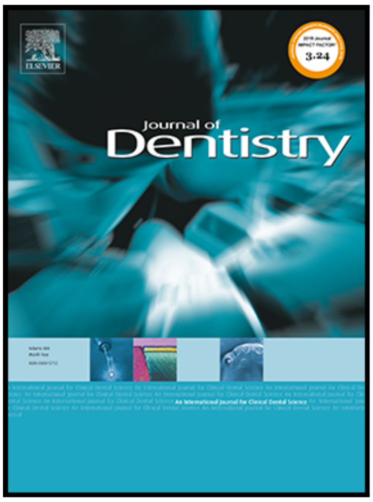

Effect of number of supports and build angle on the fabrication and internal fit accuracy of additively manufactured definitive resin-ceramic hybrid crowns

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Effect of number of supports and build angle on the fabrication and internal fit accuracy of additively manufactured definitive resin-ceramic hybrid crowns

Short title: Trueness of 3D-printed crowns based on number of supports and build angle

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ABSTRACT

Objectives: To evaluate the effect of number of supports and build angle on the fabrication and internal fit accuracy (trueness and precision) of additively manufactured resin-ceramic hybrid crowns.

Methods: A mandibular first molar crown was designed and nested on the build platform of a printer either with a 30° angle between the occlusal surface and the build platform (BLS (less support) and BMS (more support)) or its occlusal surface parallel to the build platform (VLS (less support) and VMS (more support)) to fabricate additively manufactured resin-ceramic hybrid crowns (n=14). After fabrication, supports were removed by a blinded operator and all crowns were digitized with an intraoral scanner. Fabrication accuracy (overall, external, intaglio occlusal, occlusal, and marginal) was evaluated by using root mean square (RMS) method, while internal fit was evaluated with triple scan method. RMS, average gap, and precision of these data were analyzed ($\alpha = .05$).

Results: VLS had higher overall deviations than BLS and VMS (*P*≤.039). VMS had higher occlusal deviations than BLS (*P*=.033). While BMS and BLS had higher marginal deviations than VLS (*P*≤.006), BMS also had higher values than VMS (*P*=.012). BLS led to higher precision than VMS (intaglio occlusal and occlusal surfaces) and VLS (occlusal surface) (*P*≤.008). VLS led to higher precision than BMS (marginal surface) (*P*=.027). Average gap values were similar (*P*=.723); however, BLS resulted in higher precision than VLS (*P*=.018).

Conclusions: Considering their high marginal and occlusal surface trueness, and similar internal occlusal deviations and average gaps (trueness), clinical fit of resin-ceramic hybrid crowns fabricated with tested parameters may be similar. Reduced number of supports and angled orientation may lead to higher precision of fit.

Clinical Significance

Tested resin-ceramic hybrid-printer pair may be used to fabricate crowns with reduced number of supports to maintain occlusal surface integrity without compromising the fabrication accuracy and fit.

1. INTRODUCTION

Computer-aided design and aided computer-aided manufacturing (CAD-CAM) has been commonly used in dentistry more than a decade, and in line with digital advancements, subtractive and additive manufacturing technologies are increasingly being used [1-4]. Additive manufacturing of dental prostheses has enabled possibilities to complement, expand and improve conventional dentistry, leading to smaller amount of waste, and several prostheses can be produced at the same time with a certain degree of accuracy [1, 5, 6]. In this respect, printing of dental prostheses is increasingly recognized as an alternative [7], which also leads to new clinical and scientific questions.

Advancements in additive manufacturing have enabled the use of various types of materials fabricated by using different additive technologies [8-10]. Resins are among these materials, and they are mostly processed by using vat polymerization techniques, where a vat of photosensitive liquid is polymerized by a light source that can either be a laser or a light projector [11-15]. Additively manufactured resin-based materials have been used for interim crowns and fixed partial dentures, and their fabrication trueness has been shown to be promising [1, 16], and resin-ceramic hybrids that are indicated for definitive prostheses have also been marketed in recent years [17, 18]. Given the fact that definitive prostheses must have higher accuracy along with improved mechanical and optical properties to warrant long-term stability, additively manufactured definitive crowns should be investigated for how influencing fabrication parameters may affect their fabrication accuracy and fit to ensure their clinical applicability.

Fabrication accuracy of additively manufactured prostheses depends on various factors [1, 5, 19-22], one of which is the build angle [20]. The number and geometry of supports, which can be altered during the nesting of the design data, were also shown to affect fabrication accuracy [21]. Number of supports may be reduced to eliminate the ones on critical regions such as margins or occlusal surfaces of prostheses. Even though previous studies have investigated different properties of additively manufactured resin-ceramic hybrids [7-9, 11, 17, 18, 23-28], the knowledge on the effect of number of supports and build angle on the fabrication and internal fit accuracy of additively manufactured resin-ceramic hybrid crowns is limited. Therefore, the aim of this study was to investigate the fabrication (overall, external, intaglio occlusal, occlusal, and marginal) and internal fit accuracy (trueness and precision) of resin-ceramic hybrid crowns additively manufactured with varying number of supports positioned with different build angles, comparing with digital design file. The null hypotheses were that i) number of supports and build angle would not affect the fabrication accuracy (trueness and precision) of additively manufactured resin-ceramic hybrid crowns and ii) number of supports and build angle would not affect the internal fit accuracy (trueness and precision) of additively manufactured resin-ceramic hybrid crowns.

2. MATERIAL AND METHODS

Experimental design of the present study is illustrated in Figure 1. A virtual die simulating an abutment preparation with a 1-mm-wide chamfer finish line was designed (DentalCAD 3.0 Galway; exocad GmbH, Darmstadt, Germany) and milled from a cobalt-chromium blank (Colado CAD CoCr4; Ivoclar Vivadent AG, Schaan, Liechtenstein) with a 5-axis milling machine (PrograMill PM7; Ivoclar Vivadent AG, Schaan, Liechtenstein). This die was digitized with a laboratory scanner (E4; 3Shape, Copenhagen, Denmark) and a standard tessellation language (STL) file (D-STL) was generated. A complete-coverage crown with 30 µm cement gap was designed over this D-STL to generate reference-crown STL (R-STL). To fabricate additively manufactured crowns, R-STL was imported into a nesting software (Composer; ASIGA, Sydney, Australia) and positioned in 4 different configurations on the build platform either with a 30° angle between the occlusal surface of the crown and the build platform (BLS (less support) and BMS (more support)) or their occlusal surfaces facing the build platform (VLS (less support) and VMS (more support)). The difference between the groups with more support and the groups with less support was the manual removal of the supports on occlusal fossae of the crowns after generating supports automatically for all designs. These configurations were duplicated 14 times per group for standardization of support removal process; the sample size was deemed appropriate based on a priori power analysis (for %95 CI (1-α), 95% power (1-β), and effect size of f=0.623) [1]. Layer thickness was set at 50 µm and all crowns were additively manufactured by using a light-polymerized flowable polymer resin (Crowntec; Saremco Dental AG, Rebstein, Switzerland), which comprises esterification products of 4,4'-isopropylidiphenol, ethoxylated and 2-methylprop-2enoic acid, silanized dental glass, pyrogenic silica, and initiators [29], and a digital light processing-based 3-dimensional (3D) printer (MAX UV; ASIGA, Sydney, Australia). Table 1 summarizes the duration of fabrication and the amount of material used for each group. After fabrication, crowns were removed from the build platform and cleaned with a 96% alcohol-soaked cloth until all uncured resin was completely removed and dried by using an air syringe. Curing was performed by using a xenon polymerization unit (Otoflash G171; NK Optik, Baierbrunn, Germany) under a nitrogen oxide gas atmosphere with 4000 lighting exposures [17]. A blinded operator removed supports of each crown under magnification loupes (EyeMag Pro; Carl Zeiss, Oberkochen, Germany) at ×3.5 magnification with a cut-off-wheel (Keystone Cut-off Wheels; Keystone Industries, Gibbstown, NJ, USA) and smoothened the surfaces gently to prevent errors during the alignment procedure without any adjustments to the intaglio surface (Figure 2).

Crowns were kept in a dry and lightproof box until digitized with an intraoral scanner (CEREC Primescan SW 5.2; Dentsply Sirona, Bensheim, Germany) used by a single operator (D.A.); the digitization took place within 2 days after fabrication. Crown scans were converted to their respective STL (C-STL) files. Intraoral scanner was calibrated before scanning each group and to minimize fatigue-related deviations, the operator took 5-minute breaks in between each group [11]. All scans were performed in the same temperature and humidity-controlled room, where the scan of the abutment die was performed.

To analyze the fabrication accuracy of the crowns, C-STL and R-STL files were imported into a 3D analysis software (Medit Link v2.4.4; Medit, Seoul, Korea) [1, 16, 30]. C-

STL was superimposed over the R-STL by simultaneously selecting 3 points (one point each on the occlusal, mesial triangular, and distal triangular fossae) on each file. To represent 3D deviations, color maps were generated with the maximum and minimum critical (nominal) values set at +50 µm and -50 µm and the tolerance range set at +10 µm and -10 µm [1, 16, 30-32]. Overall deviation values were automatically calculated by using the color maps and root mean square (RMS) method, which can be defined as the square root of the mean square of deviation values [32]. STL files were imported again for the evaluation of other surfaces, which were virtually separated, dividing the crown patterns into 4 parts [33]. RMS values of each surface was automatically calculated by the software after using the same superimposition process (Figure 3).

Triple scan method was used for internal adaptation analysis. This method is based on the superimposition of the scans of prosthesis, abutment tooth, and prosthesis when seated on the abutment tooth (adaptation file) to perform 3D internal fit analysis [15, 34-38]. The crowns were digitized after being seated on the abutment die (adaptation file) by using the same intraoral scanner. These scans were converted to STL files (AD-STL) and imported into the same analysis software. To virtually superimpose the crown file (C-STL) and the abutment die file (D-STL), AD-STL was initially superimposed over the D-STL to generate a merged STL, which was followed by the superimposition of the C-STL over this merged STL. For superimpositions, 3 points were selected simultaneously on each STL file, as done during the trueness analysis. These superimpositions enabled the merging of 3 different STL files on the same coordinate system. After superimpositions, AD-STL, which was not needed anymore, was deleted. The average gap between the intaglio surface of the crown and the abutment die surface was automatically calculated (Figure 4). All gap measurements were performed by the same clinician (G.C).

Variances of deviations within each group for each surface and average gap values were used to define precision. Normality of data was evaluated by using Shapiro-Wilk tests. One-way analysis of variance followed by Tukey HSD tests were performed to analyze overall RMS (trueness and precision), external surface RMS (trueness), and average gap data (precision), while Kruskal Wallis and Dunn's tests were used for every other surface (trueness and precision) and average gap data (trueness). A statistical analysis software (SPSS v22; IBM Corp, Armonk, NY, USA) was used for all analyses and the significance level was set at α=.05.

3. RESULTS

Table 2 summarizes descriptive statistics of surface RMS values. While there was a significant difference among test groups for overall RMS values (*P*=.005), the external surface RMS values of test groups were similar (*P*=.209). VLS resulted in higher overall RMS values than BLS and VMS (*P*≤.039), while the difference between every other pair was nonsignificant (*P*≥.061).

Kruskal-Wallis test showed that the difference among test groups for occlusal (*P*=.037) and marginal (*P*<.001) surfaces were significant, whereas no significant differences were observed on the internal occlusal surface (*P*=.617). For occlusal surface, RMS values of VMS were higher than those of BLS (*P*=.033). However, every other pairwise comparison was nonsignificant (*P*≥.195). For marginal surface, VLS had lower RMS values than BLS (*P*=.006) and BMS (*P*<.001). In addition, BMS led to higher RMS values than VMS (*P*=.012). The differences between VMS and VLS (*P*>.05), VMS and BLS (*P*=.263), and BLS and BMS (*P*>.05) were nonsignificant.

Test groups had similar precision when overall and external surface RMS values were considered (*P*≥.394). However, the differences among test groups for every other surface were significant (*P*≤.020). When intaglio occlusal and occlusal surface RMS values were considered, BLS had higher precision than VMS (*P*=.003). In addition, BLS had higher precision than VLS when occlusal surface RMS values were considered (*P*=.008). When marginal surface RMS values were considered, VLS had higher precision than BMS (*P*=.027) (Table 3).

No significant differences were observed among average gap data of test groups when the fit of the crowns was evaluated (*P*=.723). Precision of test groups was significantly different when average gap data was considered (*P*=0.022). BLS resulted in higher precision than VLS (*P*=.018) (Table 4). Figures 5 and 6 illustrate box-plot graphs of RMS and average gap values of each group.

4. DISCUSSION

The number of supports and build angle had a significant effect on fabrication accuracy of additively manufactured resin-ceramic hybrid crowns; BLS had higher accuracy than VMS when occlusal surface and VLS had higher accuracy than BMS when marginal surface RMS values were considered. Therefore, the first null hypothesis was rejected. However, the maximum difference in mean values among test groups was 6.65 µm (overall RMS, BLS-VLS pair), when data (trueness and precision) from the surfaces with significant differences were further analyzed. The authors think that a difference of this magnitude may not be clinically perceivable, and it can be speculated that all groups had similar fabrication accuracy. Qualitative interpretation of color maps also supports this hypothesis, as color distribution was similar in all groups. Blue, which corresponds to clinically undercountoured areas, was the primary color of the crowns when overall and external surfaces were concerned. Accordingly, tested crowns might have light or open interproximal contacts along with esthetic issues due to undercountouring. Considering that the occlusal fossae of the crowns were predominantly red, which corresponds to clinically overcountoured areas, it can be hypothesized that all crowns would require occlusal adjustments. In addition, BLS and BMS crowns may require more adjustments, particularly with laterotrusive movements as red was also visible on the buccal inclination of their buccal cusps, which may also show the effect of build angle on the fabrication trueness of overall and external surfaces (Figures 2A and 2B). However, the number of supports did not seem to affect overall or external surface trueness of the crowns as groups with similar build angle had similar color trends. Color maps of intaglio and marginal surfaces of all groups were similar and green was dominant on intaglio surfaces (Figures 2C and 2D), while orange and green were observed on margins (Figure 2E).

All groups had similar average gap values, however, BLS had higher precision than VLS. Therefore, the second null hypothesis was rejected. However, it should be noted that the mean difference between BLS and VLS was 17.5 µm, which can be considered small and may not be clinically perceptible, particularly considering that 30 µm cement gap was integrated in the CAD of the crown. Therefore, the authors think that the fit (average gap) results support the interpretation for accuracy results made above, which indicated potentially imperceptible differences in fit. Color maps, which were generated after triple scan protocol also support this outcome as a similar trend could be observed among all groups. In addition, even though no significant differences were found among test groups, VLS and VMS had similar values that were smaller than those of other groups, which is reflected in color maps with a more homogenous distribution of deviations that are within the tolerance range on intaglio surfaces. However, none of the test groups had a mean gap value of only 30 µm cement gap of the R-STL. A previous study on the marginal gap values of additively manufactured resin-ceramic hybrid crowns also reported similar results and attributed their findings to the standardized layer thickness of 50 µm [17]. However, future studies should investigate how tested parameters affect internal fit of restorations with greater cement gap values.

To the authors' knowledge, only 1 study investigated the effect of supports on the fabrication trueness of additively manufactured crowns [21]. Even though Alharbi et al [21] focused on additively manufactured interim crowns, they concluded that geometry of the supports (thin or thick) and build angle affected the fabrication trueness, which is parallel to the findings of the present study, as changing the geometry of the supports also changed the number of supports in Alharbi et al's study [21]. In the present study, only significant difference within groups that had the same build angle was found when overall RMS values of VLS and VMS were concerned; VMS had higher trueness. Given the fact that the only difference between groups with similar build angle was the absence of supports on the occlusal fossae of the same configuration, the authors think that decreased number of supports may have led to a less self-supporting structure of VLS crowns as their occlusal surface was positioned to face the build platform. However, this speculation needs further support with studies on the mechanical properties of additively manufactured resin-ceramic hybrid crowns fabricated by using tested parameters, as the difference between the overall RMS values of VLS and VMS groups was only 5.08 µm, which can be considered clinically small.

Build angle has been a broadly investigated parameter as additively manufactured products are known to be anisotropic [12]. Several studies have focused on the fabrication trueness of additively manufactured crowns fabricated by using interim materials [10, 13, 14, 21]. To the authors' knowledge, the present study is the first on the effect of build angle on the fabrication and internal fit accuracy of additively manufactured resin-ceramic hybrid crowns and therefore, comparisons with previous studies were not possible.

When the amount of resin and printing time were considered, the groups aligned with an angle required 10 more minutes for the print to be completed and the BMS group required more resin consumption. In this respect, using less supports enables potentially smoother surfaces as the surface that requires support removal is smaller, and nesting tested crowns' occlusal surfaces parallel to the build platform can be considered ecologically-friendly in the long-term.

The methodology of the present study (digitization of crowns by using an intraoral scanner and performing deviation analyses by using a 3D analysis software and RMS method) is similar to that used in previous studies, which investigated the fabrication trueness of additively manufactured prostheses [1, 16, 30, 31]. Digitization of the crowns by using an intraoral scanner was preferred as the scans of the crowns were completed in one round and possible stitching related inaccuracies that could be encountered if a desktop scanner was used were eliminated. Precision of measured deviations also supports the methodology used to fabricate and analyze tested resin-ceramic hybrid crowns, because the greatest mean difference among test groups was 3.9 µm. In addition, this methodology and scanner were used in previous studies [15, 28, 30, 31], and the accuracy of the scanner has been well-reported [39-41]. A recent study has even showed that the IOS used in the present study had similar precision to that of laboratory scanners [41]. However, considering that intraoral scanners utilize different digitization technologies that could affect the scan accuracy and the fact that laboratory or industrial scanners may also be used to digitize prostheses, a different scanner may lead to different results. Triple-scan protocol has been preferred in dental studies to analyze the internal fit of restorations with different number of units and geometries [15, 34-38]. In addition, the authors think that the methodology of the present study while using the triple-scan protocol is reliable, because the maximum mean average gap difference between test groups was 17.5 µm when the precision was considered. However, a recent study reported significant differences when comparing triple-scan protocol with different nondestructive and destructive internal fit assessment methods such as X-ray microtomography and replica technique [35]; thus, these results cannot be generalized. Only one additively manufactured resin-ceramic hybrid and one 3D printer were used. However, different printers and resin-ceramic hybrids with different filler and particle ratios within their matrices may alter obtained results. Only 2 build angles were tested, however, increasing or decreasing the angle between the build platform and the occlusal surface of the crowns may affect the outcomes. The support diameter and the connection of the support structure could also be examined in a future study. Even though the supports were removed by the same blinded operator by using magnification loupes and a low-speed handpiece, this step is rather subjective and manual removal of supports might affect the intactness of the surface of the crowns. Future studies should evaluate the effect of number of supports and build angle on other properties of additively manufactured resin-ceramic hybrid crowns that may affect clinical longevity, such as fracture resistance and wear, by using different restoration designs to corroborate the results of the present study.

5. CONCLUSIONS

Within the limitations of the present study, the following conclusions can be drawn:

1. Fabrication accuracy of tested additively manufactured resin-ceramic hybrid crowns varied depending on the number of supports and build angle. However, the maximum difference in mean values (trueness and precision) was 6.65 µm among test groups, which could be considered clinically small.
2. Tested number of supports and build angles resulted in similar internal fit (average gap values) of additively manufactured resin-ceramic hybrid crowns. However, higher precision may be achieved for fit when decreased number of supports is used.

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TABLES

Table 1. Printing parameters of each group

Test Groups	Printing Duration	Amount of Material Used
BLS	1 hour 11 minutes and 41 seconds	12.72 mL
BMS	1 hour 11 minutes and 41 seconds	14.21 mL
VLS	1 hour and 23 seconds	12.02 mL
VMS	1 hour and 23 seconds	12.25 mL

Table 2. Descriptive statistics of RMS values (µm, trueness) of each group for each surface

	Overall		External		Intaglio occlusal		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)

BLS	48.64 ±4.7^{a}	47.5 (41 - 58)	57.93 ±9.68^{a}	55 (47 - 81)	14.57 ±2.98	14^{a} (11 - 23)	9.93 ±1.38	10^{a} (8 - 12)	19.36 ±2.37	18.5^{bc} (15 - 24)
BMS	50.57 ±3.92^{ab}	51 (43 - 57)	55.07 ±6.5^{a}	53.5 (46 - 68)	15.36 ±5.68	13.5^{a} (10 - 33)	12.07 ±2.34	12^{ab} (9 - 16)	20.64 ±2.44	20.5^{c} (17 - 26)
VLS	55.29 ±3.75^{b}	55.5 (48 - 61)	57.5 ±5.10^{a}	57 (48 - 66)	14.86 ±3.76	13^{a} (10 - 22)	12.86 ±5.05	12^{ab} (7 - 26)	16.71 ±1.20	17^{a} (14 - 19)
VMS	50.21 ±6.55^{a}	49.5 (41 - 63)	60.79 ±5.86^{a}	61.5 (47 - 68)	14.43 ±5.40	11.5^{a} (10 - 26)	14.36 ±5.81	13^{b} (9 - 29)	17.64 ±2.24	17.5^{ab} (14 - 23)

Different superscript letters indicate significate differences in columns (P<.05)

Table 3. Descriptive statistics of RMS values (µm, precision) of each group for each surface

	Overall		**External**		**Intaglio occlusal**		**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)
BLS	3.4 ±3^{a}	2.1 (0.4 - 9.4)	7.2 ±6.2	5.1^{a} (0.9 - 23.1)	2 ±2.2	1^{a} (0.6 - 8.4)	1.1 ±0.8	1.1^{a} (0.1 - 2.1)	1.8 ±1.4	1.4^{ab} (0.4 - 4.6)
BMS	3 ±2.4^{a}	2.5 (0.6 - 7.6)	4.7 ±4	3.1^{a} (0.1 - 12.9)	3.6 ±4.3	2.4^{ab} (0.6 - 17.6)	1.9 ±1.2	2.1^{ab} (0.1 - 3.9)	1.9 ±1.4	1.6^{b} (0.4 - 5.4)
VLS	3.1 ±1.9^{a}	3 (1.3 - 7.3)	3.9 ±3.2	3^{a} (0.5 - 9.5)	3.1 ±1.9	2.9^{ab} (0.1 - 7.1)	3.7 ±3.3	3.5^{b} (0.1 - 13.1)	0.8 ±0.8	0.3^{a} (0.3 - 2.7)
VMS	4.8 ±4.2^{a}	4 (0.2 - 12.8)	4.4 ±3.7	3.5 (0.2 - 13.8)	4.6 ±2.6	3.9^{b} (1.6 - 11.6)	4.2 ±3.8	4^{b} (0.4 - 14.6)	1.6 ±1.5	1.4^{ab} (0.4 - 5.4)

Different superscript letters indicate significate differences in columns (P<.05)

Table 4. Descriptive statistics of average gap (trueness and precision) between intaglio surface of crown and abutment die surface

	Trueness (μm)		**Precision (μm)**	
	Mean ±standard deviation	**Median (Min-Max)**	**Mean ±standard deviation**	**Median (Min-Max)**
BLS	57.9 ±24.9	55.5^{a} (12 - 128)	14.1 ±20.2^{a}	5.9 (0.1 - 70.1)
BMS	58.5 ±16.1	56^{a} (45 - 105)	10.7 ±11.6^{ab}	9 (1.5 - 46.5)
VLS	72.9 ±36.8	61^{a} (38 - 151)	28.2 ±22.4^{b}	22.9 (2.1 - 78.1)
VMS	63.1 ±24.3	56.5^{a} (40 - 138)	15.4 ±18.4^{ab}	9.6 (2.1 - 74.9)

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

FIGURES

Figure 1. Overview of the study design

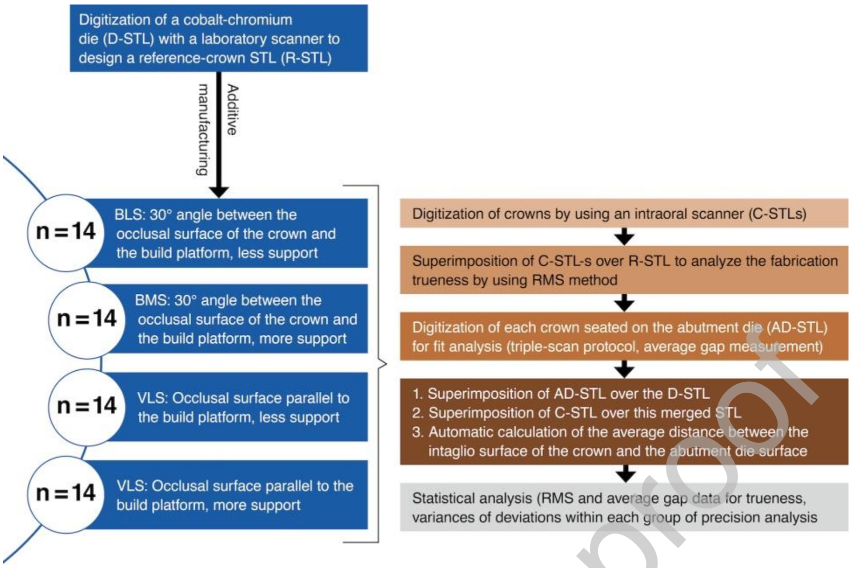


Figure 2. Additively manufactured crowns (A: Buccal aspect; B: Lingual aspect; C: Proximal aspect; D: Intaglio surface and margin)

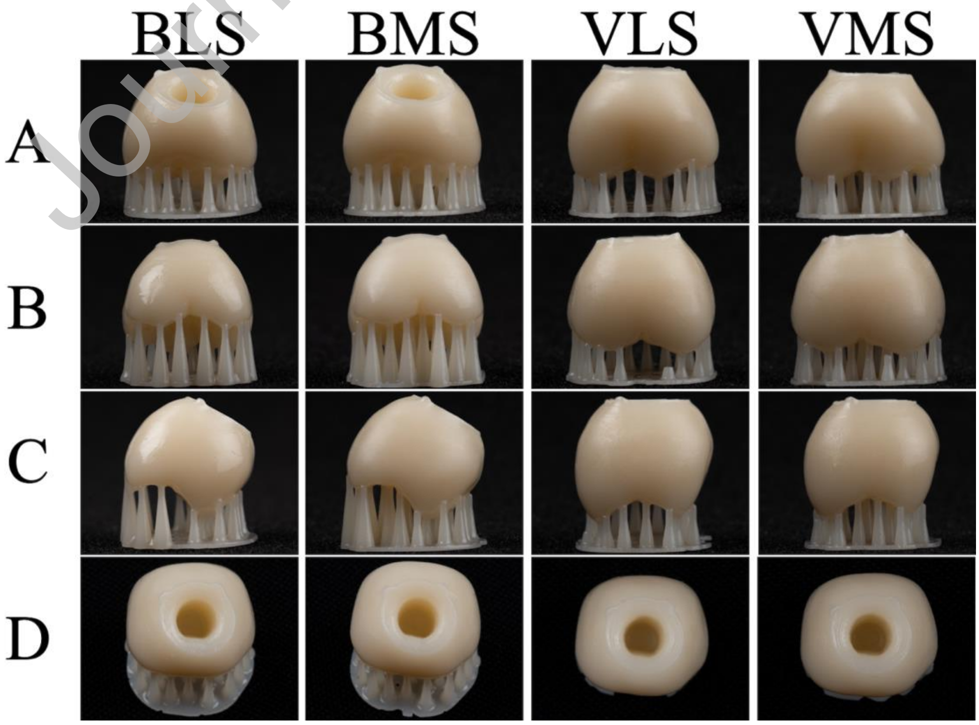


Figure 3. Color maps generated for overall and each surface analyzed within each group (A: Overall; B: External; C: Intaglio occlusal; D: Occlusal; E: Marginal)

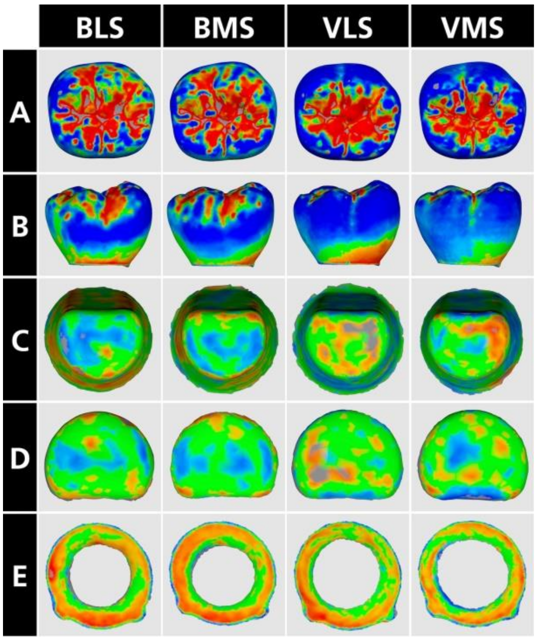


Figure 4. Representative color map of each group generated after triple-scan protocol

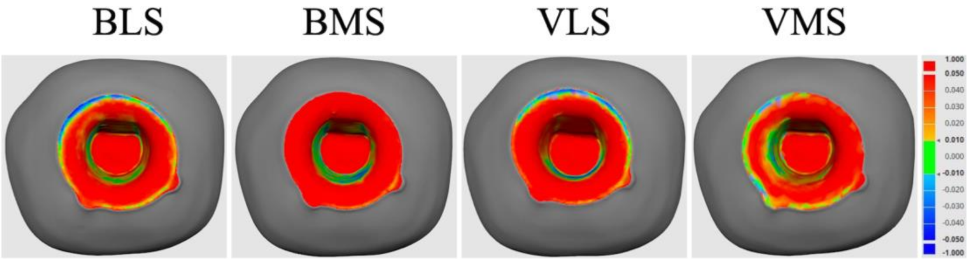


Figure 5. Box-plot graph of RMS distribution of each group for each surface evaluated

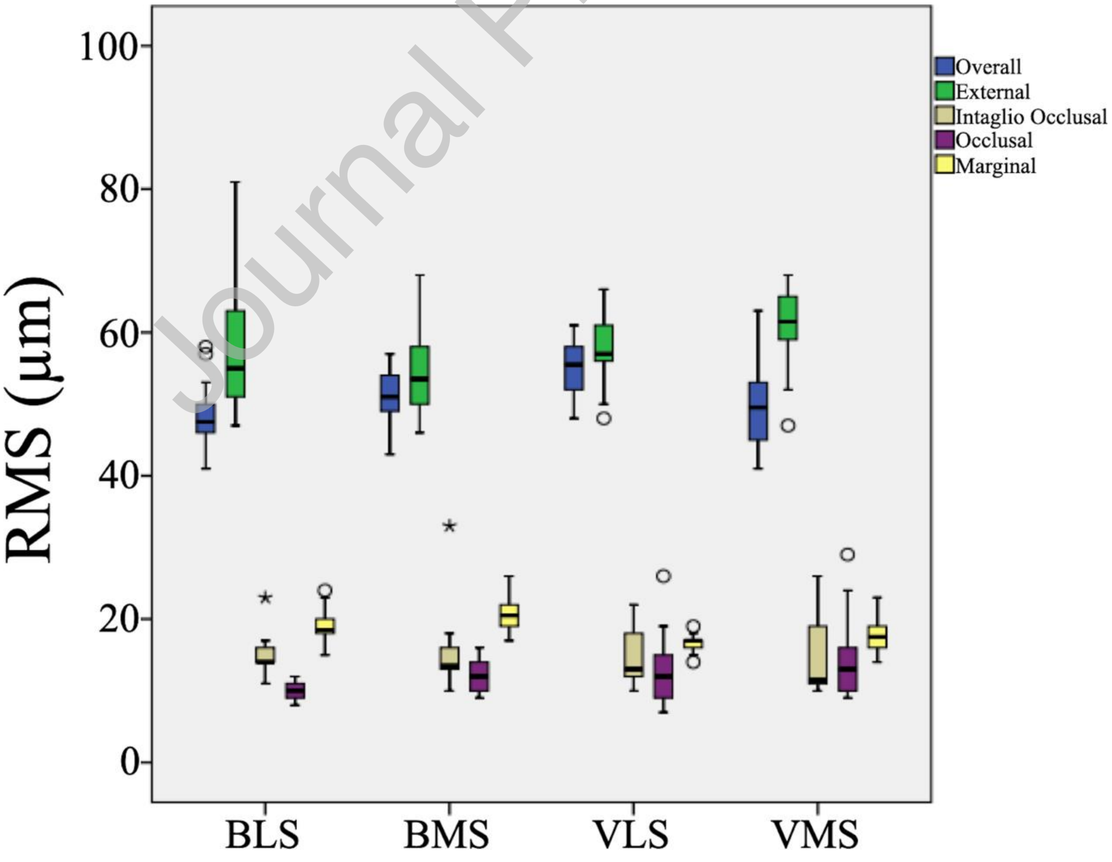
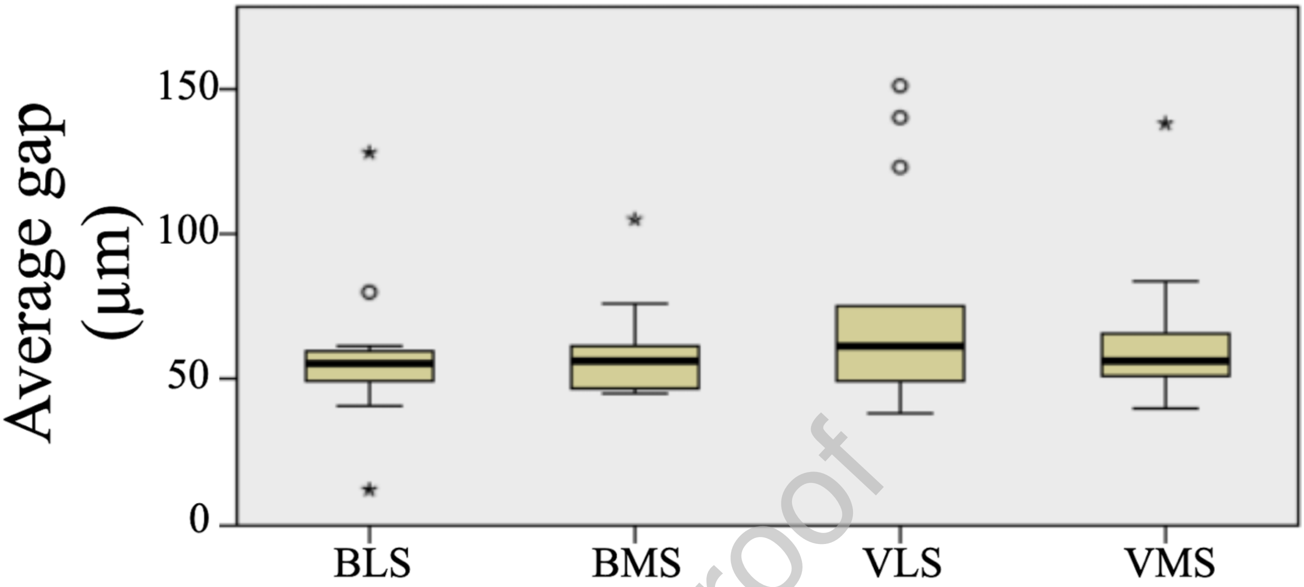


Figure 6. Box-plot graph of average gap between crowns and die for each group



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All other authors have no conflicts of interest to declare. The authors do not have any financial interest in the companies whose materials are included in this article.

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Author Statement

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: