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RESEARCH AND EDUCATION

Effect of build angle on the dimensional accuracy of monolithic zirconia crowns fabricated with the nanoparticle jetting technique

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ABSTRACT

Statement of problem. The build angle is an essential parameter in additive manufacturing. Its effect on the dimensional accuracy of zirconia restorations fabricated using the nanoparticle jetting (NPJ) technique is unknown.

Purpose. The purpose of this in vitro study was to evaluate the effect of the build angle on the dimensional accuracy of monolithic zirconia complete crowns fabricated by using NPJ.

Material and methods. Standardized artificial right maxillary incisors and mandibular first molars were prepared for ceramic complete crowns. In total, 100 monolithic zirconia crowns were fabricated using NPJ at build angles of 0, 45, 90, 135, and 180 degrees (n=10/angle for incisors and molars). The dimensional accuracies in the external, marginal, and intaglio regions were determined by superimposing the scanned data and computer-aided design data on the crowns. Root mean square (RMS) values were used to analyze the accuracy of the zirconia crowns overall and at the external, marginal, and intaglio surfaces. The Shapiro-Wilk test was used to examine the normality of data distribution. Differences among test groups were assessed using a 1-way analysis of variance and the post hoc least significant difference test (α=.05).

Results. Significant differences were found in the accuracy of monolithic zirconia incisor and molar complete crowns in the external, marginal, and intaglio regions among the 5 build angles (P<.05). For incisors, the external RMS value was lowest for a build angle of 45 degrees (18.2 ±3.0 µm), the marginal and intaglio RMS values were lowest for a build angle of 135 degrees (47.4 ±10.7 and 26.5 ±6.1 µm, respectively), and the overall RMS values did not differ significantly among the 5 build angles (P>.05). For molars, build angles of 0 degrees and 180 degrees yielded the lowest RMS values overall (22.3 ±1.5 and 21.8 ±3.2 µm, respectively) and in the external (23.2 ±2.9 and 22.3 ±2.5 µm, respectively) and intaglio (22.2 ±3.7 and 21.2 ±4.6 µm, respectively) regions. No significant difference was observed in the marginal area among the 5 build angles (P>.05). The overall RMS values reflecting dimensional accuracy for the 5 build angles were between 23.5 and 26.7 µm for incisors and 21.8 and 26.2 µm for molars.

Conclusions. The dimensional accuracy of monolithic zirconia crowns fabricated by using NPJ was affected by the build angle and was within clinically acceptable limits. (J Prosthet Dent 2023;130:613.e1-e8)

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Clinical Implications

The build angle influences the dimensional accuracy of additively manufactured restorations. Monolithic zirconia crowns fabricated using the nanoparticle jetting technique have a high degree of accuracy that is within clinically acceptable limits, regardless of the build angle.

Zirconia is used widely in prosthetic dentistry, with advantages that include excellent mechanical and esthetic properties, chemical stability, and biocompatibility.[1–3] Zirconia restorations are produced predominantly by using a computer-aided design and computer-aided manufacturing workflow involving the application of subtractive or additive manufacturing methods.[4–6] Additive manufacturing is increasingly being used in dentistry because it enables the fabrication of complex shapes while minimizing material waste and is thus a promising approach to the fabrication of dental restorations.[7–10]

Nanoparticle jetting technology is an emerging additive manufacturing technique that falls into the category of material jetting.[11] During NPJ fabrication, zirconia ink is ejected through a nozzle and deposited onto a build platform, where it accumulates in layers to create a green body with a programmed resolution of 16.000×17.625 μm and a layer thickness of 10.5 μm.[12–14] Unlike photopolymerization techniques such as digital light processing and stereolithography in which the green bodies are supported by zirconia pillars, the zirconia green body of the NPJ technique is enveloped and supported by printed support materials.[3,14] After the printing is completed, the support material is removed by immersion in demineralized water, eliminating the shape errors introduced during manual manufacturing.[13,15] The complete crowns fabricated by using NPJ have been reported to have greater dimensional accuracy and marginal adaptation than those fabricated with the milling technique or digital light processing, demonstrating the potential usefulness of NPJ for dental restorations.[16]

Additive manufacturing is influenced by various factors, and the selection of appropriate printing parameters is essential to achieve optimal clinical outcomes.[17,18] An important parameter is the build angle, determined during the initial steps of additive manufacturing, as it influences the direction of interlayer construction and the surface morphology of the restoration.[19] The build angle affects the flexural strength, compressive strength, surface roughness, and reproducibility of a definitive restoration.[20–23] The dimensional accuracy of a restoration influences its clinical adaptation and longevity,[24] with poor shape accuracy leading to suboptimal clinical fit, potentially causing plaque accumulation, microleakage, and damage to the periodontal and pulpal tissues.[25] Zirconia bars printed at different orientations have been reported to exhibit different degrees of warpage and deformation, suggesting that the build angle impacts the dimensional accuracy of additively manufactured ceramics.[13,26,27] However, previous studies of the impact of the build angle on the dimensional accuracy of restorations have focused on the resin interim crowns, investigating only the intaglio surface accuracy of complete crowns.[19,28,29] The effect of different NPJ build angles on the dimensional accuracy of complete monolithic zirconia crowns remains unclear.

Thus, this in vitro study evaluated the dimensional accuracy of incisor and molar complete crowns fabricated by using NPJ at different build angles. The null hypotheses were that the dimensional accuracy in the external, marginal, and intaglio regions would not differ among the monolithic zirconia crowns fabricated by using NPJ at different build angles.

MATERIAL AND METHODS

This study was performed according to the checklist for reporting in vitro studies guidelines. A prosthodontist (J.L.) prepared typodont right maxillary incisors and mandibular first molars (A5SAN 500; Nissin Dental Products Inc) with a diamond rotary instrument (TR13; MANI) to produce ceramic crowns with incisal and occlusal reductions of 1.0 mm and a uniform chamfer of 0.7 mm (Fig. 1). The test models were digitalized by using an intraoral scanner (TRIOS 3; 3Shape A/S), and complete crowns with the standard morphology were designed by using a design software program (DentalCAD 3.0 Galway; exocad GmbH). The cement space was set to 30 μm, extending 1.0 mm from the crown margin.

The designed crown data were converted to standard tessellation language files and imported into the NPJ system for the fabrication of complete crowns. The build angles used were 0, 45, 90, 135, and 180 degrees (Fig. 2). At the build angle of 0 degrees, the intaglio surface of the crown faced the build platform and the crown rotated at 5 angles. When the crown was positioned at 180 degrees, its occlusal and incisal regions faced the build platform. In total, 100 incisor and molar complete crowns were fabricated with 5 build angles (n=10/angle) by using an inkjet NPJ printer

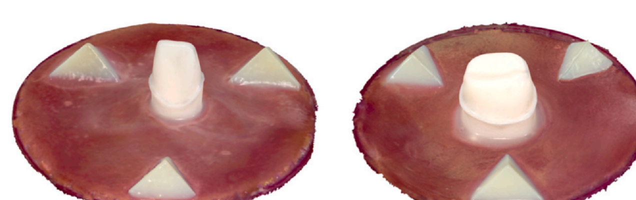

Figure 1. Resin tooth preparation for zirconia complete crowns of incisor and molar on custom base. Left image, incisor preparation. Right image, molar preparation.

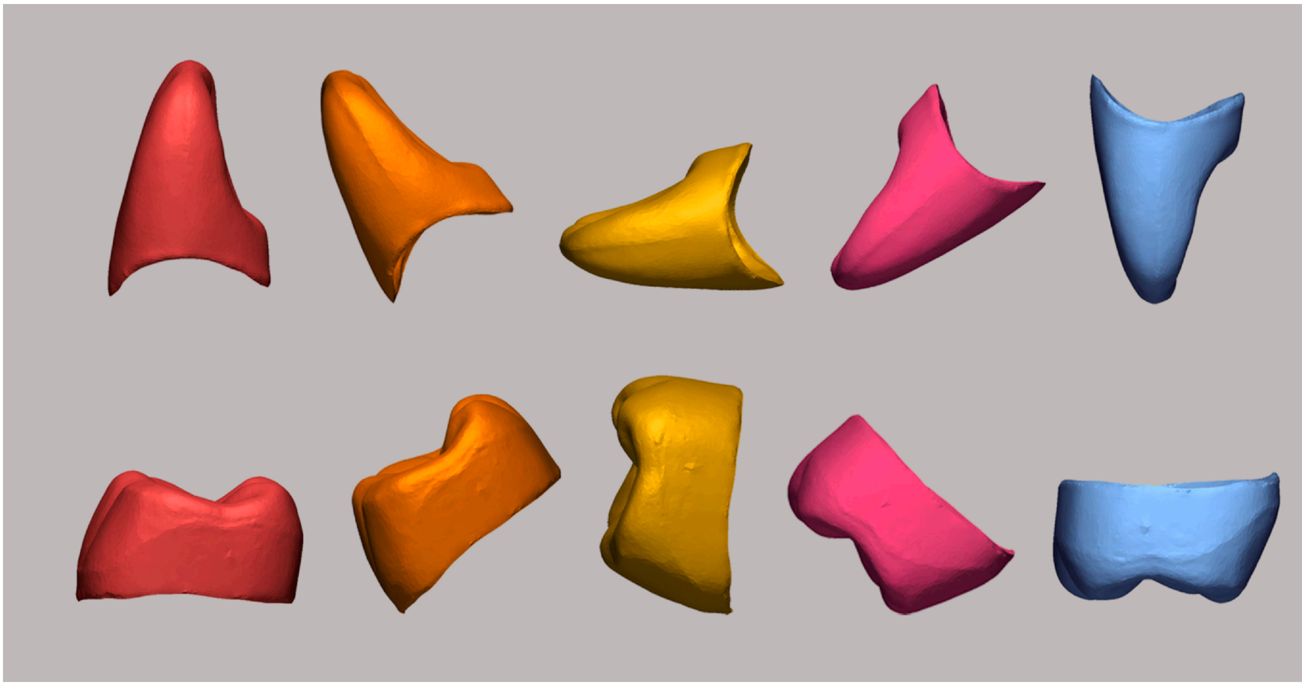

Figure 2. Illustration of build angles of incisors and molars. Upper images, incisors. Lower images, molars. From left to right, build angles 0, 45, 90, 135, and 180 degrees.

(Carmel 1400C; Xjet). During fabrication, fluid droplets of a zirconia ceramic suspension (C800; Xjet) encircled by support material (SC300; Xjet) were jetted onto a heated build tray at a layer thickness of 10.5 μm. The zirconia ink (C800; Xjet) consisted of approximately 45% zirconia powder stabilized by 3 mol% yttrium oxide combined with glycol ethers and a dispersing agent, and the support ink (SC300; Xjet) contained 31 wt% sodium carbonate blended with glycol ethers and a dispersing agent. The printed green body contained a 300-μm gap between the complete crown and the support envelope, facilitating separation of the support envelope during washing after printing. After the designed height had been achieved, the printed restoration was immersed in demineralized water for 6 to 8 hours to dissolve the support material and produce the ceramic green body. After printing and washing, the crowns were placed on a metal raster for drying in ambient air overnight. The green bodies were then debinded in a muffle furnace (Laboratory furnace RHF 1200; Carbolite) at 600 °C for 1 hour and sintered at 1450 °C for 4 hours in a high-temperature furnace (Chamber Furnace HT 16/17; Nabertherm) to achieve the final density.

An intraoral scanner (TRIOS 3; 3Shape A/S) was used to digitalize the 100 fabricated crowns, and the scanning was conducted by an experienced prosthodontist (J.L.). Repeat scans of the same crown found an RMS value of less than 15 μm, indicating the reliability of the scanning. The acquired data were imported into a measurement software program (Geomagic Studio 2013; 3D System) and aligned with CAD data by using a reference best-fit alignment method. The three-dimensional (3D) comparison was performed to determine the distances between the 2 data types in the external, marginal, intaglio (Fig. 3), and overall regions (by selecting all surfaces of the crown). Root mean square (RMS) values were computed to evaluate the dimensional accuracy of the crowns by using the following equation: $\mathrm{RMS} = \frac{\sqrt{\sum_{i=1}^{n}(X_{1,i} - X_{2,i})^2}}{\sqrt{n}}$, where n is the total number of measurement points, $X_{1,i}$ is point i in the reference data, and $X_{2,i}$ is point i in the measured data. The RMS values indicated the degree of deviation between the 2 data types, with low values indicating high degrees of 3D consistency of the superimposed data. The 3D comparison results are presented as color difference maps, with red indicating positive errors, an excess of material compared with the design data, and blue indicating negative errors, insufficient material in the fabricated crowns.

Statistical analyses were conducted with a statistical software program (IBM SPSS Statistics, v26.0; IBM Corp). The normality of data distribution was examined by using the Shapiro-Wilk test. Data from the accuracy test met normal distribution (P>.05 in the Shapiro-Wilk test), and differences among the test groups were assessed by using 1-way ANOVA and the post hoc least significant difference test (α=.05).

RESULTS

RMS values for the overall, external, marginal, and intaglio regions for incisor and molar crowns fabricated

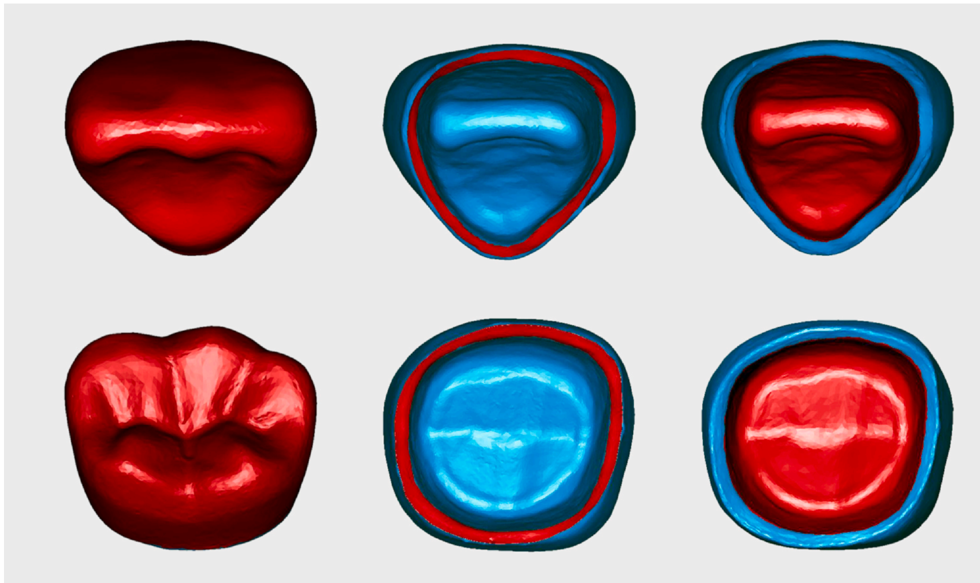

Figure 3. Regions defined for crown data. Left, external surface analysis. Middle, marginal region analysis. Right, intaglio surface analysis.

with the 5 build angles are presented in Table 1 and Table 2. A software program (G*Power v.3.1.9.6; Heinrich-Heine University) was used to calculate the post hoc actual power, which was 0.84.

For incisor complete crowns, the build angle did not affect the overall crown accuracy (*P*>.05). However, it produced significant differences in the external, marginal, and intaglio regions (*P*<.05). For the external surface, the RMS value was lowest for a build angle of 45 degrees (18.2 ±3.0 μm) and highest for an angle of 90 degrees (24.1 ±5.2 μm). For the marginal and intaglio regions, RMS values were lowest for a build angle of 135 degrees (47.4 ±10.7 and 26.5 ±6.1 μm, respectively).

With regard to molar crowns, the overall accuracy differed among the 5 build angles (*P*<.05), with RMS values lowest for 0 degrees and 180 degrees (22.3 ±1.5 and 21.8 ±3.2 μm, respectively) and highest for 45 degrees and 90 degrees (25.9 ±5.1 and 25.4 ±3.7 μm, respectively). Build angles of 0 degrees and 180 degrees produced the lowest RMS values for the external (23.2 ±2.9 and 22.3 ±2.5 μm, respectively) and intaglio (22.2 ±3.7 and 21.2 ±4.6 μm, respectively) surfaces. For

Table 1. Means ±standard deviations of root mean square values of trueness (μm) for dimensional accuracy of incisor complete crowns fabricated with 5 build angles

Group	Overall	External	Marginal	Intaglio
0 degrees	23.5 ±4.6[a]	20.0 ±5.6[a]	69.7 ±7.8[a]	28.6 ±5.6[a,b]
45 degrees	24.6 ±4.5[a]	18.2 ±3.0[a]	61.5 ±9.4[a,b]	33.4 ±8.8[a]
90 degrees	24.1 ±3.9[a]	24.1 ±5.2[b]	58.8 ±5.3[b]	23.8 ±2.5[b]
135 degrees	23.6 ±5.1[a]	22.0 ±5.1[a,b]	47.4 ±10.7[c]	26.5 ±6.1[b]
180 degrees	26.7 ±5.0[a]	22.0 ±4.7[a,b]	63.7 ±12.7[a,b]	33.2 ±5.8[a]
F value	0.824	2.662	7.393	4.774
P	.517	.045	<.001	.003

Different letters in same column indicate statistically significant differences (*P*<.05).

Table 2. Means ±standard deviations of root mean square values of trueness (μm) for dimensional accuracy of molar complete crowns fabricated with 5 build angles

Group	Overall	External	Marginal	Intaglio
0 degrees	22.3 ±1.5[a,b]	23.2 ±2.9[a,b]	44.5 ±6.8[a]	22.2 ±3.7[a,b]
45 degrees	25.9 ±5.1[c]	25.4 ±3.1[b,c]	50.4 ±7.4[a]	26.7 ±7.1[b,c]
90 degrees	26.2 ±4.5[c]	25.8 ±4.2[b,c]	47.4 ±8.9[a]	28.2 ±6.7[c]
135 degrees	25.4 ±3.7[b]	27.1 ±3.0[c]	44.4 ±6.8[a]	23.2 ±4.8[a,b,c]
180 degrees	21.8 ±3.2[a]	22.3 ±2.5[a]	42.5 ±8.0[a]	21.2 ±4.6[a]
F value	2.971	3.728	1.878	2.904
P	.029	.011	.131	.032

Different letters in same column indicate statistically significant differences (*P*<.05).

the marginal region, no significant difference was observed among the 5 build angles ($P>.05$).

The dimensional accuracies of the incisor and molar crowns were compared according to the build angles with the lowest RMS values. The comparison of the 2 different tooth groups with the greatest dimensional accuracy (135 degrees for incisors and 0 degrees for molars) revealed no significant difference in the overall, external, marginal, or intaglio region ($P>.05$).

Color difference maps are presented in Figure 4. For incisors, larger green areas were observed for build angles of 90 degrees and 135 degrees at the marginal and intaglio surfaces, whereas varying degrees of false positive error were observed for angles of 0 degrees, 45 degrees, and 180 degrees. On the external surface, the 90-degree angle produced more frequent false positive errors on the labial and lingual sides than did the other angles. For molars, the angles of 45 degrees and 90 degrees produced false positive errors on the external, marginal, and intaglio surfaces, whereas large green areas were observed for 0 degrees and 180 degrees. In all groups, errors were distributed predominantly at the tooth cusps and the occlusal-axial transition area.

DISCUSSION

This study was conducted to assess the dimensional accuracy of monolithic zirconia complete crowns fabricated by using NPJ technology with different build angles. The results revealed significant differences in crown accuracy in the external, marginal, and intaglio regions among crowns fabricated by using different build angles except for the marginal region of molars, leading to a partial rejection of the null hypothesis.

The dimensional accuracy of complete crowns significantly affects function and longevity.[24] The accuracy of the margin and intaglio surface determines the clinical adaptation of the restoration, and poor accuracy can lead to plaque accumulation and inflammation.[25] Though external accuracy can be improved through machining and polishing, high degrees of accuracy reduces the chairside adjustment time and the negative impact on occlusion.[14] The results of this study found that the build angle significantly affected the external, marginal, and intaglio accuracies of complete zirconia crowns.

The build angle did not affect the overall accuracy of incisor crowns. However, a build angle of 135 degrees yielded more accurate marginal and intaglio surfaces than the other angles. These results were consistent with those of a previous report stating that 135 degrees were the optimal build angle for the marginal and intaglio accuracy of interim resin crowns,[19] as crowns placed at 135 degrees have the most favorable self-supporting geometry.[19] However, the present study found smaller differences in RMS values among different angulations, possibly because the supporting structures consisted primarily of resin support rods when the crowns were printed by photopolymerization and the support structure's number and placement significantly influenced the accuracy of the definitive restorations.[29] Zirconia crowns fabricated by using NPJ were supported uniformly by the printed support material, reducing the influence of the self-supporting geometry on the definitive restoration.

For molars, significantly better accuracy of overall and in the external and intaglio regions was found with build angles of 0 degrees and 180 degrees than with other build angles. These results can be attributed to the smaller dimensions in the layer stacking direction and the smaller number of layers, resulting in less residual stress caused by layer interaction during sintering.[30] Additively manufactured ceramics exhibit residual stress between layers after sintering, which leads to the warpage of the definitive ceramic material.[30] Zirconia bar specimens printed with the long axis used as the build direction have been reported to exhibit more noticeable warpage than specimens printed with the short axis used as the build direction, as the long axis has more layers and consequently more residual stress.[27] In the present study, the total number of layers was minimal with build angles of 0 degrees and 180 degrees, resulting in the least residual stress and deformation after sintering. In incisors, the 90-degree angle, which resulted in the lowest number of layers among groups, also yielded low RMS values for the marginal and intaglio regions.

The color maps illustrate the locations of errors in the complete crowns built with different orientations, with false positive errors indicating an excess of material compared with the design data and false negative errors indicating insufficient material and unexpectedly high degrees of shrinkage. For the incisors, the 90- and 135-degree groups had larger green areas in the marginal and intaglio regions, indicating greater accuracy. For the molars, the 0- and 180-degree groups had larger green areas in the external, marginal, and intaglio regions, indicating greater accuracy than in the other groups. The build angle also affected error distribution, with more false-positive errors observed along the layer stacking direction. False positive errors were observed on the labial and lingual surfaces of incisors fabricated with the angle of 90 degrees, on the cusps of molars fabricated with the angles of 0 degrees and 180 degrees, and on the proximal surfaces of molars fabricated at 90 degrees. These findings were consistent with previous findings suggesting that the actual build direction length of bar-shaped zirconia specimens is greater than that of the design, indicating less shrinkage in the build

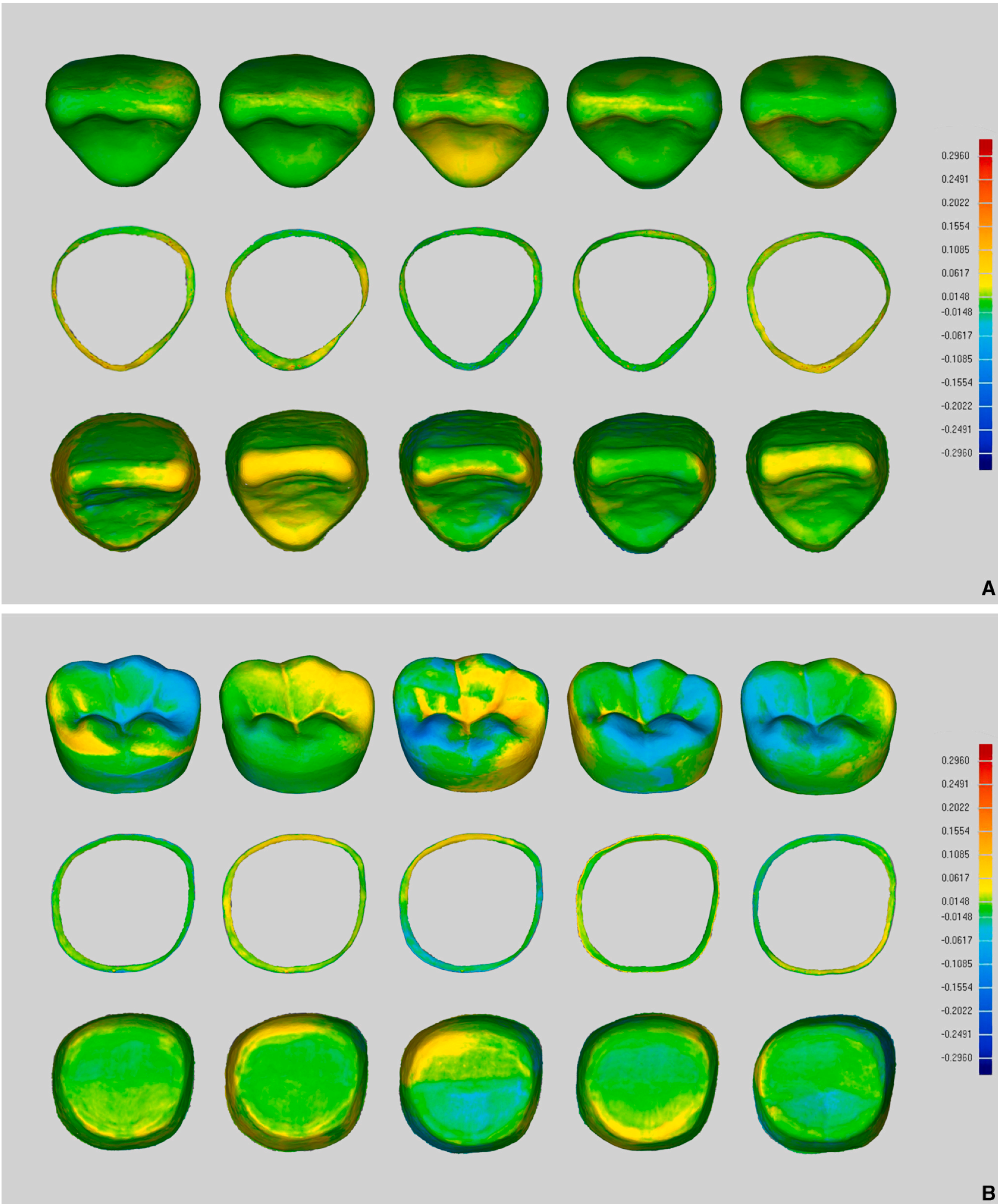

Figure 4. Representative three-dimensional comparison images of incisors and molars with different build angles. A, Incisor complete crowns. B, Molar complete crowns. Upper, middle, and lower images show external, marginal, and intaglio surfaces, respectively. From left to right, build angles 0, 45, 90, 135, and 180 degrees. Colors indicate deviation values ranging from −296 µm (*blue*) to +296 µm (*red*).

direction.[13] Moreover, delamination along the layers and defects were observed along the build direction, creating space between the layers and introducing dimensional inaccuracy.[13,27]

Although different build angles affected the accuracy of the overall, external, marginal, and intaglio regions of the complete crown, all build angles yielded RMS values of trueness for dimensional accuracy that fulfilled the clinical requirements (<100 µm).[14,31] NPJ printing with a layer thickness of 10.5 µm and resolution of 16.000×17.625 µm ensured a high degree of precision. For the clinical efficacy and durability of zirconia crowns, build angles with higher marginal and intaglio accuracy are recommended.

An intraoral scanner (TRIOS 3; 3Shape A/S) was used to digitalize the printed crowns. The manufacturer states that the scanner has an accuracy of 6.9 µm, which is sufficient for small scans of complete crowns, as in the present study. The use of a laboratory scanner to digitalize the fabricated crowns would result in data gaps because of the inability of light to reach certain regions.[32] The scan data for the fabricated crowns were compared with the design data by using a best-fit algorithm, and RMS values were calculated following the standard procedure.[33]

Limitations of this study included that a single material jetting technology of additive manufacturing method was used. Thus, the results obtained with the use of different build angles cannot be extrapolated to all 3D zirconia printing methods. Furthermore, parameters other than the build angle that can impact the effectiveness of 3D ceramic printing were not evaluated. A previous study reported that the mechanical properties of zirconia by NPJ were lower than of milled zirconia, which could be a disadvantage of NPJ.[12] Further research is needed to optimize the performance of 3D printed zirconia restorations for clinical applications.

CONCLUSIONS

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

1. The accuracy of the additive-manufactured monolithic zirconia complete crowns was affected by the build angles.
2. Build angles of 90 degrees and 135 degrees for anterior teeth and 0 degrees and 180 degrees for posterior teeth yield the greatest accuracy for zirconia crowns fabricated by using NPJ.
3. Zirconia complete crowns fabricated by using NPJ have high and clinically acceptable accuracy, regardless of the build angle.

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