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RESEARCH AND EDUCATION

Effect of maximum support attachment angle on intaglio surface trueness of anatomic contour monolithic prostheses manufactured by digital light processing and zirconia suspension

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ABSTRACT

Statement of problem. Support structures are essential for the quality of resin-based prostheses made by the digital light processing (DLP), but few studies have evaluated the effect of support structure on the accuracy of zirconia-based anatomic contour prostheses.

Purpose. The purpose of this in vitro study was to evaluate the effect of maximum support attachment angle (MSA) on the intaglio surface trueness of anatomic contour prostheses made by DLP and compare the trueness of 2-unit anatomic contour prostheses with that of those produced by milling.

Material and methods. Anatomic contour single-unit prostheses were manufactured using DLP and a suspension with 3-mol% yttria-stabilized zirconia. Four different conditions of MSA values to the vertical axis of the object (50, 55, 60, and 65 degrees) were applied (n=10). After printing, postprocessing, and sintering, all successfully produced prostheses were evaluated for intaglio surface trueness by considering the root mean square (RMS). Using the MSA showing the highest trueness, the 2-unit prostheses made by DLP (DLP group) were compared with milled (MIL group) prostheses in terms of intaglio accuracy (n=10). One-way analysis of variance and a post hoc pairwise comparison or independent *t* test were used for trueness analysis (α=.05).

Results. Three MSA groups (50, 55, and 60 degrees) were successfully produced with significant differences between the trueness of the single-unit prostheses for the groups with different MSA values (P<.05). The highest trueness was in the 50-degree MSA group. The 2-unit prostheses of the DLP group with 50-degree MSA showed significantly lower trueness than those of the MIL group (P<.05); however, the RMS values of both groups were lower than 50 µm.

Conclusions. The intaglio surface trueness of anatomic contour DLP-generated prostheses can be improved by changing the MSA. The 50-degree MSA was beneficial for the accuracy of both single-unit and 2-unit DLP-generated prostheses, produced within clinically acceptable limits. (J Prosthet Dent 2023;129:478-85)

With advances in computer-aided design and computer-aided manufacturing (CAD-CAM) technology, subtractive manufacturing has been considered the standard for fabricating ceramic prostheses. However, limited design freedom, including thin-walled features or small radii, high consumption of raw materials, considerable waste from unused remnants of milled blocks, and severe wear of tools are some of the concerns of subtractive manufacturing.[1,2] An anatomic contour monolithic prosthesis has a thin-walled ceramic shell structure with complex geometric shapes, including grooves, cusps, and fossae. Machining complex surfaces with high precision and reproducibility is challenging because of the limited access to smaller

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Clinical Implications

Considering the MSA, additional support structures positioned over the occlusal areas of anatomic contour prostheses can improve the intaglio surface accuracy of DLP-generated zirconia single-unit and 2-unit zirconia prostheses to a clinically acceptable range.

areas imposed by the tool size and machining axis.[2,3] In contrast, additive manufacturing (AM) is advantageous in terms of having almost no sensitivity to complex-shaped structures, no tool wear, and custom production.[3]

Researchers have recently focused on ceramic AM to construct complex structures such as anatomic contour monolithic prostheses by using properly formulated materials and corresponding printers.[1,3-12] A photosensitive suspension with an adequate solid loading of zirconia and homogeneous dispersion is fundamental.[13] At present, 3-mol% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP) is extensively used for dental restorations and is the material of choice for AM.[4,14] Among the various technical strategies for AM with zirconia, vat photopolymerization requires a mixture of liquid resin and ceramic powders to manufacture a complex object by selectively solidifying the ceramic suspension through controlled light-induced polymerization.[6] During vat polymerization, printing parameters, support parameters, and postprocessing protocols have been reported to influence the properties of AM objects.[15] Studies using stereolithography (SLA) or digital light processing (DLP) techniques have reported the potential and challenges of fabricating zirconia-based dental prostheses, mainly focusing on strength, density, and trueness.[3-12] DLP has higher manufacturing speed and resolution than SLA because of fast shifting and integral projecting.[16] Complex ceramic structures with a high degree of detail can be produced using DLP.[14] However, the quality of AM ceramic objects is dependent on the suspension composition, printing parameters, and support structures.[4-7,17]

Support structures are important in terms of both the accuracy and position of AM objects.[4-7] The support structure and build orientation significantly affect the dimensional accuracy of AM polymer objects.[15,18] During ceramic AM, the support structure attached to the printing object enables the construction of layers on the build platform, mainly for overhanging areas.[5] To fully reproduce the intaglio and occlusal surfaces of dental prostheses, the optimal use of support structures for ceramic AM is essential.[3,17] The geometric design of supports allows complex structures to be reproduced and minimizes residues after postprocessing.[3] The accuracy of the prosthesis in the z-direction has been reported to be improved by adding supports.[3] Trueness can be defined as the performance of the manufacturing process in reproducing an object as closely as possible to its virtual form.[19] The intaglio surface trueness of the ceramic AM crown has been reported to be affected by the support structure, showing low precision or reproducibility in the case of inadequate shapes or dimensions.[5,7,17]

Therefore, the purpose of this in vitro study was to evaluate the effect of the maximum angle of the support attachment to the vertical axis on the intaglio surface trueness of anatomic contour monolithic prostheses made by using DLP and a zirconia suspension. The research hypotheses were that the changes in maximum angle of support attachment would affect the intaglio surface trueness of the single-unit zirconia-based prosthesis made by using DLP and that the intaglio surface trueness of the 2-unit anatomic contour dental prosthesis would be different between the milling and the DLP after applying the optimal value of the maximum angle of support attachment.

MATERIAL AND METHODS

An acrylic resin mandibular right first molar (Simple Root Tooth Model; Nissin Dental Products) was prepared for an anatomic contour restoration with 1.5-mm occlusal reduction, 1 to 1.5-mm axial reduction with rounded internal line angles, and a 1-mm circumferential chamfer finish line. The prepared tooth was digitized with a laboratory scanner (T500; Medit). A virtual anatomic contour single-unit prosthesis was designed (reference CAD #1) (Dental Designer; 3Shape A/S) with a cement space of 25 μm starting from 1 mm to the finish line. Acrylic resin maxillary right first and second molars (Simple Root Tooth Model; Nissin Dental Products) were also prepared using dimensions similar to those for anatomic contour restorations and scanned. An anatomic contour 2-unit prosthesis was virtually designed (reference CAD #2) on the prepared abutments with the same cement space as the single-unit prosthesis. These two reference CAD data were used to produce the specimens in the study.

For the DLP process, the support structures were attached to the thick occlusal surface of each prosthesis by using a slicing software program (MetaMorp DLP Slicer; MetaMorp).[3] The grooves, fossae, and cusp tips were excluded from the region of support, minimizing interference with the occlusal contour of the prosthesis. The intaglio surface remained intact without the support structure to ensure fit to the abutment. Following the geometric shapes of the occlusal surface, the maximum support attachment angle (MSA) was defined as the maximum angle (degree) formed between the vertical axis of the prosthesis and the area of attached supports

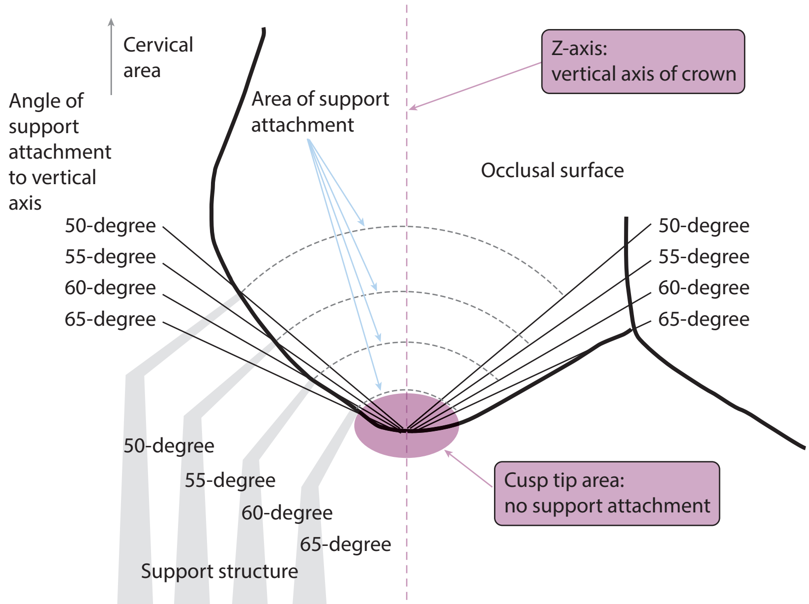

Figure 1. Schematic two-dimensional diagram of support structures attached perpendicular to surface of occlusal area of anatomic contour crown, viewed in vertical plane. Considering overhang area, 4 different MSA values (50, 55, 60, and 65 degrees) greater than 45 degrees from vertical axis of prosthesis evaluated. MSA, maximum support attachment angle.

viewed in the vertical plane and was evaluated in this study (Fig. 1). Considering the overhang area to be higher than a 45-degree angle to the vertical axis, 4 different experimental MSA values were tested to determine the highest trueness of the anatomic contour single-unit prosthesis (reference CAD #1) as follows: 50, 55, 60, and 65 degrees. Each MSA implied that the area of support attachment was distributed up to the value. In other words, the smaller the MSA, the wider the area of support attachment spread on the surface to be printed. An MSA greater than 70 degrees was excluded from the experiment so that the support structures would not be attached near the cusp tip areas. The structural unit of each support was attached perpendicular to the surface of the prosthesis, with a maximum diameter of 0.3 mm. The distance between each support structure was uniformly set as 1.0 mm. To exclude the possible effect of build orientation, each prosthesis was layered at a 0-degree angulation, with its long axis perpendicular to the build platform. Trueness analysis was performed with a clinically acceptable limit, 50 µm for the single-unit prosthesis in an absolute evaluation manner and without a control group as in previous studies.[11,20-24]

For each design group of support structures, 10 anatomic contour single-unit zirconia-based prostheses were fabricated by DLP using the reference CAD #1. A zirconia suspension (Cera-P; M.O.P) containing nanometer-sized 3Y-TZP powder, polyfunctional acrylates, and dispersant was used (Table 1). The scaling factor was calculated from the estimated shrinkage rate of the AM object after sintering, 25%±1% in every direction.

Table 1. Composition of zirconia suspension used for digital light processing

Component	Weight%
Hexanediol diacrylate	5.0
Isobornyl acrylate	1.0
Trifunctional acrylate	3.8
Dispersing agent	5.0
Photoinitiator	0.2
Di(propylene glycol)methyl ether	5.0
3 mol% yttria-stabilized tetragonal zirconia polycrystal	80.0

A DLP printer with a 3-µm resolution laser measurement sensor (Octave Light R1; Octave Light Ltd) was used to produce the prostheses with a top-down approach. The printing parameters were 50-µm layer thickness, 40×40-µm X-Y plane resolution, 5-µm Z-axis resolution, 405-nm wavelength of ultraviolet light-emitting diodes, 150-mJ exposure intensity, exposure time of 5 seconds, and 30% decrease in blade speed from the default printer setting. For each design group, the prostheses were manufactured simultaneously by using the same batch of processes located in the center of the build platform. After printing, all support structures were manually removed from the surfaces of the AM objects. The procedures were carefully performed to prevent interference with the AM objects. The AM objects were cleaned with ethanol, dried, and treated for 6 hours to a temperature of 400 °C for debinding, according to the manufacturer's instructions. Subsequently, the AM object was sintered to full density for several hours, with an increasing rate of 10

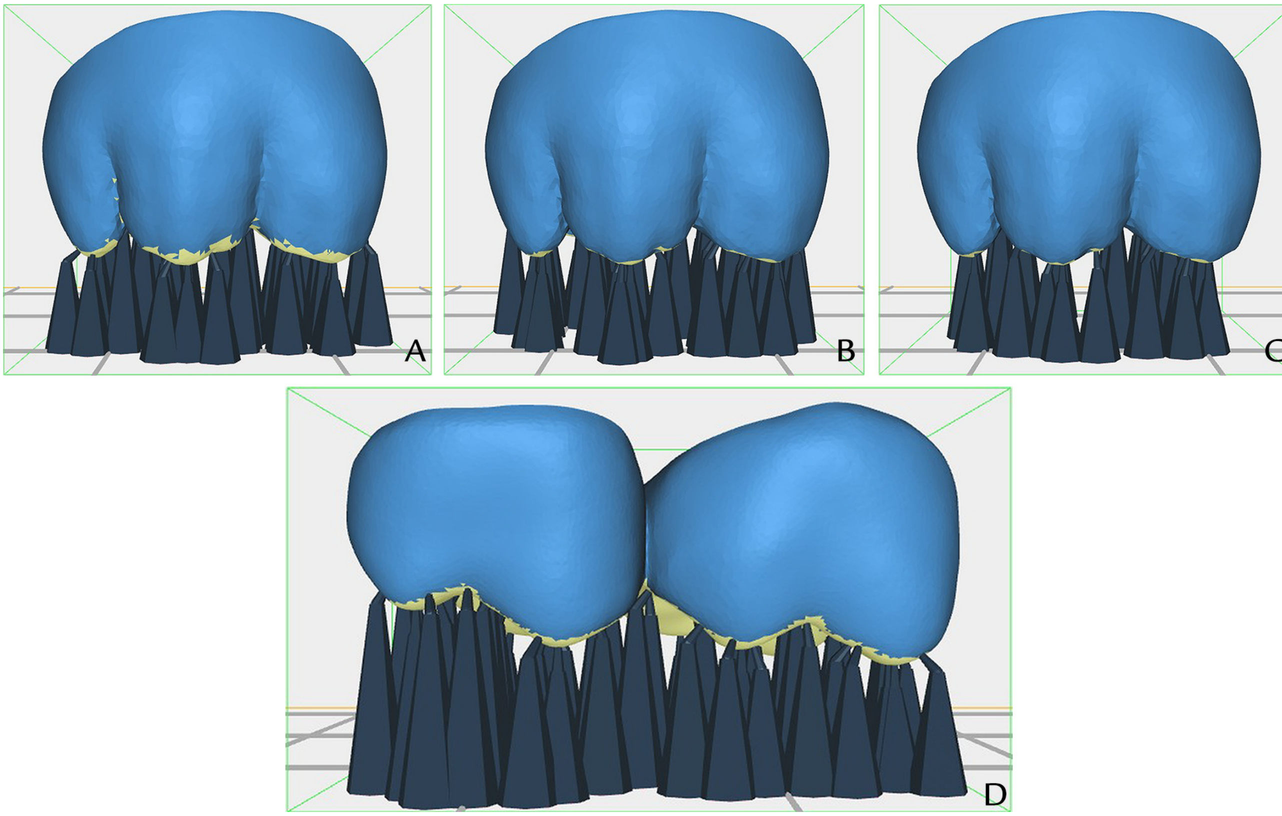

Figure 2. Computer-aided design images of support structures incorporating MSA for anatomic contour dental prostheses successfully manufactured by digital light processing and zirconia suspension. A, Single-unit prosthesis with 50-degree MSA. B, Single-unit prosthesis with 55-degree MSA. C, Single-unit prosthesis with 60-degree MSA. D, Two-unit prosthesis with 50-degree MSA. MSA, maximum support attachment angle.

°C/min and a 2-hour holding time at 1450 °C. The intaglio surfaces of the prostheses remained intact without any adjustments before and after postprocessing. If the prosthesis had any structural defect or surface damage after postprocessing, or if there were any types of directly detectable structural failures during printing (delamination or detachment), they were excluded from further analysis.

After calibration according to the manufacturer's instructions, the intaglio surfaces of the prostheses were digitized with an intraoral scanner (i500; Medit). A laboratory scanner was not used because of its limited scan angle and focal distance to the small area of the specimens.[21,24,25] The scan data of the intaglio surface of each prosthesis were superimposed on the identical field of the CAD prosthesis (reference CAD #1) and analyzed 3-dimensionally with a software program (Geomagic Control X; Geomagic Inc) to evaluate accuracy.[8,12,18] With the best-fit alignment using an iterative closest point algorithm based on point-to-point distance measurement, the root mean square (RMS) values between the scan data and reference data were measured in μm to report the trueness of the prosthesis in 4 different regions of inspection: the intaglio surface and the occlusal, margin, and axial areas. Deviation maps were also displayed with a nominal deviation of ±50 μm and a critical deviation of ±500 μm.

The MSA with the lowest RMS value for the single-unit prosthesis analysis was used to fabricate the specimens with the reference CAD #2. Anatomic contour 2-unit prostheses (n=10, Group DLP) were manufactured with the same DLP printer and zirconia suspension. All the printing parameters, postprocessing, and thermal treatment schedules were identical to those of the single-unit prosthesis. As a control group using the same reference CAD #2, 10 zirconia-based prostheses (Group MIL) were also fabricated from a milling block (Luxen ML Multi A3; Dentalmax Co) using a CAM software program (HyperDent; Follow-me! Technology) and a 5-axis milling machine (Arum 5X-300; Doowon). The milled prostheses were sintered according to the manufacturer's protocol. For both groups, no further adjustments were made for the intaglio or outer surfaces after production. The intaglio surfaces of all 2-unit prostheses (DLP-generated and milled) were scanned with an intraoral scanner (i500; Medit). Scan data of the intaglio surfaces of the prostheses were superimposed on the identical field of the CAD prosthesis (reference CAD #2) and analyzed (Geomagic Control X; Geomagic Inc). With the best-fit alignment,

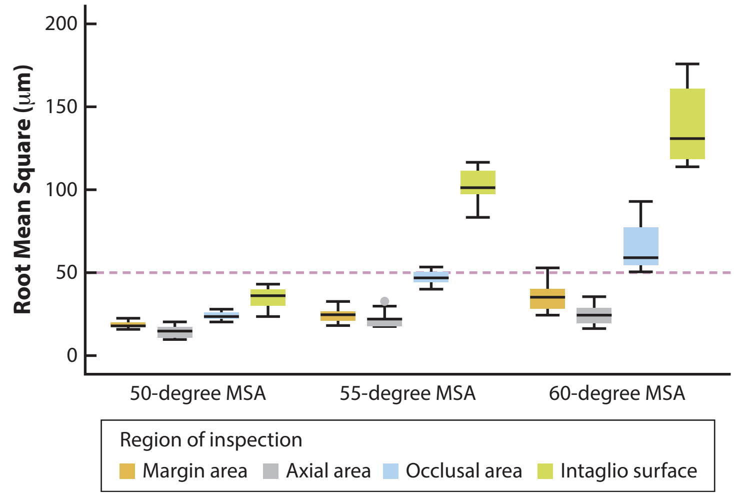

Figure 3. Box-whisker plot of RMS (μm) values of anatomic contour zirconia single-unit prostheses measured at 4 different intaglio regions of inspection (margin, axial, occlusal, and intaglio surface areas) for 3 successfully produced groups of MSA (50, 55, and 60 degrees). Clinically acceptable limit of intaglio surface trueness (RMS) was suggested as 50 μm (dotted red line). MSA, maximum support attachment angle; RMS, root mean square.

the RMS values of the intaglio surface were measured to compare the trueness of the prosthesis in 4 different regions: the intaglio surface and occlusal, margin, and axial areas.

Descriptive statistics using means and standard deviations, calculated from the measured RMS values at 4 different regions of inspection for each design, were analyzed for the single-unit and 2-unit prostheses. The normality and equality of variances were assessed by using the Shapiro−Wilk and Levene tests. Individual 1-Way ANOVAs were conducted to compare the RMS values of experimental MSA groups for each region of inspection, and a post hoc pairwise comparison was adjusted by using the Bonferroni method (α=.05). To compare the RMS values of the DLP and MIL groups, individual independent *t* tests were performed for each of the areas (α=.05). All data were analyzed by using a statistical software program (IBM SPSS Statistics, v25.0; IBM Corp) (α=.05).

RESULTS

Of the 4 groups with different MSA values, all the specimens from 50-degree, 55-degree, and 60-degree MSA groups were successfully manufactured (Fig. 2). In contrast, all the specimens from the 65-degree MSA group were excluded from the analysis because of structural failures (delamination between layers or detachment from the platform) during AM. As shown in Figure 2, smaller MSA values represented more support structures spread over more expansive areas. Only the mean RMS values of the 50-degree MSA group were lower than 50 μm, regardless of the inspected regions (Fig. 3). The mean RMS value of the total area of the intaglio surface was significantly higher in the 60-degree MSA group than in the other groups (P<.001) (Table 2). At the margin area, the 60-degree MSA group showed a significantly higher RMS value than the other groups (P<.001). At the axial and occlusal areas, the 50-degree MSA group showed significantly lower RMS values than the other groups (P<.05). The 50-degree MSA group showed the highest trueness of the monolithic single-unit prosthesis (Fig. 4).

Table 2. Mean ±standard deviation of root-mean-square (μm) values of anatomic contour zirconia single-unit prostheses measured at 4 different regions of inspection (margin, axial, occlusal, and intaglio surface areas) for 3 successfully produced groups of MSA

Group	Margin Area	Axial Area	Occlusal Area	Intaglio Surface
50-degree MSA	18.3 ±2.1[a]	14.5 ±3.6[c]	23.9 ±2.5[e]	35.0 ±6.8[h]
55-degree MSA	24.6 ±4.4[a]	22.3 ±5.2[d]	46.9 ±4.2[f]	103.3 ±10.4[i]
60-degree MSA	36.2 ±9.4[b]	24.8 ±6.3[d]	65.1 ±15.1[g]	138.0 ±24.0[j]

MSA, maximum support attachment angle. Different letters within each column indicate statistically significant differences (P<.05).

An analysis of the DLP group with the 2-unit prosthesis specimens produced with an MSA of 50 degrees revealed statistically significant differences between the 2 prosthesis groups at each region of inspection (P<.001) (Table 3 and Fig. 5). The DLP group had significantly higher RMS values than the MIL group (P<.001); however, all specimens showed RMS values smaller than 50 μm, within the clinically acceptable range regardless of the inspection region (Figs. 5 and 6).

DISCUSSION

Based on the results of this study, MSA significantly affected the intaglio surface trueness of DLP-generated anatomic contour dental prostheses, supporting the research hypothesis. Under the 50-degree MSA, the

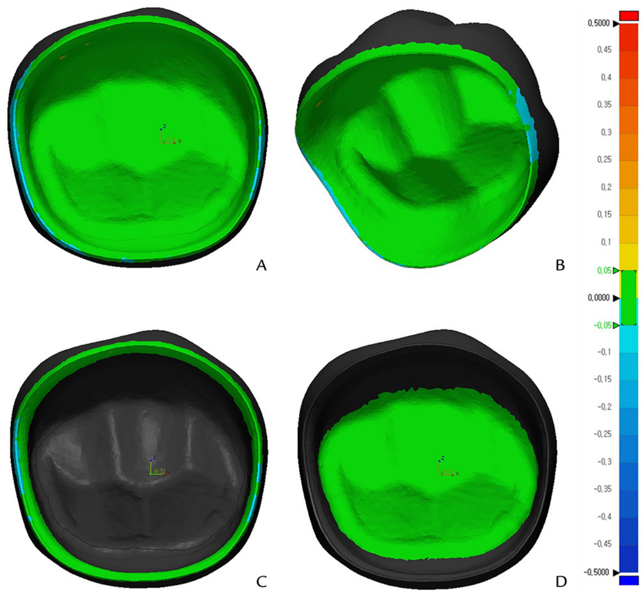
Figure 4. Three-dimensional color deviation map of intaglio surface of anatomic contour zirconia single-unit prostheses manufactured by digital light processing with 50-degree MSA. A, B, Intaglio surface (total). C, Margin area. D, Occlusal area. Nominal deviation ±50 µm, and critical deviation ±500 µm. MSA, maximum support attachment angle.

anatomic contour 2-unit prostheses produced by DLP showed mean RMS values less than 50 µm, which, even though significant differences were observed between the MIL and DLP groups, were clinically acceptable.

Support structures are essential for successfully layering complex objects with sufficient detail and integrity during the AM process.[1,4,5] However, if the support structures are inadequately located on the AM objects, the increased duration of the printing process, extra work of postprocessing, and increased risk of damaging products can occur.[1,3-6,15] Regarding the support attachment for the AM, some areas were theoretically considered suitable for the precision of the prosthesis, such as the proximal or smooth surfaces.[5] However, support structures were not attached to those areas because they may have had thin-walled structures close to the margin areas, possibly damaging or deforming the AM object during postprocessing.[3]

Considering the printability of zirconia suspension and its postprocessing, an MSA larger than 70 degrees or smaller than 45 degrees was regarded as inappropriate because it did not sufficiently support the entire structure, eventually leading to delamination or detachment by the movement of the recoating blade owing to insufficient adhesion to the build platform.[4] The difficulty in removing support structures may be attributed to using the same material for the AM objects and support structures.[4] During removal and further sintering, suboptimal support structures may lead to increased material loss and warpage during treatment, eventually leading to inaccurate geometry.[5] The smaller MSA group had more support structures, which had to be removed during postprocessing, over more expansive areas than the larger MSA group. Nevertheless, more support structures are advantageous since the 50-degree MSA exhibited the highest trueness with mean RMS values less than 50 µm.

The trueness of ceramic AM prostheses or fixtures has been evaluated.[7-12] The intaglio surface trueness of AM zirconia dental prostheses has been reported to be comparable with or inferior to those of milled prostheses; however, all the specimens were within the limit of clinical acceptance, with RMS values less than 50 µm.[7,9-12] The clinically acceptable limit in this study for trueness analysis was set to 50 µm as in previous studies.[11,20-24] Since the experiment with single-unit prostheses was to investigate the influence of MSA on trueness to meet the clinically acceptable guidelines, the absolute value of 50 µm was used to evaluate DLP-generated specimens rather than comparing DLP-generated specimens with a control group. In this study, using the 50-degree MSA, all the measured RMS values of the intaglio surfaces of DLP-generated zirconia single-unit and 2-unit prostheses were below 50 µm. The light source, techniques, and suspension composition could be different among the evaluated protocols; however, it can be concluded that AM enables the fabrication of anatomic contour monolithic prostheses with sufficient accuracy and reliability.[14]

Optimizing the AM process for the material, considering the geometry and characteristics of the printed objects, is essential.[15] In the present study, a top-down approach was used for DLP. A bottom-up approach may be useful because it requires fewer materials and is less expensive than a top-down approach.[14,26] However, the top-down approach has advantages over the bottom-up approach for ceramic AM in terms of the number of support structures required, the light intensity without reduction, and no detachment movement at each layer.[27]

Limitations of the present study include that a dedicated device for zirconia AM has not been optimized for dental application. Among numerous AM techniques, none has been determined as the best option for producing ceramic dental prostheses. However, the effect of MSA on the trueness of anatomic contour prosthesis was revealed, highlighting the importance of support attachment design during AM with zirconia suspension. Only 2 types of dental prostheses (single- and 2-unit) were evaluated. The dimension and geometric complexity of various forms of fixed prostheses should be tested in the future. The sintering shrinkage and color reproduction of ceramic AM objects still have to be

Table 3. Mean ±standard deviation and (minimum, maximum) of root-mean-square (μm) values of anatomic contour zirconia 2-unit prostheses produced with 50-degree MSA, measured at 4 different intaglio regions of inspection (intaglio surface and margin, axial, and occlusal areas)

Group	Intaglio Surface	Margin Area	Axial Area	Occlusal Area
MIL	19.1 ±1.3^{a}(17.6, 21.2)	23.5 ±4.3^{c}(19.3, 31.5)	16.9 ±1.9^{e}(13.4, 19.5)	15.1 ±2.3^{g}(12.7, 20.4)
DLP	29.5 ±2.8^{b}(25.9, 33.9)	34.8 ±2.2^{d}(31.8, 37.7)	29.9 ±5.6^{f}(23.8, 38.6)	19.2 ±1.1^{h}(17.3, 21.2)

DLP, digital light processing; MIL, 5-axis milling; MSA, maximum support attachment angle. Different letters within each column indicate statistically significant differences ($P<.001$) with individual independent *t* tests.

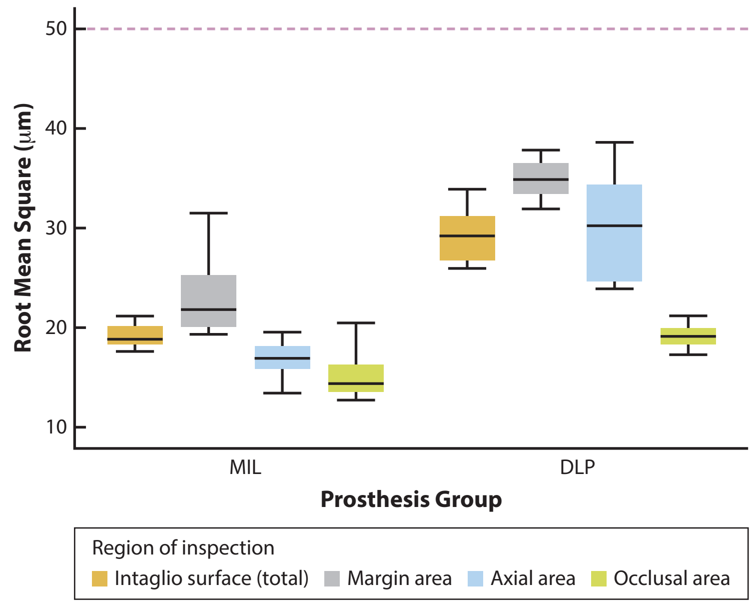

Figure 5. Box-whisker plot of RMS (μm) values of anatomic contour zirconia 2-unit prostheses produced with 50-degree MSA, measured at 4 different regions of inspection (intaglio surface, margin, axial, and occlusal areas) for groups MIL and DLP. Clinically acceptable limit of intaglio surface trueness (RMS) suggested as 50 μm (*dotted red line*). DLP, digital light processing; MIL, 5-axis milling; MSA, maximum support attachment angle; RMS, root-mean-square.

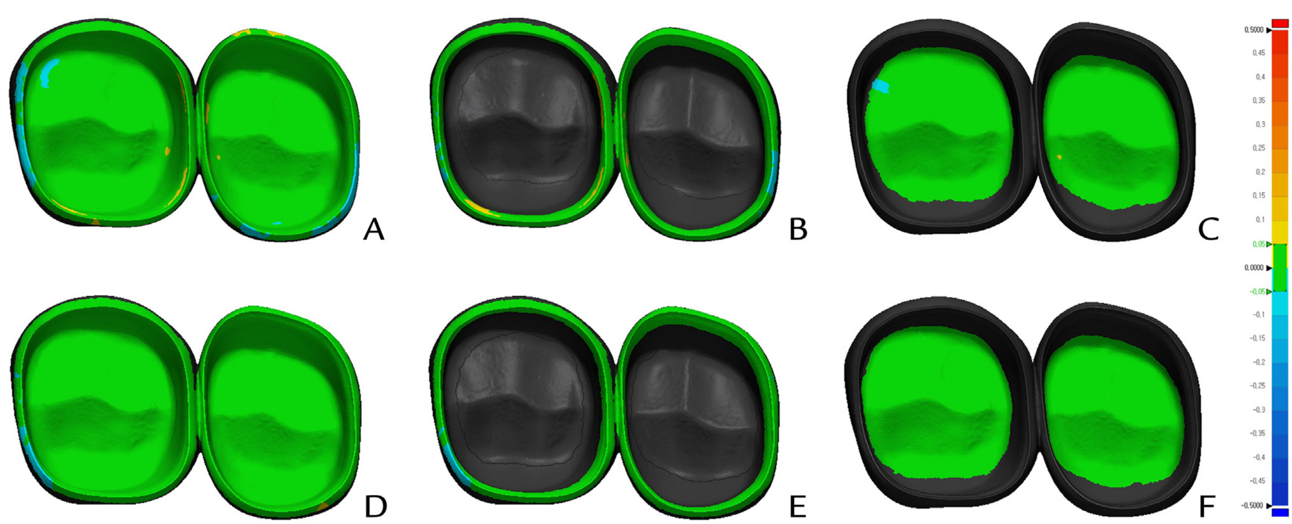

Figure 6. Three-dimensional color deviation map of intaglio surface of anatomic contour zirconia two-unit prostheses manufactured by digital light processing (upper row) with 50-degree MSA and by five-axis milling (lower row). A, D, Intaglio surface. B, E, Margin area. C, F, Occlusal area. Nominal deviation ±50 μm, and critical deviation ±500 μm. MSA, maximum support attachment angle.

overcome for dental application. Lastly, the external surface of the prosthesis was not examined since the support structures were attached to the occlusal surface. The area of attached support structures might differ from the original design of the object after postprocessing, which necessitates further research.

CONCLUSIONS

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

1. The intaglio surface trueness of anatomic contour monolithic prostheses can be improved by changing the maximum support attachment angle (MSA) during DLP using a zirconia suspension.
2. With the use of an MSA of 50 degrees, the intaglio surface trueness of a DLP-generated prosthesis was less than 50 μm, which was within the clinically acceptable limit.

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