学位論文

CAD/CAM restorations fabricated over intraoral-scan-aided reverse tapered preparations

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INTRODUCTION

The geometry of prepared teeth and the amount of tooth structure removed are important contributors to the mechanical, biological, and esthetic success of fixed partial prostheses. Such geometric forms will provide retention and resistance to the abutment tooth and they should be maximized to improve the clinical serviceability of dental restorations. In this regard, Jorgensen[1] demonstrated in 1955 that, as the total occlusal convergence (TOC) angle of a prepared tooth increases, its ability to retain a restoration decreases in a hyperbolic relationship with parallel axial walls providing maximum values, and highly converging walls providing the least. However, dental students, residents, general dentists, and prosthodontists do not routinely achieve parallel walls or optimal TOC angles (less than 10°) as it is a clinically challenging task prone to preparation undercuts.[2-4]

In fact, the reported frequency of preparation undercuts in prepared teeth ranged from 59.1% (final year students, in vitro)[3] to 30.7% (experienced general dental practitioners, in vivo)[4] when attempting to achieve low TOC values. In addition, it has been shown that mean TOC angles vary depending on whether the tooth preparation was completed in a preclinical setting or in real clinical situations.[5-9] Usually, lower TOC angles are achieved in preclinical situations although Annerstedt et al.[9] found that dental students achieved lower TOC angles (19.4°) than the ones created by dentists (22.1°); therefore, realistic TOC angles fluctuate within the 10°-22° range[2] with no apparent correlation to the operator's level of education or experience.[2, 9,10-14]

On the other hand, the latest version of The Glossary of Prosthodontic Terms[15] defines an undercut as "any irregularity in the wall of a prepared tooth that prevents the withdrawal or seating of a wax pattern or casting", and as general principle, undercuts should be avoided during tooth preparation or blocked out to a great extent before making a conventional impression so as to prevent distortion of the impression when it is removed from the mouth. However, in a fully digital workflow, neither casting nor wax patterns are used but rather digital models of abutment teeth recorded with a camera (intraoral scanner). Therefore, reverse tapered preparations (negative TOC angles) are not a restricting factor for digital impressions because the scanner will record them as long as it is rotated to completely visualize the whole preparation.[16]

Moreover, to overcome a minor preparation undercut dentists usually remove (overprepare) dental structure until a tapered preparation is obtained.[10] This could be prevented to some extent without sacrificing the integrity of the definitive restoration if clinicians take advantage of the undercut-blocking algorithms from the CAD software at the design stage of a fully digital workflow, provided that the software can successfully manage them.

This fully digital restorative workflow is meant to avoid the error-prone multistep process of conventional impressions, gypsum cast production, extraoral digitalization,[17] and conventional manufacturing of dental crowns by using a more standardized, reliable, and predictable approach.[18-20] However, the workflow is not exempt from errors, and inaccuracies that may arise during its execution[21-24] will have a cumulative effect throughout the production process. If these errors are not controlled, threshold values[25-37] for the marginal, and internal fit of dental restorations could be crossed, compromising the biological, esthetic and mechanical success of such restorations.[38-41]

Furthermore, the main concern when fabricating dental crowns over reverse tapered preparations would be the long-term mechanical stability of such restorations because the virtual space generated after digitally blocking out those abutments will be filled with a non-uniform cement film whose intrinsic properties will influence on the retentive strength and fracture resistance of such crowns under aging conditions.

In this context, to the best of the author's knowledge, no published study has yet addressed the effects of undercut-blocking algorithms of the CAD software on definitive dental restorations or quantified the amount of dentine that could be preserved with this strategy. Therefore, the purpose of this study was to develop a new minimally invasive concept to create dental restorations with the aid of intraoral scanners within a fully digital workflow. The null hypothesis was that minimally invasive reverse tapered preparations can be accurately recorded with direct digital scanning, and that the fit and mechanical properties of CAD/CAM crowns made from those impressions would be similar to the ones from conventional preparations.

MATERIAL AND METHODS

Digital model preparation

A resin maxillary left central incisor (Nissin Dental Products Inc., Kyoto, Japan) was scanned with a desktop scanner (KaVo Arctica Scan; Smartoptics Sensortechnik, Bochum, Germany), and a mesh of the tooth surface was generated with proprietary software. The surface meshing was followed by nonuniform rational B-splines (NURBS) conversion to obtain a 3D model. Starting from the intact tooth model, a total of 9 preparations were created with general-purpose CAD software (Rhinoceros 3D for Windows; McNeel North America, WA, USA) by removing tooth structure in increments with different total occlusal convergence (TOC) angles in the mesiodistal aspect, namely -8°, -6°, -4°, 0°, 4°, 8°, 12°, 16°, and 22° preparations (Fig. 1). The preparation was for a complete ceramic crown in accordance with standard guidelines.[42]

Experiment 1: Determination of the accuracy of impressions made on reverse tapered preparations and quantification of volumetric differences among different abutment tooth geometries

1.1 Reference model and reference scan

All previously created models were printed (ProJet 3500HD Max; 3D Systems, Morrisville, NC, USA) in acrylic resin to obtain a physical reference model. Each of these 9 reference models was scanned 5 times (n = 5) with the reference scanner (Rexcan DS; Solutionix, Seoul, South Korea [manufacturer's specifications: accurate to within 10 µm]), and the resulting reference scan data set (R_1-R_5) was further compared with all other test groups.

1.2 Conventional silicone impressions

Forty-five conventional 2-step impressions were made with polyvinyl siloxane (PVS) material (Examixfine putty/wash; GC Corp., Tokyo, Japan), with 5 copies obtained (n = 5) for every reference model (-8°, -6°, -4°, 0°, 4°, 8°, 12°, 16°, and 22° preparations). To simulate the clinical workflow, all impressions were made with prefabricated, individual acrylic trays of 4 mm thickness coated with tray adhesive (Adhesive; GC Corp., Tokyo, Japan). All impression materials were mixed in standardized proportions according to the manufacturer's recommendations at room temperature (25°C) and ambient humidity by a single investigator (JC). The preliminary putty impressions were made first, with a plastic foil on top of the reference model, and left for 8 minutes to polymerize. The second step included the removal of the plastic foil, injection of the wash material, and removal of the impressions after 8 minutes of polymerization time. Once obtained, all impressions were disinfected for 10 minutes (MD 520; Dürr Dental AG, Bietigheim-Bissingen, Germany), cast after 8 hours with a Type IV gypsum (New Fujirock; GC Corp., Tokyo, Japan), and stored for 48 hours. Next, all gypsum casts were scanned once with the reference scanner and the data were exported as STL files.

1.3 Extraoral and intraoral scanning

All previously prepared gypsum casts (5 casts per reference model) were scanned once with a desktop scanner (KaVo Arctica Scan; Smartoptics Sensortechnik, Bochum, Germany; KAV) according to the manufacturers' instructions and exported as STL files. This resulted in 5 extraoral scans (n = 5) of the same reference model. For the direct digital impressions group, a matting powder (Okklusionsspray; Yeti Dental, Engen, Germany) was used to pretreat the surface of the reference model before obtaining 5 optical impressions per model (n = 5) with the TRIOS 2 Color Pod intraoral scanner (3Shape A/S, Copenhagen, Denmark; TRI). The impression-taking process started with the capture of images at the buccal side towards the palatal side and from the mesial side towards the distal side; the whole process lasted on average 20 seconds and approximately 120 images were captured to reconstruct the 3D model of the abutment. This scan data was sent to the manufacturer for postprocessing and further exported as STL data files.

1.4 Accuracy measurement

Data handling and computations were performed with metrology software (Geomagic Control 2014; 3D Systems, Morrisville, NC, USA). Artifacts from the visualized data sets and unnecessary data below the simulated preparation margin were removed. To compare the test groups with the reference model, 1 scan was selected randomly from the 5 reference data sets (R_1-R_5) with a smart phone application (Undecided; Deadmans Productions, NY, USA) and imported into the metrology software along with the data sets from the PVS, KAV, and TRI groups. An initial manual alignment of the scans was done with the subsequent use of the software's best-fit algorithm. The maximum deviation accepted for the best-fit alignment was set at 0.1 µm for reference scans and 1 µm for test scanning data. The 3D deviation spectrum was set at 15 color segments, max/min critical was set at ±50 µm, and max/min nominal was set at ±10 µm. For quantitative analysis of 3D differences, the mean quadratic deviation (root mean square, RMS)[43-45] of the virtual reference object compared with the test objects was registered, while for the visual analysis of deviation patterns, color-coded images were saved as screenshots. The trueness values of each test group were obtained by superimposing each model scan (n = 5) with the reference scan, whereas precision values were calculated as the mean RMS between all superimposition combinations within 1 test group (n = 10, Fig. 2).

1.5 Volumetric Analysis

Abutment tooth models (-8°, 0°, 12°, and 22° preparations) were imported into Geomagic Control and the software automatically calculated volume values. To compare the models among one another, superimpositions of 4 models taken by pairs were carried out, resulting in 6 comparisons. For this purpose, an initial manual alignment of the models was performed with the subsequent use of the software's best-fit algorithm (maximum deviation accepted =1 µm). After the superimposition, the volumetric difference (mm^3) between pairs of models were registered for quantitative analysis of 3D deviations and presented as descriptive data; for the visual analysis of deviation patterns, color-coded images were saved as screenshots (Fig. 3A,B).

1.6 Statistical analysis

All RMS values were analyzed by statistical software (XLSTAT v2014; Addinsoft, NY, USA). The Shapiro-Wilk test for normality and the Levene test for equality of variances were performed ($\alpha = 0.05$). Statistical differences between the test groups were analyzed by 2-way ANOVA with 2 factors (type of impression and TOC angle) and pairwise post hoc comparisons were done with the least significant difference (LSD) test ($\alpha = 0.05$).

Experiment 2: Determination of the fit of crowns made over reverse tapered preparations.

2.1 Reference casts

Models created in experiment 1, namely -8°, -4°, 0°, 8°, 12°, 16°, and 22° preparations (Fig. 4) were printed (ProJet 3500HD Max; 3D Systems, Morrisville, NC) in acrylic resin (VisiJet M3 Crystal; 3D Systems, Morrisville, NC, USA) to obtain a physical reference model.

2.2 Intraoral digital impressions and crown fabrication

A thin uniform layer of a matting powder (Okklusionsspray; Yeti Dental Produkte, Engen, Germany) was used to pre-treat the surface of the reference model before obtaining 10 optical impressions (n = 10) per model with TRIOS Color Pod. The scan data were directly sent to the manufacturer (3Shape) for postprocessing and then exported as STL data files.

The resulting 70 digital impressions (7 groups; n = 10) were imported into KaVo multiCAD software version 2.8.0 (KaVo Dental GmbH, Biberach, Germany) and zirconia crowns were designed with the system's default parameters (50 µm cement space) for all abutments with positive TOC angles. Abutments with negative TOC angles were also designed with default settings plus two extra procedures, namely a digital block out at 0° (parallel to the abutment's long axis, Fig. 5) and an extra gap set to 50 µm (results from a pilot study) in the mesiodistal aspect. Then, all datasets were sent to a 5-axis milling unit (KaVo Arctica, KaVo Dental GmbH, Bismarckring, Germany), and crowns were milled out from semi-sintered zirconia blanks (ZS-B70/20, KaVo Dental GmbH, Bismarckring, Germany). Once milled, all restorations were sintered to their final dimensions for 6 hours at 1,450°C.

2.3 Marginal and internal fit measurement

The silicone replica technique[46-48] was used to measure the fit of the restorations. Crowns were filled with polyvinyl siloxane light-body (Examixfine Injection type; GC Corp., Tokyo, Japan) and seated on the abutment tooth with finger pressure to mimic the insertion step of a crown. Once the light-body silicone set, the excess of material was trimmed and all crowns were gently removed from the model. A thin film of pink light body remained attached to the abutment tooth model, representing the misfit of the restoration. This fragile film was fixed with a polyvinyl siloxane medium-body (Examixfine Regular type; GC Corp., Tokyo, Japan). Once set, the stable replicas were sectioned with a razor blade mesiodistally and buccolingually yielding 4 slices per crown. Twelve thickness points of the replica were measured (Fig. 6). The points from "1" to "6" were included in the buccolingual direction section and points from "7" to "12" were included in the mesiodistal direction section. Marginal discrepancy was defined as the distance between the points representing the restoration margin and the preparation finish line (points 1, 6, 7, and 12). For internal gap measurement, the gap width at the middle of axial wall (points 2, 5, 8, and 11) and the middle of the incisal edge (points 3, 4, 9, and 10) were measured. The thickness of the light-body polyvinyl siloxane representing the discrepancy between the crown and the abutment tooth was measured with a stereomicroscope (SMZ 745T; Nikon Corp., Tokyo, Japan) at ×50 magnification.

2.4 Statistical analysis

Descriptive statistics, including means, standard deviations, medians, and interquartile ranges of the fit accuracy were calculated for each group with XLSTAT v2014 computer software (Addinsoft, New York, NY). Shapiro-Wilk test for normality and the Levene test for equality of variances were performed ($P < 0.05$). Statistical differences among the test groups that followed a normal distribution were analyzed by one-way ANOVA with the post hoc Tukey test ($\alpha = 0.05$) whereas for nonparametric data the Kruskal–Wallis test, followed by the Dunn/Bonferroni multiple comparison test was applied ($P < 0.05$).

Experiment 3: Determination of retentive strength of crowns made over reverse tapered preparations after 1- year water storage.

3.1 Abutment preparation

Models created in experiment 1, namely -8°, -4°, 0°, 12°, 16°, and 22° preparations (Fig. 7 and 3) milled out from polymethylmethacrylate (PMMA) disks (Yamahachi Dental Mfg Co, Aichi, Japan) to obtain a physical reference model (n = 10 per TOC angle).

3.2 Fabrication of zirconia crowns

A thin uniform layer of a matting powder (Okklusionsspray; Yeti Dental, Engen, Germany) was used to pre-treat the surface of the reference models before obtaining 10 optical impressions per TOC angle with TRIOS Color Pod (3Shape A/S, Copenhagen, Denmark). The scan data were directly sent to the manufacturer (3Shape) for postprocessing and then exported as STL data files.

The resulting 60 digital impressions were imported into KaVo multiCAD software version 2.8.0 (KaVo Dental GmbH, Biberach, Germany) and zirconia crowns were designed with the system's default parameters (50 µm cement space) for all abutments with positive TOC angles. Abutments with negative TOC angles were also designed with default settings plus two extra procedures, namely a digital block out at 0° (parallel to the abutment's long axis) and an extra gap set to 0.05 mm[16] in the mesiodistal aspect. Also, a cylindrical handle was designed on the top of the crowns for the pullout test. Then, all datasets were sent to a 5-axis milling unit (KaVo Arctica, KaVo Dental GmbH, Biberach, Germany) and crowns were milled out from semi-sintered zirconia blanks (ZS-B70/20, KaVo Dental GmbH, Biberach, Germany). Once milled, all restorations were sintered to their final dimensions for 6 hours at 1,450°C.

3.3 Cementation of zirconia crowns

The intaglio of the zirconia crowns was airborne-particle abraded (Rocatec Pre, 110 µm, 20 mm distance, 200 kPa; 3M ESPE, MN, USA). Then, crowns were filled with RelyX Unicem 2 (3M ESPE, MN, USA) in accordance with the manufacturers' instructions and seated on the abutment teeth with finger pressure to mimic the insertion step of a crown. Later, we removed excess cement thoroughly with an explorer and light curing was carried out on the buccal, lingual, mesial, and distal surfaces for 20 seconds each. After cementation, all specimens were placed in a 37°C distilled water bath.

3.4 Pullout test

The 60 crowns (10 per TOC angle) underwent 1 year of storage in distilled water at 37°C ahead of performing the debonding procedure. Before debonding, all specimens were embedded in acrylic resin (Unifast III, GC Corp., Tokyo, Japan) to facilitate their precise positioning and mounting in a universal testing machine (Autograph AG-20kNG, Shimadzu Corporation, Kyoto, Japan). All cemented crowns were removed along the long axis of the abutment tooth at a crosshead speed of 0.5 mm/min (Fig. 8). The force at dislodgment (in newtons) and nature of decementation were recorded. The retentive strength (MPa) was calculated individually for each abutment tooth dividing the registered retentive forced (N) by the surface of the tooth preparation (mm^2). This surface value was computed from the TRIOS-generated STL dataset using the area-measuring tool of Rhinoceros 3D software.

The type of failure mode was divided into 4 categories according to Johnson et al.[49-51] namely, category 1: cement remnants located mainly on the abutment tooth (over 75%), category 2: cement remnants located on the crown's intaglio and the abutment tooth (between 25% and 75%), category 3: cement remnants located mainly on the crown's intaglio (over 75%), and category 4: fracture of the abutment tooth without crown separation. To characterize the pre-cementing condition of the abutments, the surface of 2 intact specimens was examined using scanning electron microscopy (SEM; JSM 6335-SEM, JEOL Ltd., Tokyo, Japan). SEM photos were made operating at ×50 and ×500 magnification to evaluate the intaglio and abutments' surface condition after the dislodgment of the crowns.

3.5 Statistical analysis

Descriptive statistics, including means, standard deviations, medians, and interquartile ranges of the retentive strength values were calculated for each group with XLSTAT v2014 computer software (Addinsoft, New York, NY, USA). The Shapiro-Wilk test for normality and the Levene test for equality of variances were performed ($\alpha = 0.05$). Statistical differences among the test groups were analyzed using the 1-way ANOVA test followed by the post hoc Tukey test ($\alpha = 0.05$). Data concerning the type of failure mode are presented as relative frequencies.

Experiment 4: Determination of the fracture resistance of crowns made over reverse tapered preparations with or without 30 days of water storage.

4.1 Abutment preparation

Models created in experiment 1, namely -8°, 0°, and 12° preparations (Fig. 9) were milled out from polymethylmethacrylate (PMMA) disks (Yamahachi Dental Mfg Co, Aichi, Japan) to obtain a physical reference model (n =20 per TOC angle).

4.2. Fabrication of glass ceramic crowns

A thin uniform layer of a matting powder (Okklusionsspray; Yeti Dental, Engen, Germany) was used to pre-treat the surface of the reference model before obtaining 10 optical impressions (n = 10) per model with TRIOS Color Pod (3Shape A/S, Copenhagen, Denmark). The scan data were directly sent to the manufacturer for postprocessing and further exported as STL data files. The resulting 30 digital impressions were imported into KaVo multiCAD software version 2.8.0 (KaVo Dental GmbH, Biberach, Germany) and crowns were designed with default parameters (50 µm cement space) for all abutments with positive TOC angles whereas abutments with negative TOC angles were digitally blocked out at 0° and had an extra mediodistal gap set to 0.05 mm.[16] Then, all datasets were sent to a 5-axis milling unit (KaVo Arctica, KaVo Dental GmbH, Biberach, Germany), and crowns were machined from Vita Mark II blocks (Vita Zahnfabrik, Bad Säckingen, Germany). After machining, all crowns were tried onto their respective dies, adjusted if needed, and glassed using a predefined firing schedule.

4.3 Cementation of glass ceramic crowns

Before cementation, the internal surface of all crowns was etched with 5% hydrofluoric acid for 60 s and immediately rinsed with flowing deionized water for 1 min. Dies were ultrasonically cleaned in deionized water (3 min) as well and dried with air. Silane (Clearfil Ceramic Primer, Kuraray Noritake Dental Inc., Okayama, Japan) was applied to the etched internal surface of all crowns according to the manufacturer's instructions. Then, all crowns were filled with a self-adhesive resin cement (RelyX Unicem 2; 3M ESPE, MN, USA) in accordance with the manufacturers' instructions and seated on the abutment dies with finger pressure to mimic the insertion step of a crown. Excess cement was removed after 2 s of light curing from two opposite directions at the margin. Light curing was carried out on their surfaces for 20 seconds each. After cementing, all specimens were placed in a 37°C distilled water bath for 24 hours.

4.4 Fracture test

After 24 hours of water storage, the 60 specimens were assigned to 2 groups: 1 group (n = 30) was immediately loaded till fracture to determine the fracture resistance, and the second group (n = 30) underwent 1 month of storage in distilled water ahead of performing the compressive loading procedure. Before loading, all specimens were embedded in acrylic resin (Unifast III, GC Corp., Tokyo, Japan) to facilitate their precise positioning and mounting in a universal testing machine (Autograph AG-20kNG, Shimadzu Corporation, Kyoto, Japan). All cemented crowns were loaded at 45° in the palatal incisal third at a crosshead speed of 0.5 mm/min (Fig. 10). To achieve even force distribution, a 0.5mm tin foil was placed between the incisal edge and the loading jig. The load to fracture (in newtons) and its failure mode were recorded.

4.5 Statistical analysis

Descriptive statistics, including means, standard deviations, medians, and interquartile ranges of the retentive strength values were calculated with XLSTAT v2014 computer software (Addinsoft, New York, NY, USA). The Shapiro-Wilk test for normality and the Levene test for equality of variances were performed ($\alpha = 0.05$). Statistical differences among the test groups were analyzed using the repeated measures ANOVA test with 2 levels (debonding after 24h or 1 month of water storage) followed by the post hoc Tukey test ($\alpha = 0.05$).

RESULTS

Experiment 1: Determination of the accuracy of impressions made on reverse tapered preparations and quantification of volumetric differences among different abutment tooth geometries

An overview of the results and statistics is presented in Tables 1-3 and Figure 11. The overall trueness values of all test groups indicated that group TRI had the smallest deviation, with a mean RMS value of 19.1 µm, followed by group KAV (23.5 µm) and group PVS (26.2 µm). Statistically significant differences occurred among all impression techniques ($P < 0.001$). The 2-way ANOVA indicated a significant difference in both the main effect type of impression and TOC angle ($P < 0.05$). A significant interaction was not indicated ($P = 0.162$; Table 2). The post-hoc LSD test showed that impressions from group TRI were significantly more accurate than impressions from groups PVS and KAV when the TOC angle was below 8° ($P < 0.05$). Qualitative analysis revealed that casts from group TRI showed a very homogenous deviation pattern (Fig.12) with no local deviations higher than +45 µm (yellow to red) whereas groups PVS and KAV had local deviations at the incisal and proximal area of the abutment tooth, especially when the TOC was below 0°; in some cases (0° and -4°), such deviations reached up to -100 µm (navy blue).

Overall precision values were identified to be the most accurate for group TRI (11.9 µm), followed by group PVS (18.0 µm) and group KAV (20.7 µm). Statistically significant differences occurred among all impression techniques ($P < 0.0001$). TRIOS showed the highest precision values for all TOC angles tested. Two-way ANOVA indicated a statistically significant interaction between the effects of the type of impression and TOC angle on the precision of single-tooth dental impressions ($P = 0.0002$; Table 2). Visual analysis showed marked local deviations on the buccal and mesiodistal aspect of the abutment tooth in groups KAV and PVS (Fig. 13). Larger deviations (up to ±50 µm, red/navy blue) were visible in the PVS and KAV groups when the TOC was below 0°. Moreover, the deviation pattern was relatively homogenous across all casts for the group TRI, except for the incisal edge, where deviations reached up to +30 µm (yellow to red).

Figures 3A, B shows superimposition combinations (4 models, taken by pairs) to quantify volumetric differences among models, namely -8 degrees vs. 0 degrees (8.1 mm^3), -8 degrees vs. 12 degrees (18.2 mm^3), -8 degrees vs. 22 degrees (28.8 mm^3), 0 degrees vs. 12 degrees (10.1 mm^3), 0 degrees vs. 22 degrees (20.7 mm^3), and 12 degrees vs. 22 degrees (10.6 mm^3). Considering 12 degrees as the most-textbook-recommended taper for tooth preparations, a -8-

degree preparation saved up to 10% (18.2 mm^3) of tooth structure. Furthermore, a digitally blocked out -8-degree preparation preserved approximately 15% (28.8 mm^3) more dental structure than a 22-degree preparation. On the other hand, the qualitative analysis of different tooth preparations showed a marked reduction of tooth structure in the incisal third (Fig 3B).

Experiment 2: Determination of the fit of crowns made over reverse tapered preparations.

In the present experiment, the Shapiro-Wilk ($P = 0.84$) and the Levene ($P = 0.27$) test were not significant for the marginal fit values, meeting equality assumptions. However, no equality of variances was found for axial and incisal fit values ($P < 0.001$). The results are summarized in Table 4 and Figures 14, 15A, and 15B. The mean marginal fit of -8° crowns (58.2 ±6.0 µm) was statistically different ($P < 0.0001$) from all the remaining crowns (range 42.1 - 47.3 µm). The Kruskal-Wallis test revealed statistical significance in the internal fit (axial and incisal) of crowns among those with negative and positive TOC angles ($P < 0.0001$). The largest median axial discrepancies were found in the -8° (165.5 µm) and -4° (130.8 µm) groups; however, when evaluating the incisal fit, they showed the smallest discrepancies (67.3 µm and 81.8 µm, respectively).

Experiment 3: Determination of retentive strength of crowns made over reverse tapered preparations after 1- year water storage.

In the present experiment, the Shapiro-Wilk ($P > 0.05$) and the Levene ($P = 0.52$) test were not significant for the retentive strength values after 1 year of water storage, meeting equality assumptions. The results are summarized in Figure 16 and Tables 5-7. The mean retentive force of -8° crowns (409.4 ± 62.5 N) after 1 year of water storage was statistically different from all the remaining crowns (range 186.1 - 352.1 N) with the highest mean retentive force found in the -8° group (3.2 MPa) and the lowest mean value in the 22° group (1.2 MPa).

One-way ANOVA indicated that the TOC group had a significant impact on the retentive strength ($P < 0.0001$) of zirconia crowns. Multiple comparison of TOC groups with Tukey test showed that the retentive strength values of groups -8° and -4° were significantly higher than the retentive strength values of groups 12°, 16° and 22° ($P < 0.05$) (Table 6).

The percentage of specimens with cement residue after the removal of the crowns according to location is presented in Table 7. After 1 year of water storage, cement remnants were found predominantly on the crowns' intaglio (category 3) although 5 out of 60 abutments showed failure type 4 and another 3 abutments presented category 2 failures (Fig. 17 A, B).

Experiment 4: Determination of the fracture resistance of crowns made over reverse tapered preparations with or without 30 days of water storage.

In the present study, the Shapiro-Wilk ($P > 0.05$) and the Levene ($P = 0.96$) test were not significant for the load to fracture values after 24 hours of water storage, meeting equality assumptions. Also, equality of variances was found for the fracture resistance after 30 days of water storage (Shapiro-Wilk test: $P > 0.05$; Levene test: $P = 0.26$). The results are summarized in Figure 18 and Tables 8. Mean load to fracture values after 24-hour water storage were 205.6 ± 42N (-8°), 233.8 ± 38 N (0°), and 218.2 ± 39 N (12°), whereas mean load to fracture values after 30-day water storage were 190.1 ± 31 N (-8°), 223.7 ± 34 N (0°), and 229.8 ± 41 (12°).

Repeated measures ANOVA indicated that the TOC angle had no significant impact on the load to fracture values ($P > 0.07$) of glass ceramic crowns. There was not a statistically significant difference ($P = 0.625$) between both test conditions (24 h versus 30 days of water storage) and neither the interaction of water storage and the TOC angle within subgroups ($P = 0.471$) was significant. Multiple comparison of different TOC groups with Tukey test showed that regardless of the water storage period, load to fracture values of all groups were not statistically significant ($P > 0.05$).

DISCUSSION

The present investigation aimed at exploring and developing a new minimally invasive concept to create dental restorations with the aid of intraoral scanners within a fully digital workflow. As dental impressions conform the gateway to the digital workflow, any error that may arise during this step of the workflow will have a cumulative effect throughout the production process (e.g. data acquisition error, modeling error or fabrication error) and it will directly influence the fit of definite restorations as well as their mechanical and clinical performance.

Accuracy of impressions and volumetric differences among tooth preparations

On the basis of the results of the present in vitro study, the null hypothesis that conventional and digital dental impressions are equally accurate was rejected. The accuracy of groups PVS and KAV was affected when the TOC angle was close to 0°, while impressions made with TRIOS were not. This result is in accordance with a previously published study,[17] except that intraoral scanning seems not to be affected by the TOC angle of a preparation.

Undercuts (negative TOC angles) should generally be avoided during tooth preparation or blocked out to a great extent before making a conventional impression to prevent distortion of the impression when it is removed from the mouth. However, negative TOC angles neither restrict the making of intraoral digital impressions nor are detrimental to their accuracy. Furthermore, if a minor undercut is recorded at the first stage of a fully digital workflow, the clinician can either remove more dental structure to obtain a tapered preparation or whenever possible take advantage of the algorithms from the CAD software to overcome. Naturally, preserving dental structure without sacrificing the integrity of the definitive restoration is desirable, provided that the design software can successfully manage negative TOC angles.

Differences in trueness and precision were found depending on the TOC angle of the abutment tooth and the impression technique. Impressions made with TRIOS showed the highest trueness and precision values even when negative angles were included in the abutment tooth. Groups PVS and KAV differed significantly from group TRI when the TOC angle was close to 0°. Casts from group KAV showed the lowest precision in relation to group TRI (11.9 µm versus 20.7 µm). This outcome is in agreement with that of Vandeweghe et al.[52] who reported large deviations in casts digitized with the KaVo scan. One of the explanations for this outcome could be the accumulation of dimensional errors originating from the impression material, gypsum, and digitization process. A second factor could be the nature of the light used by the KaVo scanner (white-light scanner), as Jeon et al.[53] showed that blue-light scanners exhibited greater precision than white-light scanners. A third explanation may be the threshold value for this scanner (the manufacturer specifies an accuracy of at least 20 µm). Contrary to these possible detrimental factors, if the margins of the extraoral scanned casts had been ditched, their accuracy might have improved[17] because ditching facilitates the automatic identification of the preparation margin by the scanning software. In contrast, Su and Sun[54] found that the precision of single-tooth intraoral impressions (TRIOS) and extraoral digitization (D800; 3Shape) was similar in either anterior (13.33 µm versus 14.89 µm) or posterior abutment teeth (7.0 µm versus 8.67 µm). Therefore, deviations found in group KAV must have been influenced by the type of scanner and the TOC angle rather than the technique itself.

A comparison of the results of the present study with previously published research on the accuracy of single-tooth intraoral digital impressions showed that previous studies reported trueness values of 27.9 µm (CEREC),[43] 19.2 µm (CEREC Bluecam)[55] and 6.9 µm (TRIOS),[56] and precision values of 13.3 µm (TRIOS),[54] 10.8 µm (CEREC Bluecam),[55] and 4.5 µm (TRIOS),[56] while the present work found trueness values as accurate as 19.1 µm and precision values as accurate as 11.9 µm. Different values reported in different studies can be explained by the different study design and improvements in the devices.

The results of the present study should be interpreted with caution as it has been shown that intraoral digital impressions are highly accurate when scanning single or partial fixed prosthesis preparations but their accuracy is limited for complete-arch impressions.[57] This may be due to the lack of fixed references[58] when a surface is scanned. Thus, the first image recorded by the scanner is the reference and all subsequent images will be stitched to the previous one by a best-fit algorithm that represents the best possible overlap of images. Each overlap has an inherent error and it can be anticipated that the longer the scanning field the larger the error introduced. A clear example of this would be that Ender and Mehl[57] reported deviations of up to 170 µm in the posterior area during complete-arch scanning, whereas trueness values as small as 6.9 µm were found for single-tooth digital impressions.[56] Moreover, the accuracy of earlier versions of intraoral scanners was shown to be affected by the tilt angle of the scanner if this angle exceeded the tooth's axial wall angle of divergence.[59] However, this no longer seems to be a limiting factor for modern versions especially as intraoral scanners are constantly being updated.

Furthermore, the fully digital workflow is not exempt from errors[21] and inaccuracies may arise from the digitizing device and its underlying scanning technology, digitizing environment (blood, saliva, natural, and external light source), scanning strategy, and scanned data processing (alignment algorithms). Also, a transformation error (9.7 μm)[60] can occur in the CAD stage when direct digital data acquisition is transferred to the CAD software. This is related to the software's ability to reconstruct missing tooth surfaces using a biomimetic approach (with B-Splines, Hermit, or NURBS).[21] Finally, additional inaccuracies can be introduced (from 5 to 25 μm)[23] in the CAM stage by the CAM software, the numerically controlled machine tool, and the milling machine process (including mechanical loads, vibrations, and tool wear).

On the other hand, the volumetric analysis showed that a mesiodistal inverse tapered preparation (negative TOC angle) could preserve up to 15% of dental structure. Although there is no consensus about the minimal thickness of dentine required to preserve pulp vitality, 1.8–19% of vital abutment teeth have been reported to develop endodontic diseases after preparation for complete crowns in an observation period of 1–25 years.[61-65] Furthermore, tooth preparation can be still regarded as a "blind" procedure because dentists perform this task without knowing the precise proximity of the pulp to the prepared surface in spite of the efforts made to measure its size and proximity. Therefore, preserving as much tooth structure as possible without sacrificing the integrity of the definitive restoration is always desirable.

In this study, when a -8° preparation was digitally blocked out at the CAD stage, approximately 28 mm^3 of dental structure could be preserved (relative to a 22°- preparation). To put the relevance of this seemingly small amount of volume into perspective, one should keep in mind that the average pulpal volume of an adult maxillary central incisor[66] is approximately 21 mm^3. Therefore, preserving such amount of tooth structure is definitely not negligible.

This study has several limitations. Idealized preparations of a maxillary left central incisor were used to make both conventional and digital impressions. The 3D-printed resin models differ from human enamel and dentin in terms of hardness, wettability, surface roughness, and light reflection. The absence of sulcular fluid, blood, saliva, patient movements, and temperature-related distortions differ significantly from the clinical setting. In addition, as this study used only 1 elastomeric impression material, 1 desktop scanning system, and 1 intraoral scanner, general conclusions should be drawn carefully.

Fit of crowns made over reverse tapered preparations

No study has previously evaluated the effect of undercut-blocking algorithms of the CAD software on the fit of dental crowns fabricated over conventional and reverse tapered preparations. According to the results of this study, the null hypothesis was rejected. Crowns made on abutments with -8° convergence angle showed a statistically significant marginal discrepancy in relation to all TOC angles tested; however, marginal fit values of this study are in agreement with previous investigations that stress the clinical importance of keeping the marginal fit below 120 µm.[25-32,34] Regarding the internal fit, an average axial fit of 100–250 µm is reported most frequently[25,28-30,35-37] although there is no conclusive research indicating an "ideal" internal fit value. In our study, an inverse TOC angle-dependent relationship between the axial and the incisal fit was observed. Axial discrepancies of up to 298 µm were registered in the -8° group, whereas incisal fit values of up to 255.1 µm were found in the 22° group. Larger axial discrepancies found in the -8° group can be explained by the virtual space generated after executing the digital block out procedure (Fig.2); in contrast, large incisal discrepancies found in crowns from the 22° group may be related to the diameter of the milling tool of the CAM machine since highly tapered preparations have reduced tooth structure with sharp internal angles that tend to be overmilled.[18,24]

Another explanation for the fact that crowns made over positive TOC abutments tended to show higher fit values at the incisal edge could be that such crowns did not reach their final position. To ensure complete seating of a crown over its abutment, the cement space set at the CAD stage plays an important role, and according to Grajower and Lewinstein[67] the cement space of a restoration should be set to at least 50 µm, of which 30 µm would be filled with cement and the remaining 20 µm, would facilitate the seating of the crown in the presence of potential manufacturing distortions. This investigation used default parameters (50 µm cement space) on abutments with positive TOC angles whereas reverse tapered abutments (negative TOC angles) had also default settings plus a digital block out of the undercuts (Fig. 2) and an extra gap set to 50 µm (in total 100 µm) in the mesiodistal aspect only. From the relatively high incisal fit values found in this study, it can be argued that 50 µm might not be the suitable cement space for zirconia crowns; however, there is no "ideal" cement space value that would guarantee the best fit of a crown independently of the CAD/CAM system used as Boitelle et al.[68] showed in a recent meta-analysis. They reported that cement space values ranged from -20 to 1000 µm depending on the intrinsic properties of the CAD/CAM system used although 50-60 µm were more frequently reported.

On the other hand, this study used the silicone replica technique to measure the fit of dental crowns. For this purpose, a light-body elastomeric impression material thin film was fixed with a polyvinyl siloxane medium-body and measured with a stereomicroscope. Unfortunately, this is a 2-dimensional assessment method that can be further biased by the sectioning procedure of the replicas, the cutting position, the number of cuts/points evaluated, and the observer. Despite of these shortcomings, the silicone replica technique is a nondestructive, accurate, and reliable method that has been used in vivo and in vitro.[46-48]Moreover, destructive methods or micro-CT–based techniques would have been time-consuming, expensive, or not even feasible since zirconia is a tough and highly radiopaque material.

Although zirconia crowns may not be the first choice for highly demanding esthetic cases, its use in the present study is justified by the fact that among the materials used for all-ceramic crowns, zirconia shrinks considerably after the sintering process. This volumetric change that zirconia experiences may interfere with the correct fit of crows made over reverse tapered preparations. However, this study demonstrated that the undercut-blocking algorithms of the CAD software could successfully manage mesiodistal TOC angles below zero and produce well-fitting dental crowns, regardless of the material used.

A comparison of the results of the present study with previously published research on the overall fit of crowns produced with a fully digital workflow showed that previous studies reported marginal discrepancies of 18.45 µm (Lava COS),[31] 30 µm (CEREC Bluecam),[30] 41µm (iTero),[30] 48µm (Lava COS),[30, 32] 49µm (Lava COS),[27] 51 µm (Lava COS),[28] 83 µm (CEREC Bluecam), [28] 88 µm (True Definition),[26] 91 µm (Lava COS),[29] 106.6 µm (TRIOS),[25] 112 µm (TRIOS),[26] and 149 µm (CEREC OmniCam),[26] and overall internal fit values of 82 µm (axial)/275.4 µm (oclusal) (TRIOS),[25] 128 µm (axial)/297 µm (oclusal) (CEREC Bluecam),[27] 128.96 µm (axial)/198.96 µm (oclusal) (Lava COS),[29] 130 µm (axial)/181 µm (oclusal) (Lava COS),[27] 29 µm (overall, Lava COS),[30] and 50 µm (overall, iTero),[30] 88 µm (overall, CEREC Bluecam),[30] while the present work found median marginal fit values as large as 58.2 µm and internal discrepancies as wide as 161.8 µm (axial)/125.3 µm (oclusal). Different values reported in different studies can be explained by the different study design.

Among the studies evaluating the relationship between the TOC angle and the fit of dental crowns, five in vitro studies measured the variation of marginal fit according to the angle of preparation. All of them involved CAD/CAM systems (1 intraoral and 4 desktop scanners). Four studies conducted before cementation [36,69-71] found that angulation did not influence the marginal fit, whereas Iwai et al. [70] and Beuer et al.[72] (cemented restorations), reported that tooth preparations with a TOC angle below 6° had statistically significant marginal discrepancies. This can be explained by the possible distortion of the 3D model of abutments with a TOC-angle less than 6° as it was demonstrated that desktop scanners could not accurately reproduce low TOC angles.[16,17] In contrast, intraoral scanners can record low TOC angles, although to date, only one study [36] evaluated and showed that the fit of crowns with a low TOC angle (4°) fabricated from direct digital impressions were not affected by the preparation convergence angle. More laboratory and clinical studies are needed in this regard to draw robust conclusions.

In this study, the KaVo multiCAD software was used to design zirconia crowns after making impressions with the TRIOS scanner. The software has an algorithm to block out minor undercuts at 0° and to provide extra space in the direction where negative angles (undercuts) are located (eg. mesiodistal or buccolingual). With this setup and considering the high accuracy that 5-axis milling machines offer,[21-23] zirconia crowns could be successfully milled over reverse tapered preparations yielding clinically acceptable mean marginal fit values (58.2 ±6.0 µm). In terms of internal fit, there was a marked difference in the axial fit between conventional and reverse tapered preparations (298 µm versus 111.5 µm, maximum registered values). These findings are in accordance with the results of recent studies[25,28-30,35-37] describing an average axial fit of 100–250 µm although extreme values from 29 [30] to 1316 µm[73] were also reported.

This study has several limitations. Direct digital impressions were made on idealized preparations of a maxillary left central incisor. The 3D-printed resin abutments differ from human enamel and dentin in terms of hardness, wettability, surface roughness, and light reflection. The absence of sulcular fluid, saliva, patient movements, and temperature-related distortions differ significantly from the clinical setting. The 2-dimensional nature of the replica technique and the limited number of points measured. Also, as this study used only 1 intraoral scanner and 1 specific milling machine, general conclusions should be drawn carefully.

Retentive strength of crowns made over reverse tapered preparations after 1-year water storage.

The null hypothesis that the retentive force of zirconia crowns is not influenced by the TOC angle was rejected as significant differences were found among all TOC angles tested. The second null hypothesis that 1 year of water storage will not influence the mean retentive strength was also rejected. In this study, the mean retention ranged from 1.5 to 2.7 MPa after 1 year of water storage. The TOC angle had a significant influence on crown retention with the -8° group showing the highest values (2.7 MPa) and the 22° group the least (1.5 MPa).

The results of the current investigation are in agreement with the majority of reported studies that stress the importance of the total convergence angle to restoration retention[1,42,74,75] and confirm the well-known inverse relationship between the TOC angle and the retentive strength of dental crowns. Regarding this fact, Jørgensen[1] reported retentive strength values ranging from 0.79 MPa to 0.17 MPa for 5° and 25° taper groups, respectively. Zidan and

Ferguson[74] evaluated the retention of metal crowns cemented to abutment teeth with 3 different tapers (6°, 12° and 24°) and they found that abutments with a TOC angle of 6° provided the highest retention (7.57 MPa) followed by 12° (6.02 MPa) and 24° (5.49 MPa). Ali et al.[75] found that 15° abutment tooth preparations showed a mean coping removal strength (MPa) of 6.0 (Panavia F 2.0), 4.8 (Clearfil SA), and 5.5 (RelyX Unicem Clicker), whereas 30° preparations had retentive strength values of 2.8 (Panavia F2.0), 3.0 (Clearfil SA), and 2.6 (RelyX Unicem Clicker). Different values reported in these studies can be explained by the different study design and cements used.

On the other hand, since the virtual space generated after digitally blocking out a reverse tapered preparation will be filled with cement, it is important to anticipate its possible impact on the long-term retentive strength of dental restorations. In this regard, there is no conclusive information yet as Jorgensen and Esbensen[76] reported that greater cement thickness (of zinc phosphate cement) results in decreased retention of restorations, whereas Son et al.[77] showed that the retentive force to zirconia copings were not affected by the internal gap width (either 40 or 160 μm) if resin cements are used.

In addition, the longevity of the bond stability between the zirconia crown and luting cement and the cement and the abutment tooth is influenced by factors such as exposure to saliva, mechanical stress during mastication, and temperature variations. Therefore, the need for artificial aging to simulate the conditions of the oral environment in laboratory studies is well established. The most common methods are long-term water storage, thermocycling, or a combination of both. In this respect, Inokoshi et al.[78] in a recent meta-analysis on bonding effectiveness to zirconia ceramics found that both "water storage" and "thermocycling" significantly affected the predicted bond-aging resistance with water storage showing a stronger correlation (r = -0.4) than thermocycling (r =-0.15). Therefore, water storage could be regarded as the preferred method to age composite cement-zirconia bonds in the assessment of bond strength and durability.

In the present study, retention after 1-year water storage were similar to the ones reported by Ernst et al.[79] who found that 1 year of water storage did not affect the retention of zirconia crowns cemented with resin cements to extracted human teeth. Also, after thermocycling and storing zirconia crowns in water for 1-year, Ehlers et al.[80] found higher or equal median retentive strengths for Relyx Unicem Aplicap (from 3.1 to 3.4 MPa), RelyX Unicem Clicker (from 4.1 to 4.2 MPa), iCEM (from 2.3 to 2.7 MPa), SpeedCem (from 1.3 to 1.6 MPa), and Panavia 21 (from 1.7 to 2.5 MPa). To the best of the authors' knowledge, no further comparisons can be made since studies evaluating the retentive strength of zirconia crowns fabricated over different TOC angles and after long-term water storage do not exist.

Furthermore, the retention of zirconia crowns after 1-year water storage in this study (Table 5) and in the study conducted by Ehlers et al.[80] (range: 1.4 - 4.2 MPa) were below 5 MPa and their clinical serviceability might not be ensured. However, in a 5-year prospective cohort clinical study, Dogan et al.[81] found that all anterior zirconia crowns cemented with no surface pretreatment of the intaglio surface and a self-adhesive resin cement (RelyX Unicem) did not experience retention loss throughout the study period. Also, in a recent retrospective cohort study of up to 12 years, Miura et al.[82] did not find retention loss in the 63 anterior zirconia crows evaluated. In contrast, Larsson et al.[83] in a recent systematic review on the clinical success of zirconia crowns found that loss of retention is a frequent problem in the posterior region. Therefore, it can be hypothesized that since masticatory forces in the anterior region (white males) are, on average, 150 ±18 N (versus 505 ±53 N in the posterior region),[84] retentive forces found in the present study (range 186.1 – 409.4 N) are strong enough to bear such dislodging forces.

On the other hand, cement residuals were found predominantly on the crowns' intaglio (category 3) although 5 out of 60 abutments showed failure type 4 and another 3 abutments presented category 2 failures. These results are similar to a previous study, which demonstrated that the mode of failure was not influenced by water storage.[51]

This study has several limitations. Direct digital impressions were made on idealized preparations of a maxillary left central incisor. The milled PMMA resin abutments differ from human enamel and dentin in terms of hardness, wettability, surface roughness, light reflection, and bonding properties; therefore; retention may be improved if the substrate were human dentine. The absence of sulcular fluid, saliva, patient movements, and temperature-related distortions differ significantly from the clinical setting. In addition, as this study used only 1 intraoral scanner, 1 specific milling machine, and evaluated 1 resin cement, general conclusions should be drawn carefully.

Fracture resistance of crowns made over reverse tapered preparations after 30-day water storage.

The null hypothesis was accepted ($P > 0.07$) as none of the TOC angle tested showed a significant impact on the load to fracture values of glass ceramic crowns after 30-day water storage. However, it is important to anticipate the possible impact of the cement film occupying the virtual space generated after the digital block-out on the long-term mechanical stability of dental restorations.

In this regard, Scherrer et al.[38] tested feldspathic ceramic tabs cemented to composite with resin cement thicknesses ranging from 26 ± 11 µm to 297 ± 48 µm and noticed a gradual decrease of the fracture strength that became statistically significant at a cement thickness of 300 µm. May et al.[39] proved that under wet cyclic testing conditions, glass ceramics crowns with an occlusal cement layer of 50 µm were more resistant than those cemented with 500 µm (246.4 ± 22.9 N versus 158.9 ± 22.9 N). In contrast, when testing lithium disilicate tabs cemented to human dentine with a 300-µm thick film of RelyX Ultimate, it was found that the mean fracture resistance was 1176.02 ± 159.81 N.[40] Prakki et al.[41] also found that higher cement film thickness (300 µm) resulted in increased fracture resistance (982 ±22 N) for 1-mm ceramic plates cemented to bovine dentine. Therefore, it can be hypothesized that large internal fit values (above 300 µm) may impact the fracture resistance of ceramic materials in a material-dependent fashion.

Since glass ceramics crowns per se are weaker than hybrid resin, monolithic lithium disilicate or zirconia crowns, the mechanical properties of the cement may play an important role in the load to fracture values. Regarding this, the elastic modulus of the cement is of importance because it will provide a "cushion" effect allowing a bending strain of the restoration under load that could lead to a tensile fracture of the ceramic material at the cementation interface. Finite element analysis studies with a cement space of 50-100 µm[85,86] have demonstrated a limited effect of cement thickness on the stress on a crown; however, it has been shown that a cement space of 500 µm reduces the fracture resistance of aged glass ceramic crowns.[39]

On the other hand, Koolstra et al.[87] with a mathematical model predicted that maximum possible protrusive bite forces on an incisor is approximately 100 N, and Regalo et. al.[84] found that forces in the anterior region, in white males, are, on average, 150 ±18 N (versus 505 ±53 N in the posterior region). In this study, 24-h water storage mean load to fracture values were above 200 N for all TOC angles tested. These values decreased slightly (190.1 N in crowns made over -8° abutments) after 30-day water storage although no significant statistical difference was found between both water storage conditions (P = 0.625). Therefore, it can be hypothesized that the load to fracture values found in the present work are strong enough to bear protrusive masticatory forces.

This study presents some intrinsic limitations, including the lack of thermocycling, the use of only feldspathic ceramics, one type of cement, cementation of crowns over PMMA abutments and the use of idealized preparations. Therefore, general conclusions must be stated carefully as clinical trials are required to validate the results of this investigation, However, within the limitations of this study, it has been demonstrated that anterior glass ceramics crowns made over reverse tapered preparations offer the advantage of being minimally invasive with a fracture resistance similar to crowns made on conventional 12° abutment tooth preparations.

CONCLUSIONS

Within the limitations of this in vitro study, the following conclusions were drawn:

1. Intraoral scanning with TRIOS can accurately record abutment tooth preparations independently of their geometry.
2. A -8° reverse tapered preparation could aid to preserve approximately 10-15% tooth structure than a conventional (12°-22° degrees) preparation.
3. The marginal (45.5 - 58.2 µm) and internal fit (axial: 130.8 - 165.5 µm; incisal: 67.3 - 81.8 µm) of zirconia crowns made over reverse tapered preparations is within clinically accepted values (marginal: <120 µm; internal: 100 - 250 µm).
4. The retentive strength of crowns fabricated over reverse tapered preparations was statistically significantly higher than that of crowns made on abutments with a TOC angle higher than 12° after 1-year water storage.
5. The fracture resistance of crowns fabricated over reverse tapered preparations were similar to that of crowns made on abutments with a TOC angle of 0° and 12° after 30-day water storage.

Finally, it has been demonstrated that intraoral scanners could accurately record individual reverse tapered preparations and that the fit, retention and fracture resistance of CAD/CAM restorations derived from this minimally invasive concept were within clinically accepted values.

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Table 1. Trueness and precision (mean RMS-values ±SD) of conventional and digital impressions (µm)

Impression technique		Total Occlusal Convergence (TOC)									
		-8 degrees	**-6 degrees**	**-4 degrees**	**0 degrees**	**4 degrees**	**8 degrees**	**12 degrees**	**16 degrees**	**22 degrees**	**Overall mean**
PVS	**Trueness**	29.1±2.2	26.5±8.1	32.6±8.4	26.7±6.8	27.5±4.5	28.7±7.4	20.2±6.1	22.2±1.7	22.4±4.7	26.2±6.6
	Precision	14.6±1.1	20.9±5.3	21.0±4.2	19.4±3.3	15.8±3.0	17.2±4.6	18.7±2.3	17.8±3.7	16.9±2.7	18.0±3.9
KAV	**Trueness**	24.3±5.0	21.6±4.9	26.5±4.1	26.1±6.7	22.5±5.2	25.0±8.7	23.1±7.4	21.7±3.1	20.4±2.7	23.5±5.5
	Precision	21.3±5.0	21.6±5.6	18.7±1.9	21.2±3.8	19.0±2.8	21.9±5.8	21.4±4.9	21.7±5.1	19.6±3.7	20.7±4.4
TRI	**Trueness**	19.9±1.7	17.9±1.1	20.6±1.0	18.4±1.5	18.1±1.7	15.8±0.9	20.4±1.6	20.3±2.1	20.2±1.1	19.1±2.0
	Precision	13.4±1.8	11.1±3.8	13.4±1.8	11.1±1.2	12.8±1.6	11.7±1.9	12.2±2.3	10.0±2.1	11.0±1.6	11.9±2.3

SD, standard deviation; RMS, root mean square; PVS, polyvinyl siloxane impressions; KAV, extraoral scanned casts with the KaVo scanner; TRI, intraoral digital impressions made with TRIOS.

Table 2. Results of 2-way ANOVA.

Parameter	Source	*df*	SS	MS	F	*P*
Trueness	Impression technique	2	0.001	0.001	25.144	<0.0001
	TOC angle	8	0.000	0.000	2.083	0.044
	Impression technique x TOC	16	0.001	0.000	1.386	0.162
Precision	Impression technique	2	0.004	0.002	150.682	<0.0001
	TOC angle	8	0.000	0.000	1.355	0.217
	Impression technique x TOC	16	0.000	0.000	2.432	0.002

P<0.05 indicates significant difference.

Table 3. Statistical significance between test groups for trueness measurement according to 2-way ANOVA with post hoc LSD test (α=0.05)

		PVS									KAV									TRI								
	TOC	**-8**	**-6**	**-4**	**0**	**4**	**8**	**12**	**16**	**22**	**-8**	**-6**	**-4**	**0**	**4**	**8**	**12**	**16**	**22**	**-8**	**-6**	**-4**	**0**	**4**	**8**	**12**	**16**	**22**
	-8		0	0	0	0	0	X	X	X	0	X	0	0	X	0	0	X	X	X	X	X	X	X	X	X	X	X
	-6			X	0	0	0	X	0	0	0	0	0	0	0	0	0	0	X	X	X	0	X	X	X	X	X	X
	-4				0	0	0	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
P	**0**					0	0	X	0	0	0	0	0	0	0	0	0	0	X	X	X	X	X	X	X	X	X	X
V	**4**						0	X	0	0	0	0	0	0	0	0	0	0	X	X	X	X	X	X	X	X	X	X
S	**8**							X	X	X	0	X	0	0	X	0	0	X	X	X	X	X	X	X	X	X	X	X
	12								0	0	0	0	X	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	16									0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	X	0	0	0
	22										0	0	0	0	0	0	0	0	0	0	0	0	0	0	X	0	0	0
	-8											0	0	0	0	0	0	0	0	0	X	0	0	X	X	0	0	0
	-6												0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	-4													0	0	0	0	0	0	X	X	0	X	X	X	X	X	X
K	**0**														0	0	0	0	0	X	X	0	X	X	X	0	0	0
A	**4**															0	0	0	0	0	0	0	0	0	X	0	0	0
V	**8**																0	0	0	0	X	0	X	X	X	0	0	0
	12																	0	0	0	0	0	0	0	X	0	0	0
	16																		0	0	0	0	0	0	0	0	0	0
	22																			0	0	0	0	0	0	0	0	0
	-8																				0	0	0	0	0	0	0	0
	-6																					0	0	0	0	0	0	0
	-4																						0	0	0	0	0	0
T	**0**																							0	0	0	0	0
R	**4**																								0	0	0	0
I	**8**																									0	0	0
	12																										0	0
	16																											0
	22																											

0, no statistical difference; X statistical difference. TOC, total occlusal convergence angle (degrees); PVS, polyvinyl siloxane impressions; KAV, extraoral scanned casts with KaVo scanner; TRI, intraoral digital impressions with TRIOS.

Table 4. Marginal and internal fit of anterior zirconia crowns according to the TOC angle (μm)

TOC angle	Marginal fit	Axial fit		Incisal fit		n
	Mean μm ± SD	Median μm	Interquartile range	Median μm	Interquartile range	
-8 degrees	58.2 ±6.0	165.5	161.8 to 172.6	67.3	64.4 to 72.5	10
-4 degrees	45.5 ±3.5	130.8	128.8 to 133.3	81.8	76.6 to 88.4	10
0 degrees	43.5 ±3.2	69.8	69.1 to 70.5	88.8	82.1 to 93.4	10
8 degrees	47.3 ±6.2	70.3	66.5 to 75.6	118.3	103.0 to 129.8	10
12 degrees	44.8 ±4.2	74.8	72.6 to 77.0	125.3	120.3 to 127.9	10
16 degrees	45.3 ±3.0	75.3	73.4 to 87.1	127.8	115.9 to 133.0	10
22 degrees	42.1 ±3.2	83.3	81.1 to 88.0	125.3	116.0 to 129.8	10

SD, standard deviation; TOC, total occlusal convergence.

Table 5. Retentive strength (MPa) of tooth preparations with different TOC angles after 1-year water storage.

Statistic	-8 degrees	-4 degrees	0 degrees	12 degrees	16 degrees	22 degrees
Maximum	3.2	3.1	2.9	2.5	2.2	2.1
3rd Quartile	3.0	2.8	2.7	2.0	2.1	1.5
Mean ± SD	2.7 ± 0.4	2.4 ± 0.4	2.4 ± 0.3	1.8 ± 0.3	1.8 ± 0.3	1.5 ± 0.2
Median	2.9	2.4	2.5	1.7	1.8	1.4
1st Quartile	2.6	2.2	2.3	1.6	1.6	1.3
Minimum	1.9	1.8	1.9	1.4	1.4	1.2

SD, standard deviation

Table 6. *P*- values after 1 year of water storage. (One-way ANOVA; α =0.05)

TOC angle	-8	-4	0	12	16	22
-8°		0.560	0.466	< 0.0001	< 0.0001	< 0.0001
-4°			0.868	0.003	0.005	< 0.0001
0°				0.002	0.004	< 0.0001
12°					1.000	0.322
16°						0.233
22°						

White cell, no statistical difference; red cell, statistical difference.

Table 7. Percentage of specimens with cement remnants according to location after 1 year of water storage.

TOC angle	Category 1	Category 2	Category 3	Category 4
-8°	0	0	70	30
-4°	0	0	80	20
0°	0	0	100	0
12°	0	10	90	0
16°	0	20	80	0
22°	0	0	100	0

Table 8. Load to fracture values (N) of tooth preparations with different TOC angles after 24-hour or 30-day water storage.

Statistic	**-8 degrees**		**0 degrees**		**12 degrees**	
	24-hour	*30-day*	*24-hour*	*30-day*	*24-hour*	*30-day*
Maximum	313.8	254.9	299.1	296.2	271.6	304
3rd Quartile	219.6	190	260.1	241	244.5	266
Mean ± SD	205.6 ± 42	190.1 ± 31	233.8 ± 38	223.7 ± 34	218.2 ± 39	229.8 ± 41
Median	195.6	180.5	234.4	221.1	219.2	207.9
1st Quartile	174.8	174.6	205.9	207.6	192.4	201.5
Minimum	161.8	156.9	178.5	166.7	139.3	178.5

SD, standard deviation.

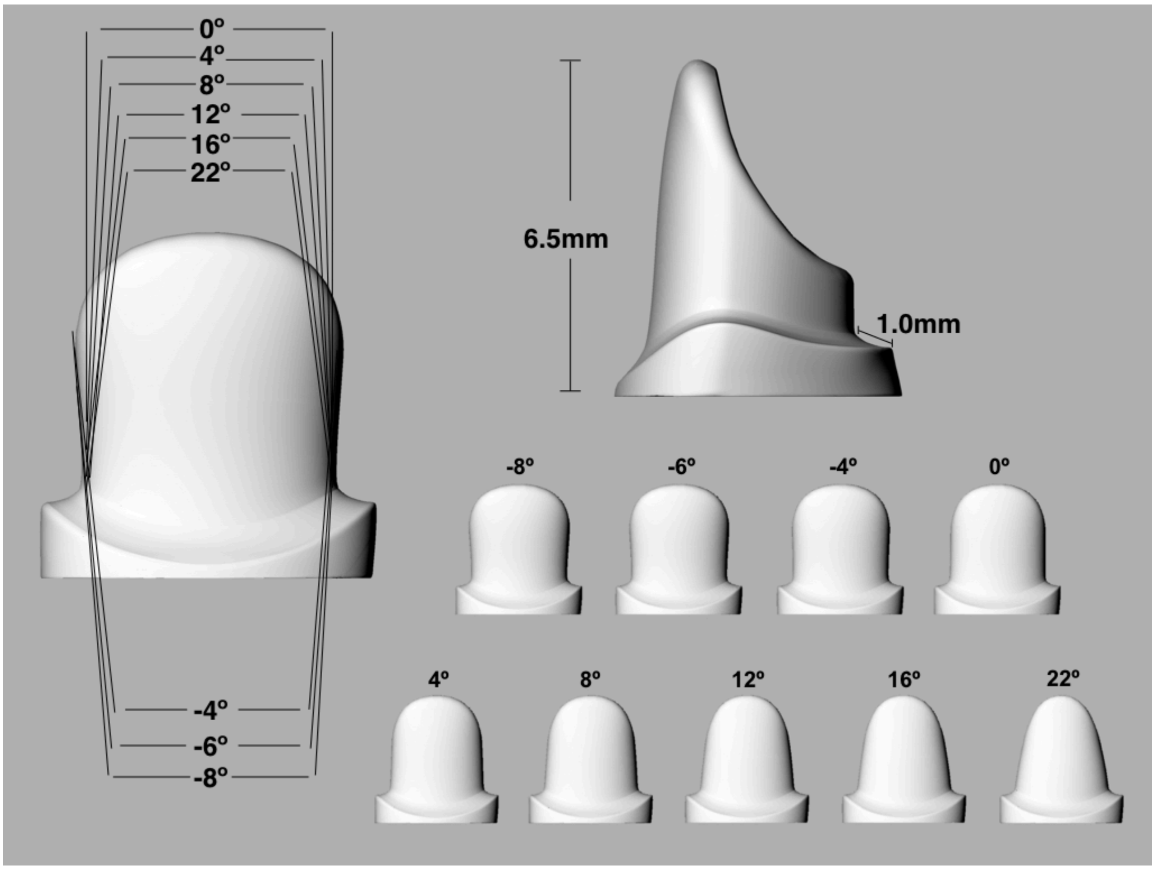


Figure 1. Schematic presentation of overall shape of preparations with varied convergence angles of mesial and distal walls.

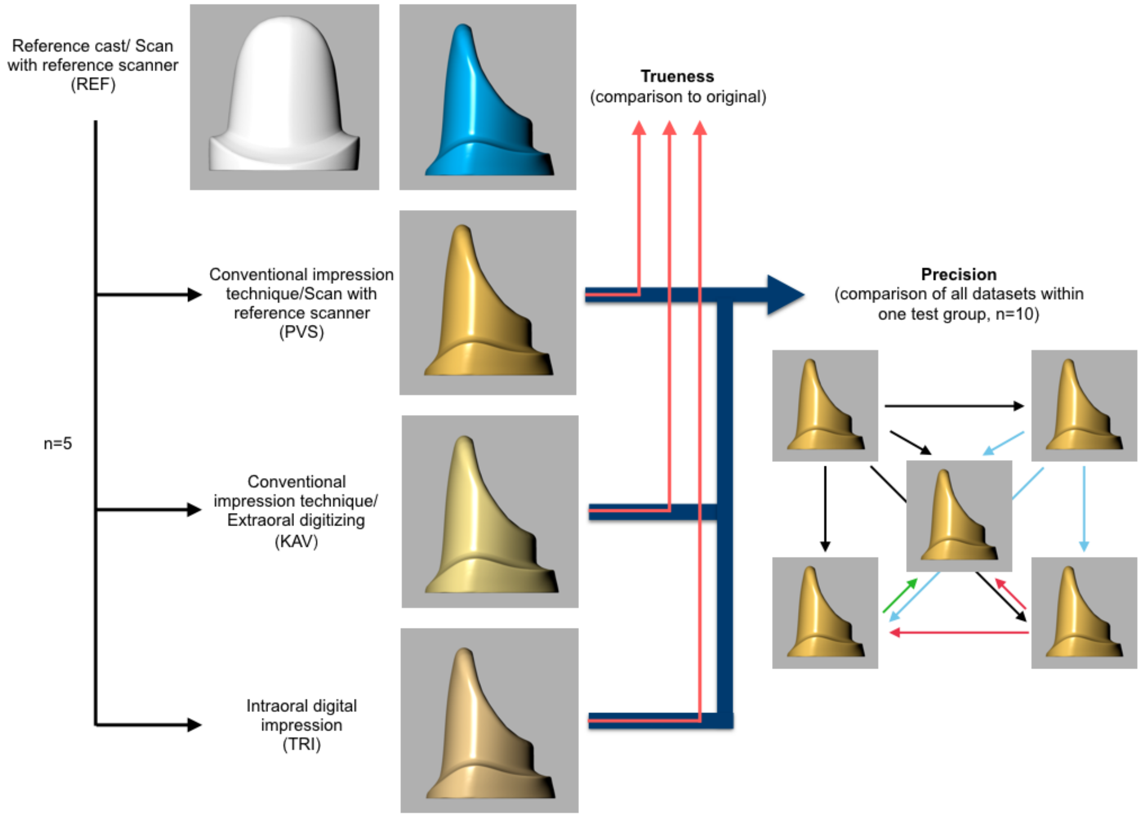


Figure 2. Description of the superimposition procedure for single-tooth conventional and digital impressions in order to evaluate their trueness and precision. Precision is defined as the deviation of multiple measurements within one test group and trueness as how far a measured result deviates from the actual size of the measured object (reference model).

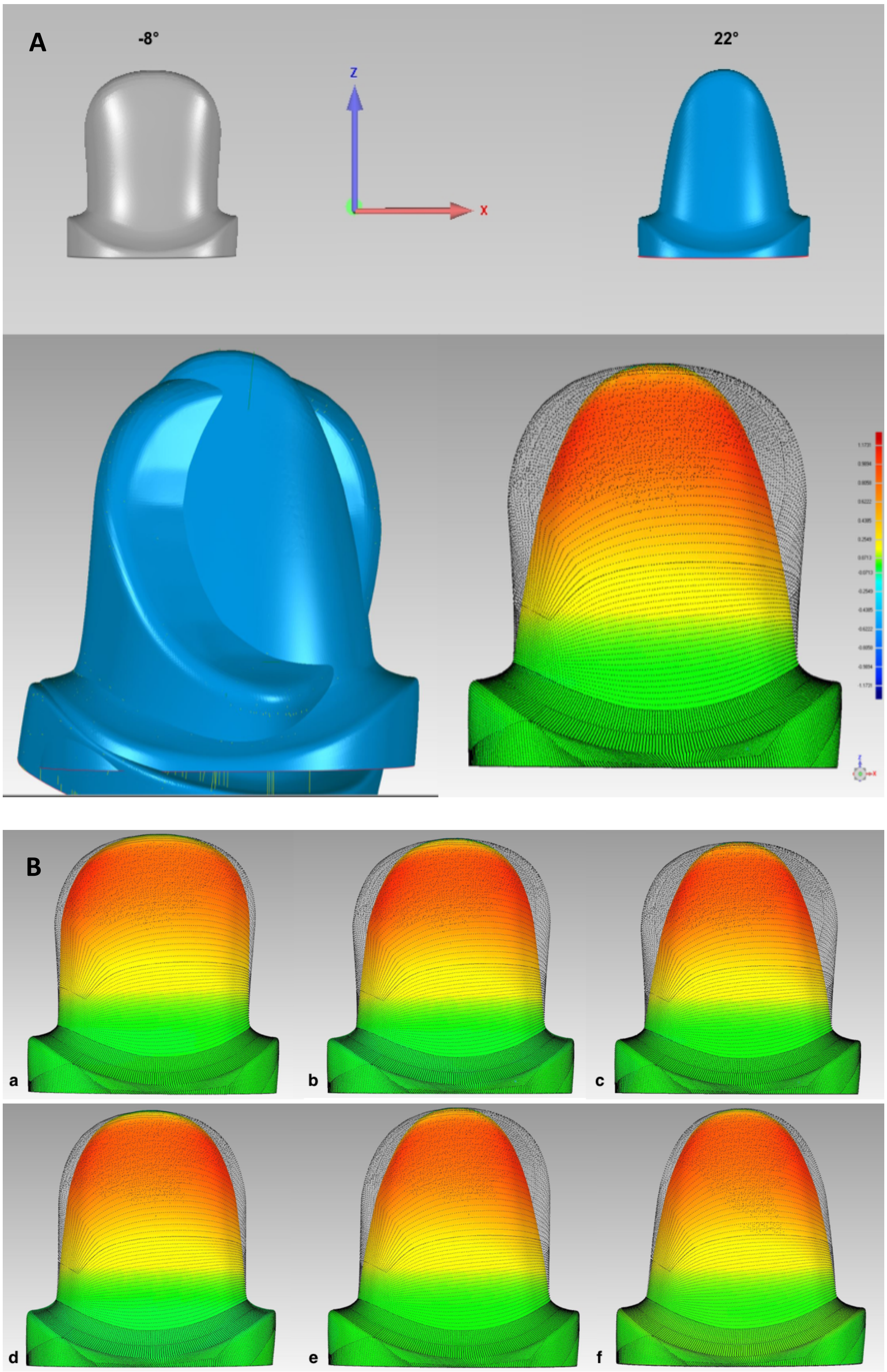


Figure 3. (A) Superimposition of 2 models with the best-fit algorithm of Geomagic Control software (using the same XYZ axis) to calculate volumetric differences. Lower left figure: Best-fit algorithm in process. Lower right figure: Alignment completed. (B) Superimposition combinations (4 models, taken by pairs) to quantify volumetric differences among models. (a) -8 degrees vs. 0 degrees. (b) -8 degrees vs. 12 degrees. (c) -8 degrees vs. 22 degrees. (d) 0 degrees vs. 12 degrees. (e) 0 degrees vs. 22 degrees. (f) 12 degrees vs. 22 degrees.

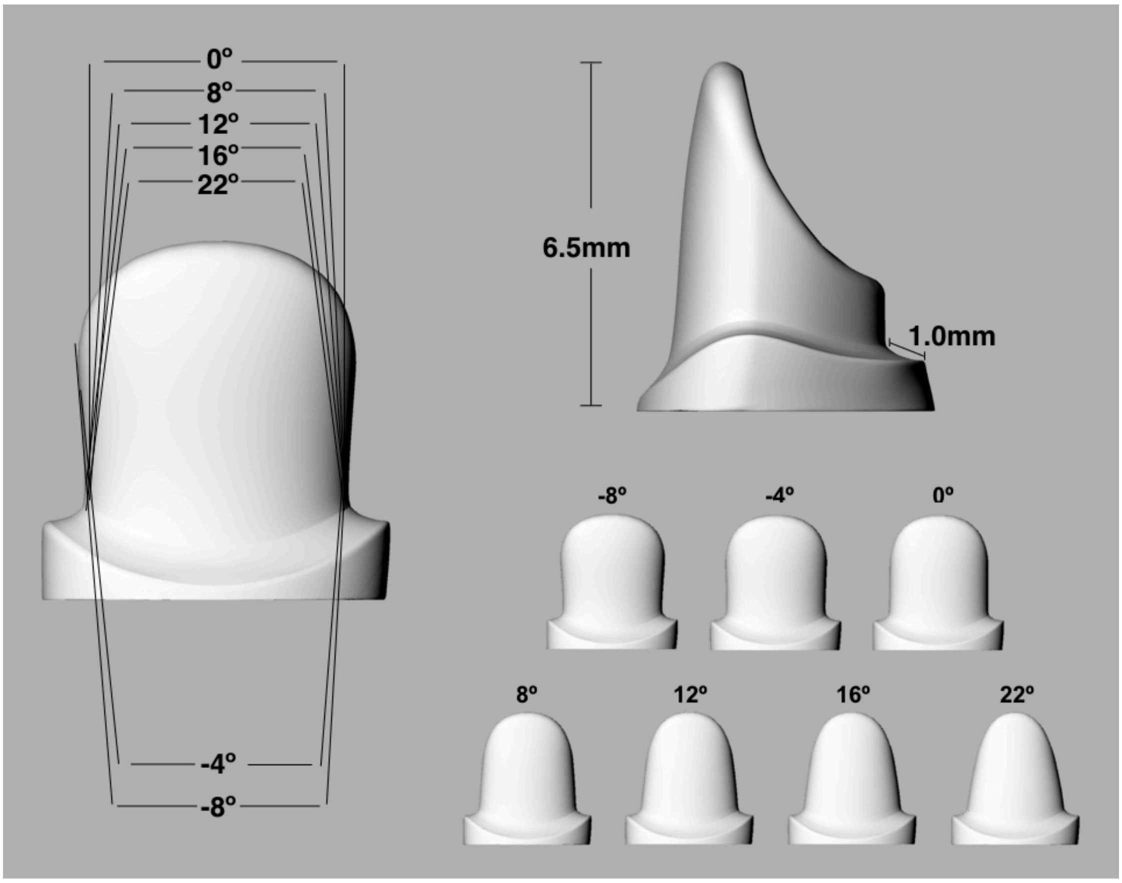


Figure 4. Simulated crown preparations with different convergence angles of mesial and distal walls.

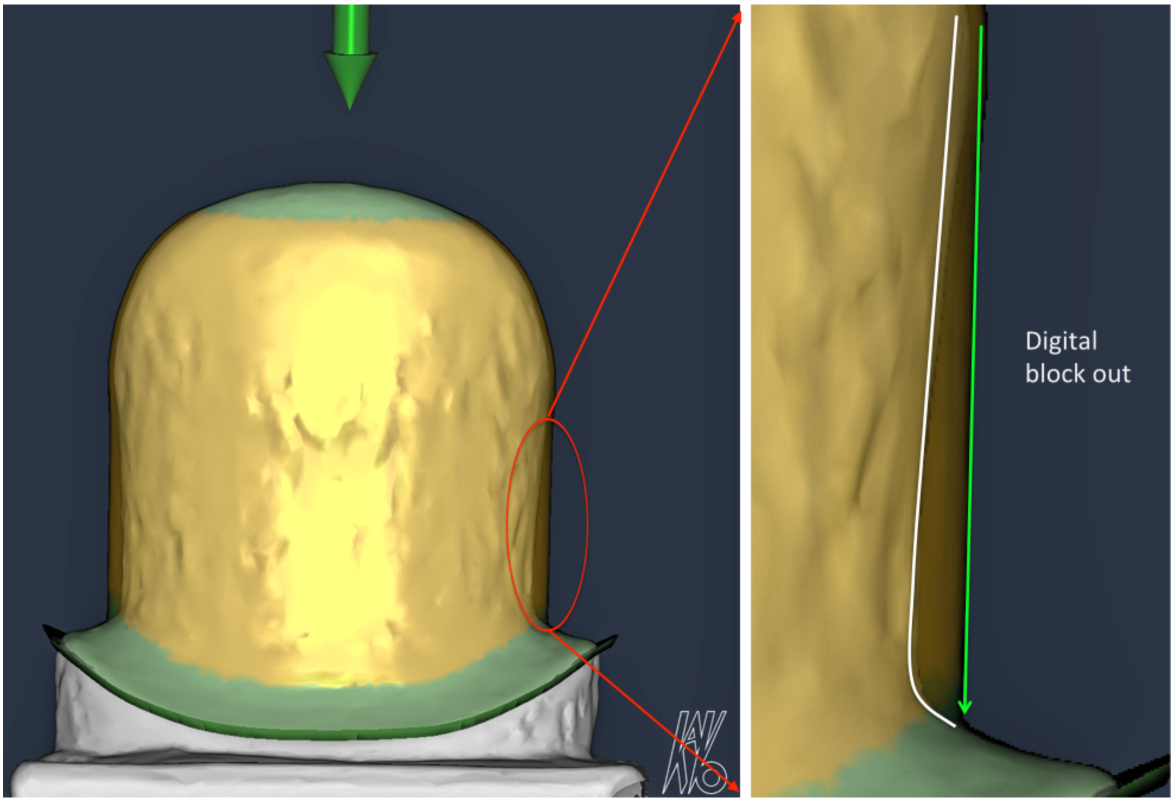


Figure 5. Digital block-out of a -8° preparation at 0° (parallel to the abutment's long axis).

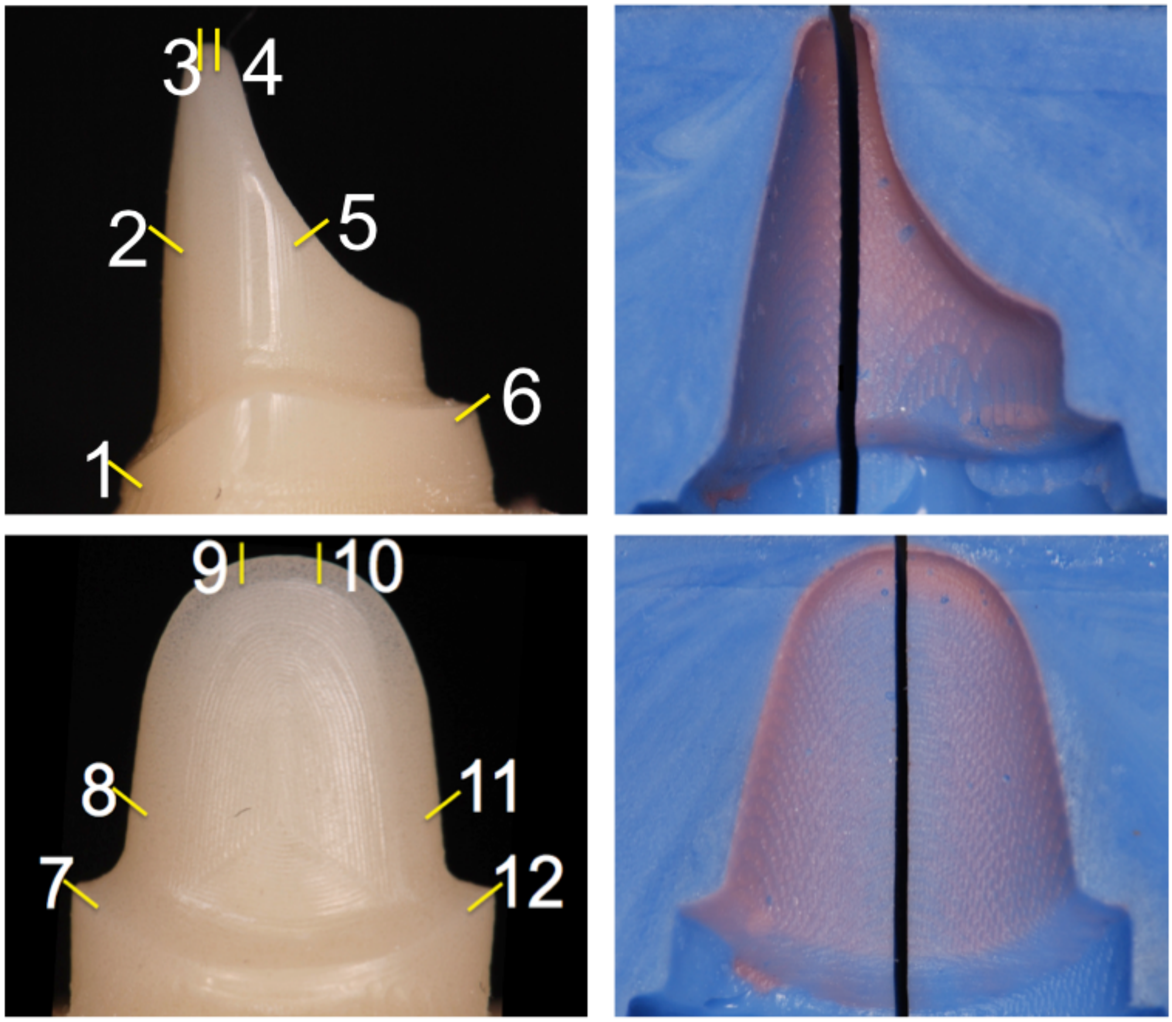


Figure 6. Measuring points for evaluation of crown fit in the silicone replica. The points from "1" to "6" were located in the buccolingual direction section, and points "7" to "12" were included in the mesiodistal direction section. Points 1, 6, 7, and 12 were positioned on the margin; 2, 5, 8, and 11 were on the axial wall, and 3, 4, 9, and 10 were on the incisal edge. The two figures on the right side show the cuts of an actual silicone replica.

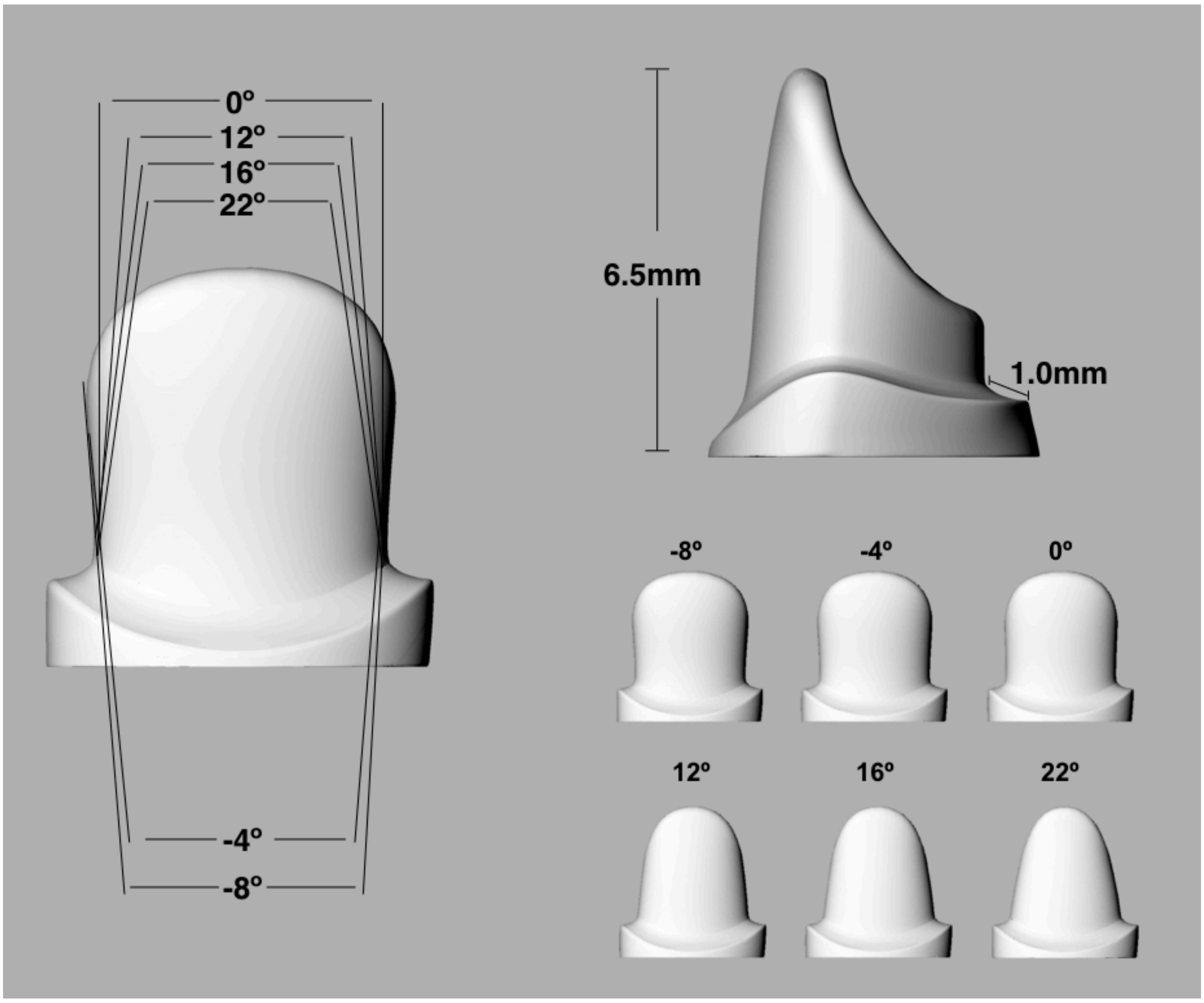


Figure 7. Schematic presentation of overall shape of preparations with varied convergence angles of mesial and distal walls.

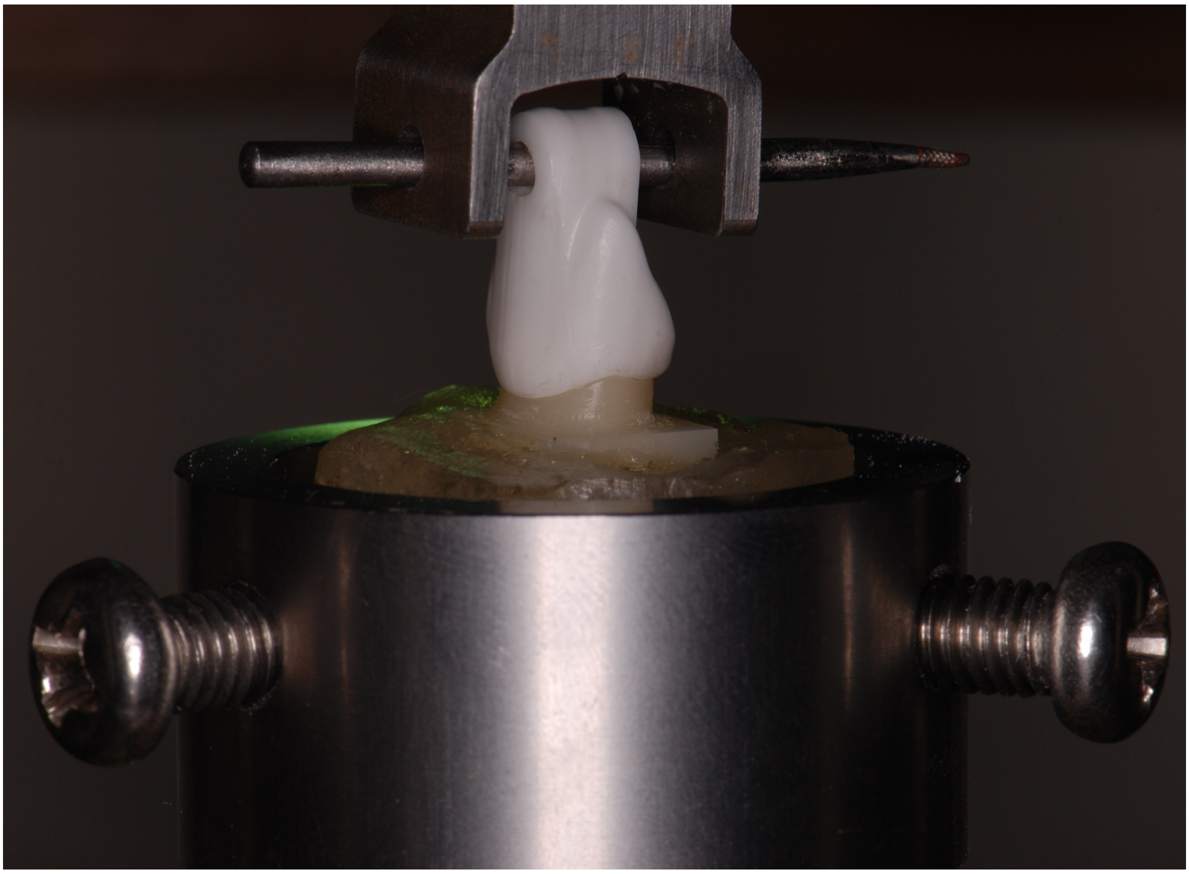


Figure 8. Predislodgment setting

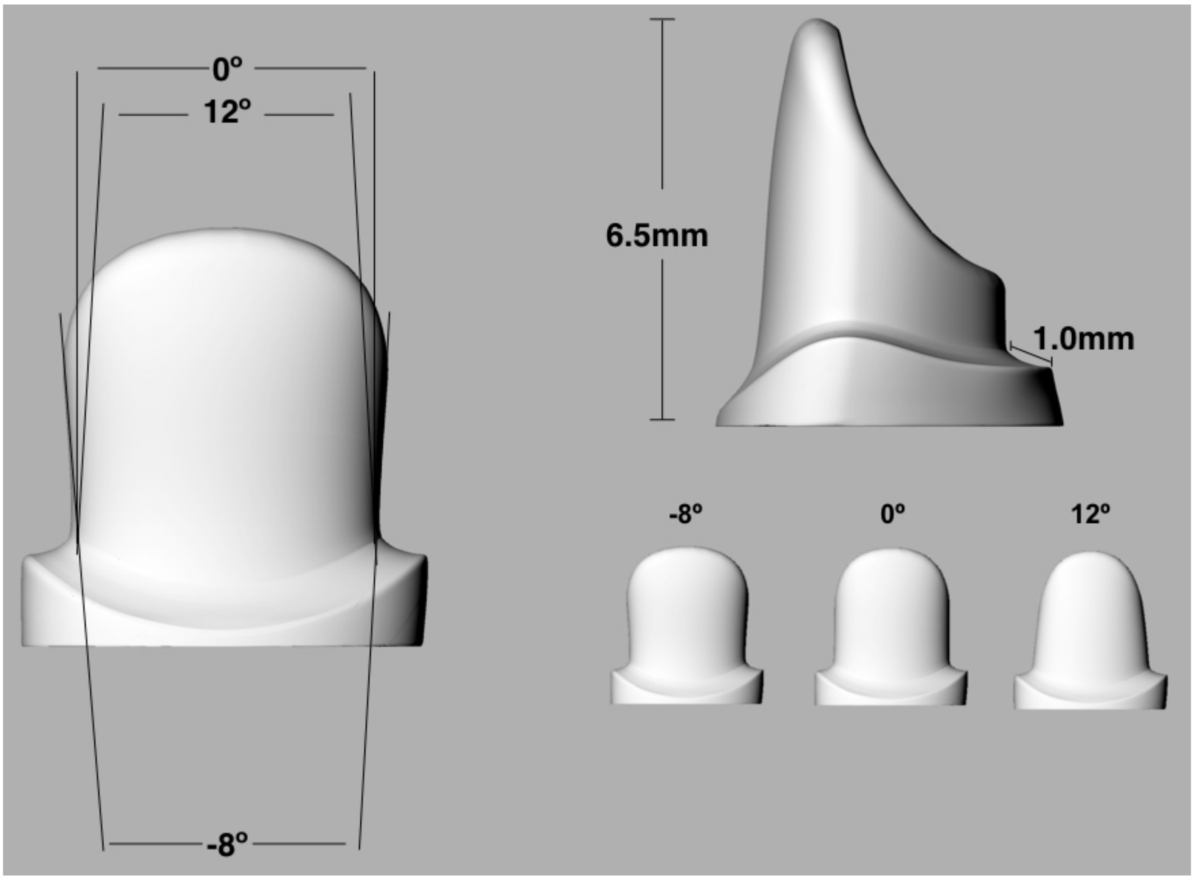


Figure 9. Simulated crown preparations with different convergence angles of mesial and distal walls.

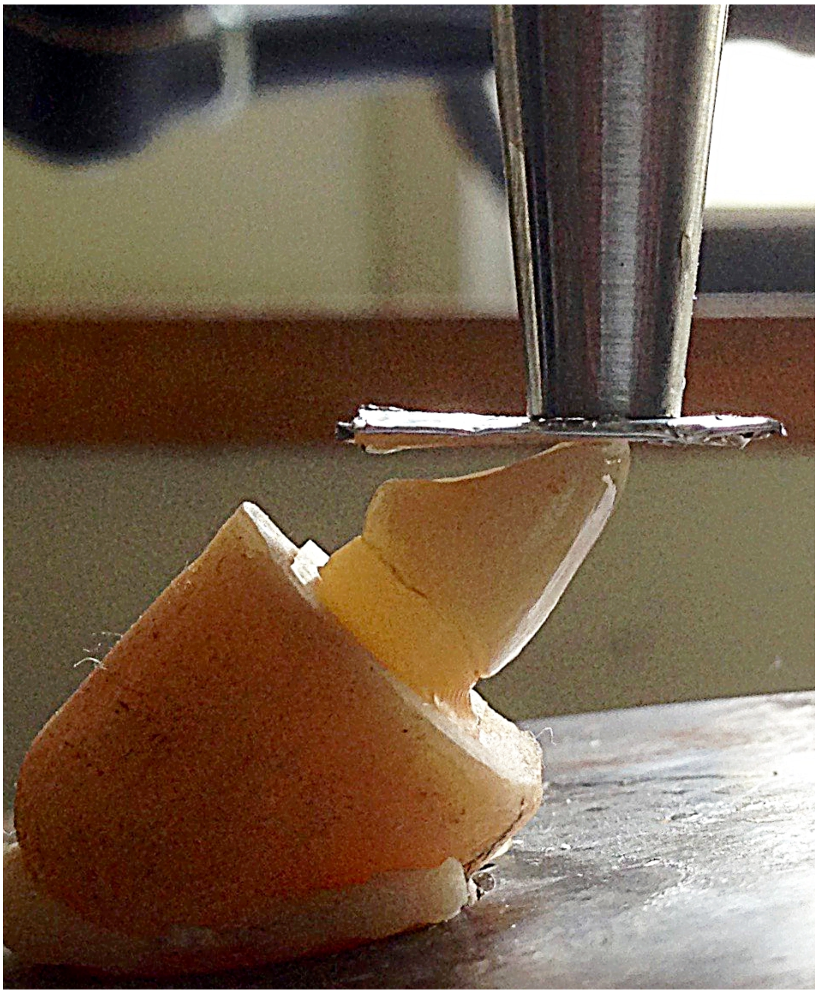
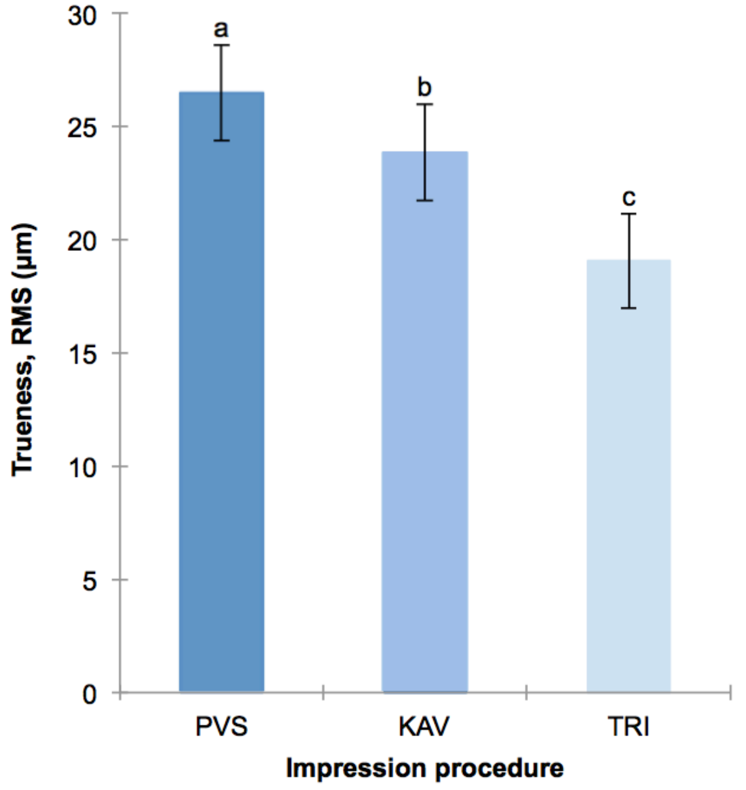


Figure 10. Preloading setting



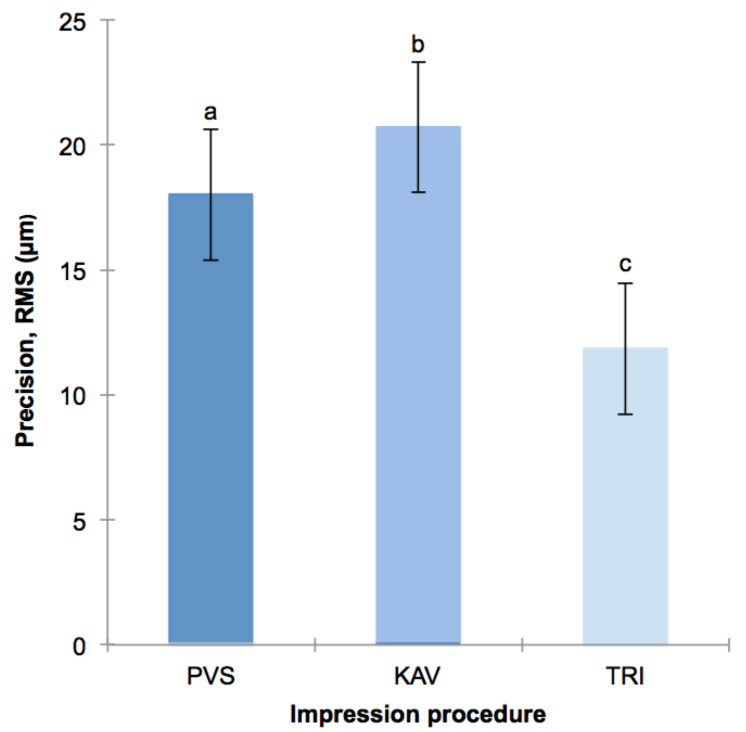


Figure 11. Accuracy (trueness and precision.) of conventional and digital impressions (µm) (Groups with different lowercase letters indicate significant differences at $P<0.05$). PVS, polyvinyl siloxane impressions; KAV, extraoral scanned casts with KaVo scanner; TRI, intraoral digital impressions with TRIOS.

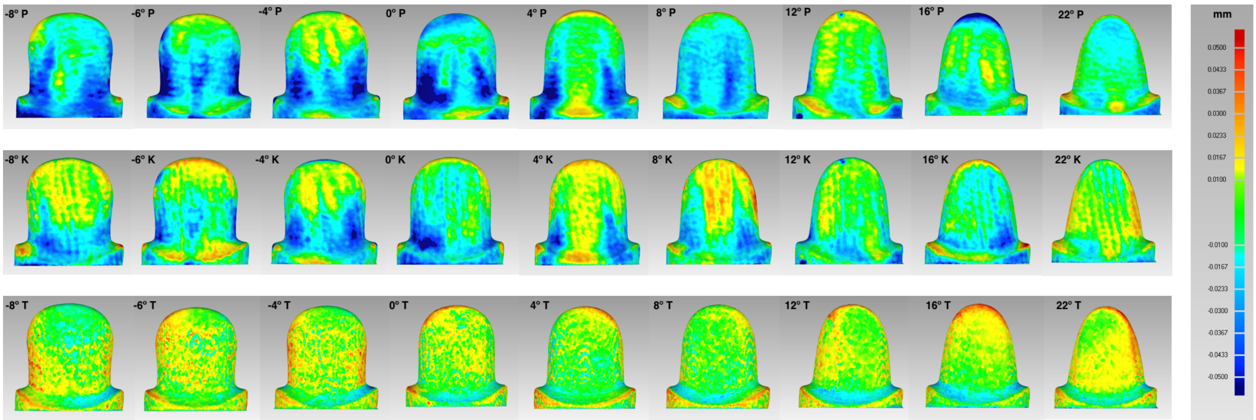


Figure 12. Typical deviation pattern between test impression and reference model (trueness). Deviation range color coded from +50 µm (dark red) to -50 µm (dark blue). Max/min nominal ±10 µm (green). P, polyvinyl siloxane impressions; K, extraoral scanned casts with KaVo scanner; T, intraoral digital impressions with TRIOS.

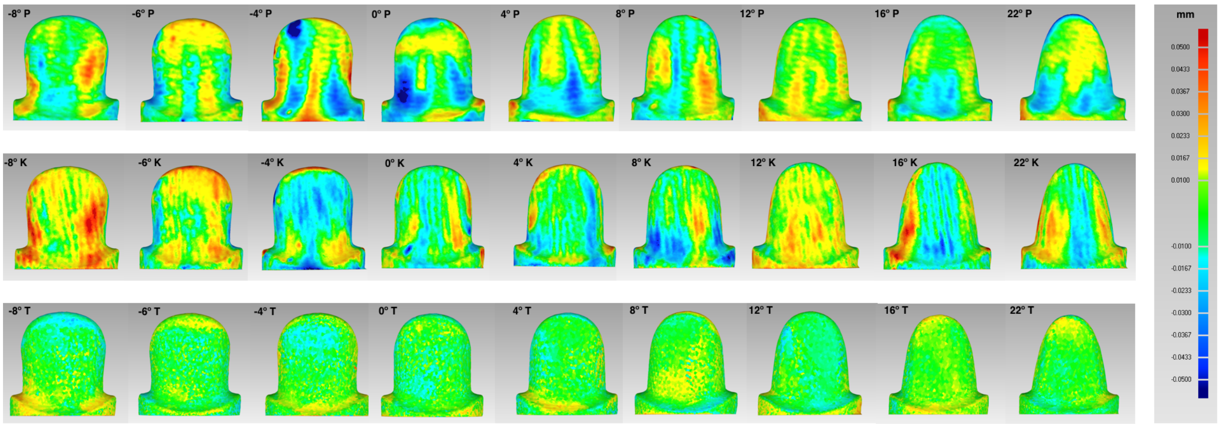


Figure 13. Representative deviation pattern between impressions of one test group (precision). Deviation range color coded from +50 µm (dark red) to -50 µm (dark blue). Max/min nominal ±10 µm (green). P, polyvinyl siloxane impressions; K, extraoral scanned casts with KaVo scanner; T, intraoral digital impressions with TRIOS.

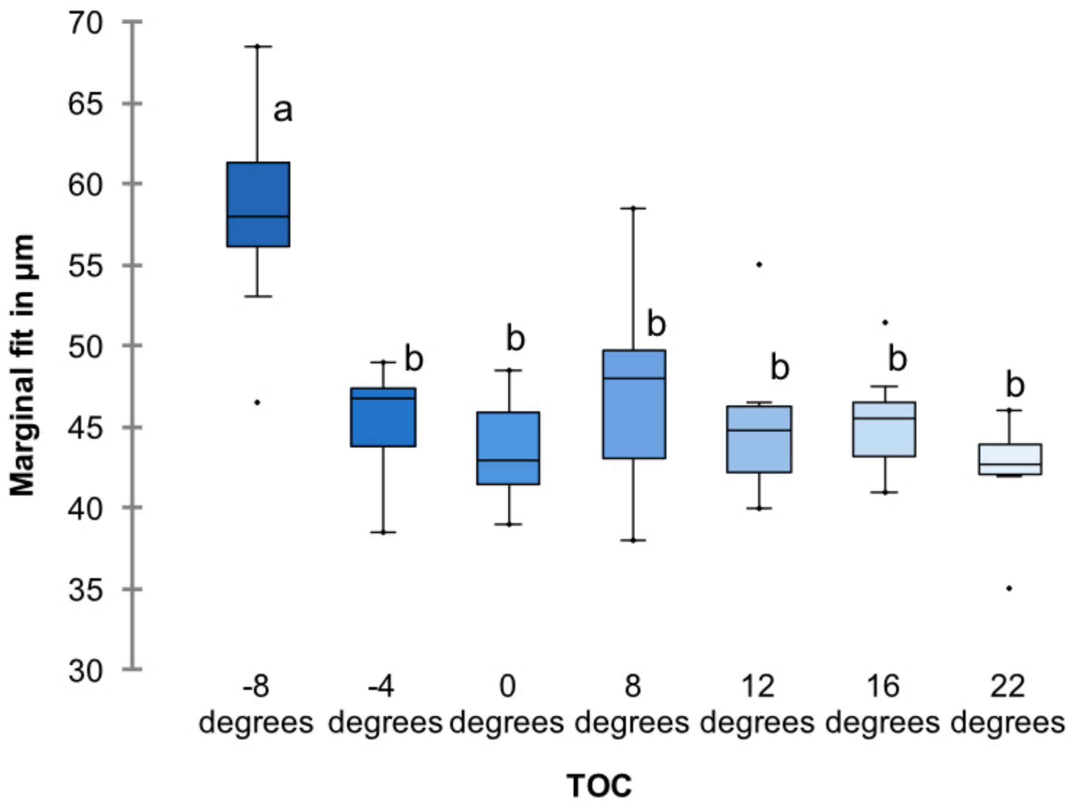


Figure 14. Marginal fit values according to the total occlusal convergence (TOC) angle. (Different letters indicate significant differences at $P < 0.05$).

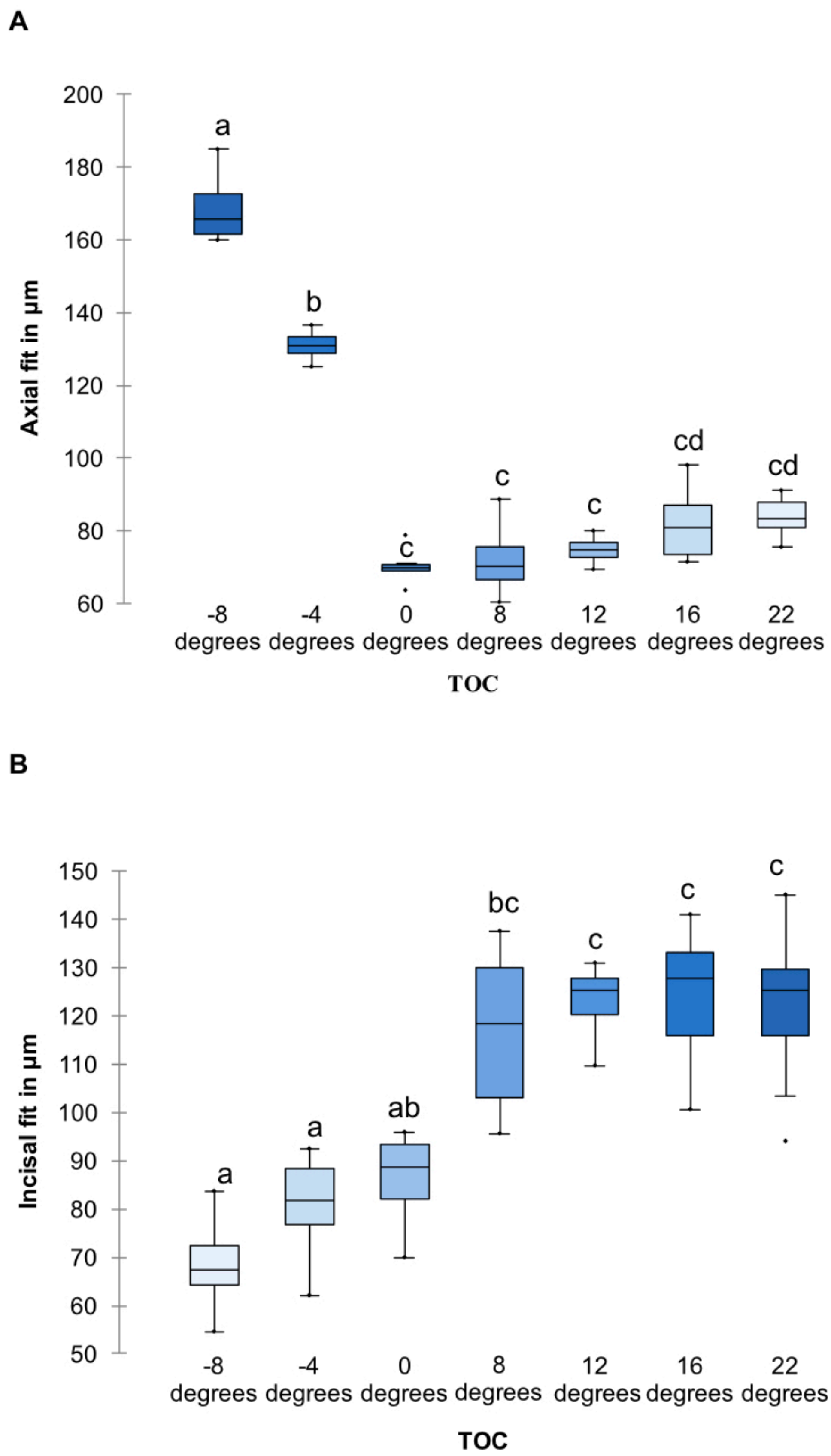


Figure 15 A, B. Internal fit values according to the total occlusal convergence (TOC) angle. (Different letters indicate significant differences at $P < 0.05$).

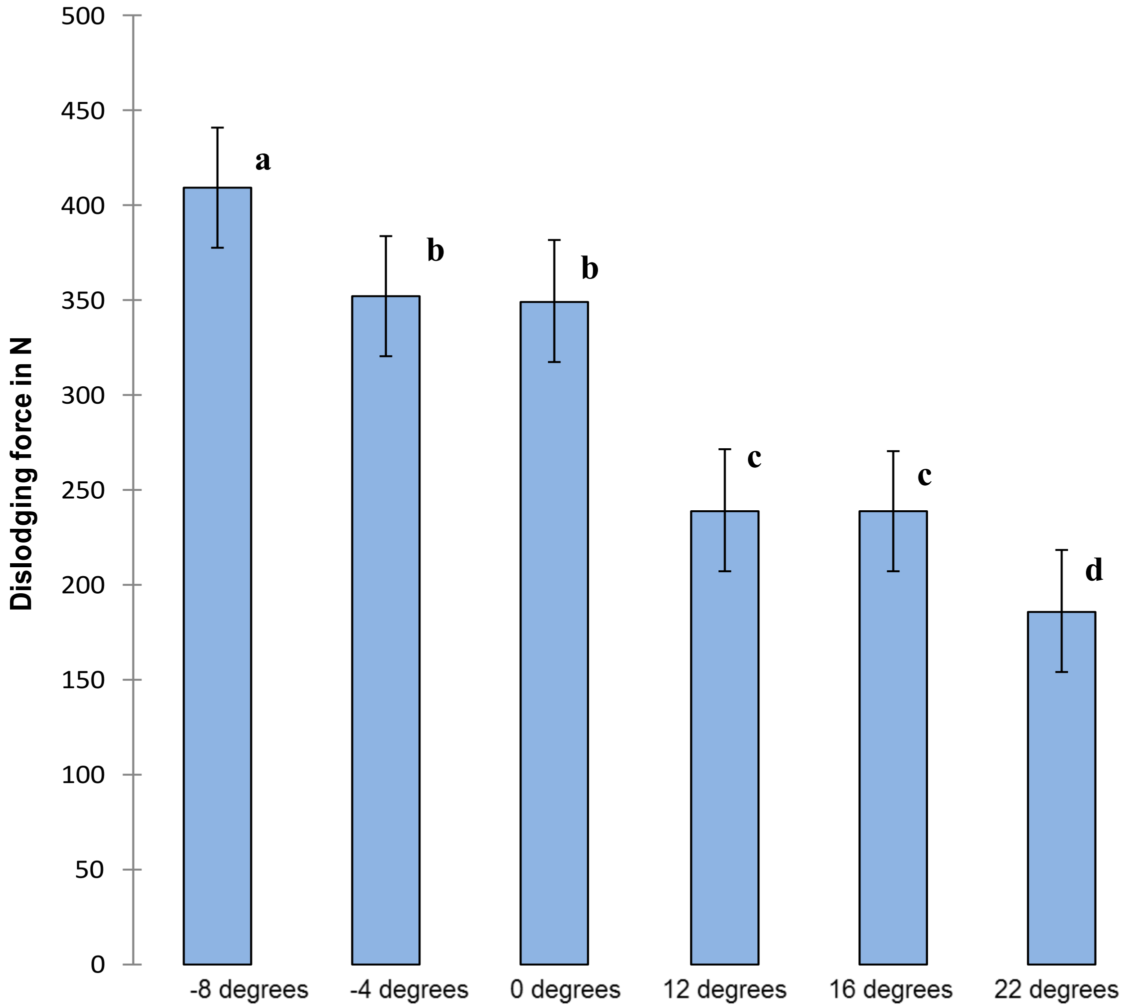
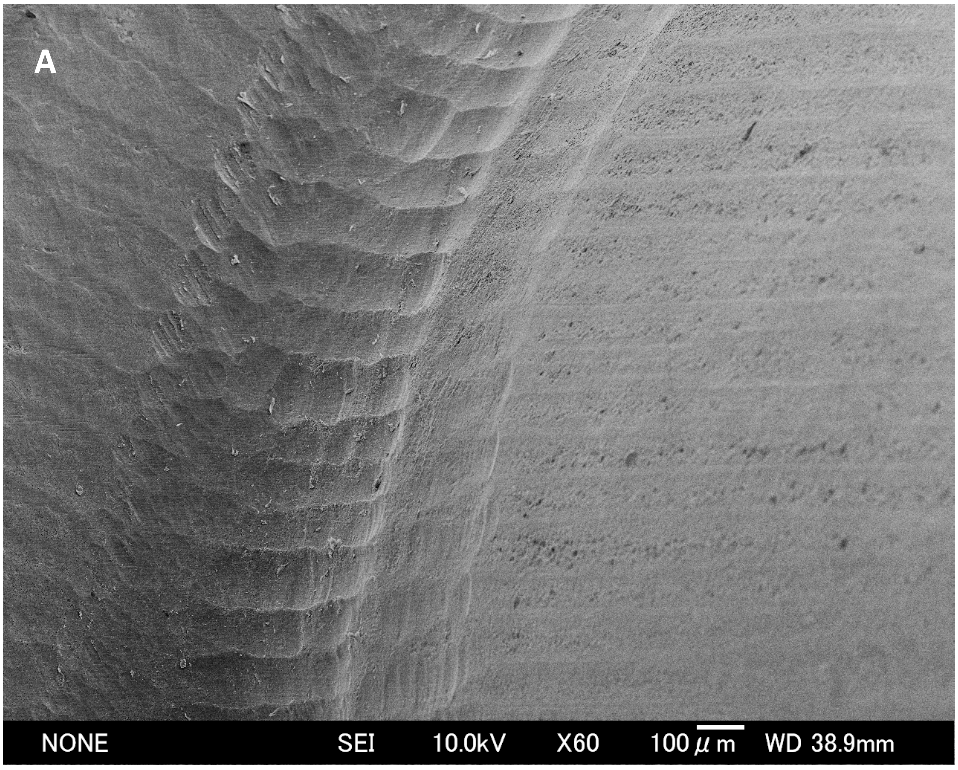


Figure 16 A, B. Mean dislodging force and standard deviations of crowns made over reverse tapered preparations after 1-year water storage (same letters, $P > 0.05$; One-way ANOVA; n =10).



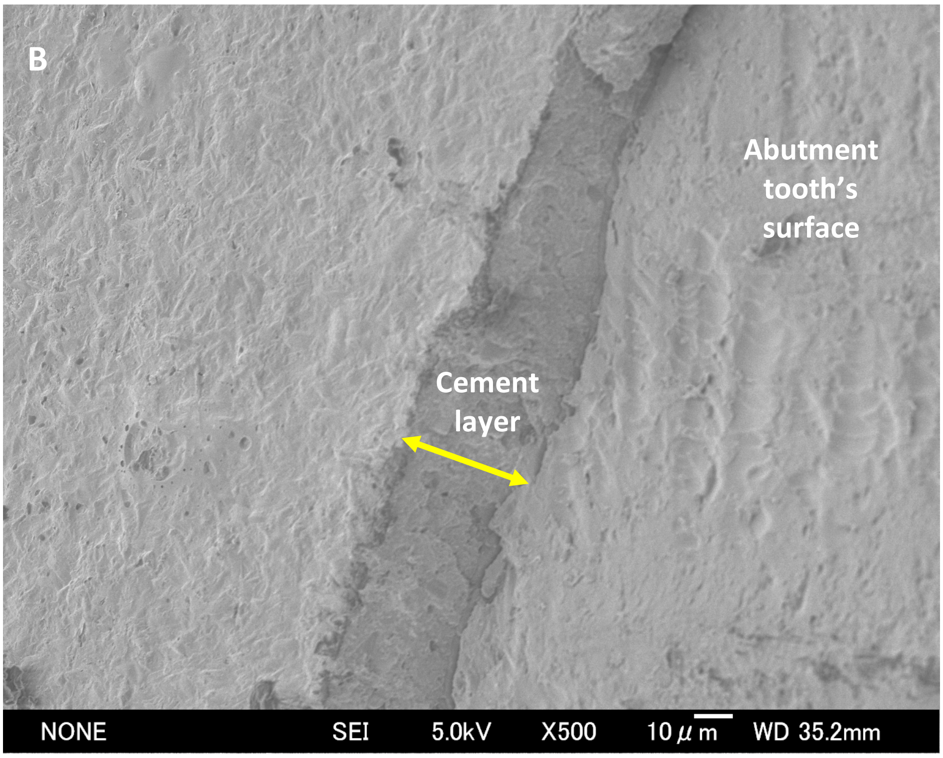


Figure 17 A, B. SEM observations on the abutment tooth surface before cementation(A) and after adhesive failure (B)

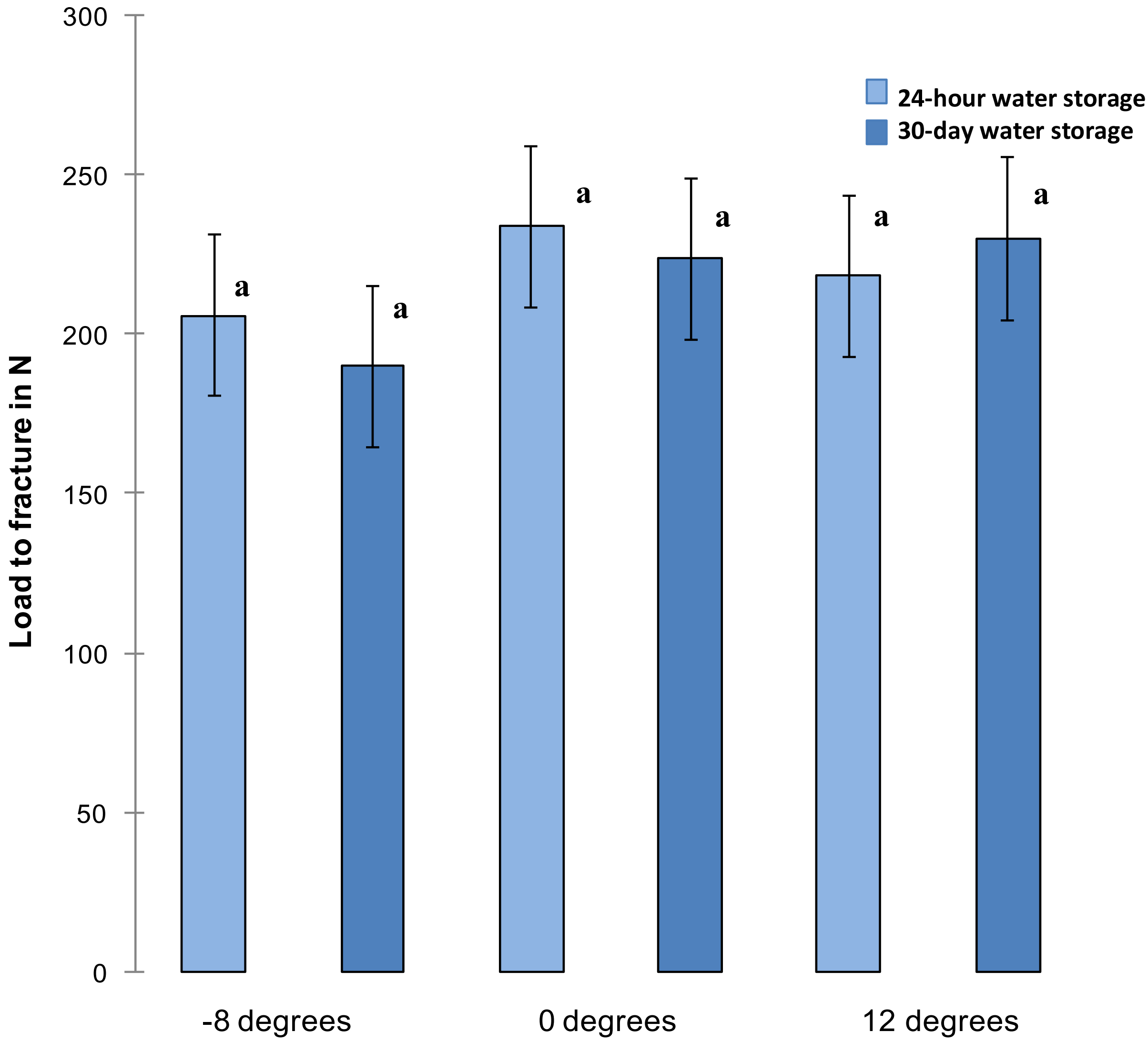


Figure 18. Mean fracture resistance and standard deviations of crowns made over reverse tapered preparations (same letters, $P > 0.05$; repeated measures ANOVA; n = 10).