

Evaluation of the adaptation of zirconia-based fixed partial dentures using micro-CT technology

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Abstract: The objective of the study was to measure the marginal and internal fit of zirconia-based all-ceramic three-unit fixed partial dentures (FPDs) (Y-TZP - LAVA, 3M-ESPE), using a novel methodology based on micro-computed tomography (micro-CT) technology. Stainless steel models of prepared abutments were fabricated to design FPDs. Ten frameworks were produced with 9 mm² connector cross-sections using a LAVA™ CAD-CAM system. All FPDs were veneered with a compatible porcelain. Each FPD was seated on the original model and scanned using micro-CT. Files were processed using NRecon and CTAn software. Adobe Photoshop and Image J software were used to analyze the cross-sectional images. Five measuring points were selected, as follows: MG - marginal gap; CA - chamfer area; AW - axial wall; AOT - axio-occlusal transition area; OA - occlusal area. Results were statistically analyzed by Kruskal-Wallis and Tukey's post hoc test ($\alpha = 0.05$). There were significant differences for the gap width between the measurement points evaluated. MG showed the smallest median gap width (42 μm). OA had the highest median gap dimension (125 μm), followed by the AOT point (105 μm). CA and AW gap width values were statistically similar, 66 and 65 μm respectively. Thus, it was possible to conclude that different levels of adaptation were observed within the FPD, at the different measuring points. In addition, the micro-CT technology seems to be a reliable tool to evaluate the fit of dental restorations.

Descriptors: Computer-Aided Design; Denture, Partial, Fixed; Ceramics.

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Introduction

The use of ceramic materials to produce large frameworks, such as those in three- and four-unit fixed partial dentures (FPDs), has been enabled by the introduction of CAD-CAM technology (computer-aided design-computer-aided manufacturing) in dentistry and by the development of high fracture toughness zirconia-based ceramics.¹ Yttria partially stabilized tetragonal zirconia (Y-TZP) was initially introduced in the medical field as a hip implant material, due to its excellent mechanical performance and biocompatibility.² In the dental clinic, Y-TZP ceramic is indicated as a framework material for crowns and large FPDs in both the anterior and posterior areas of the mouth.¹

Y-TZP frameworks are produced using CAD-CAM technology, by

milling partially or densely sintered pre-fabricated blocks. Milling densely sintered blocks produced by hot isostatic pressure (HIP) has the advantage of ensuring better adaptation of the final crown. However, milling hard structures is time-consuming and causes excessive wear of the milling burs. On the other hand, using partially sintered blocks increases the efficiency of the milling process. In such cases, the CAD-CAM system should produce larger restorations to compensate the sintering shrinkage, and to ensure adequate fit of the crown.³⁻⁵

The literature reports mean failure load values between 981 and 3480 N for three-unit Y-TZP FPDs,⁶⁻⁹ and values ranging from 706 to 1262 N for four-unit Y-TZP FPDs.^{10,11} In addition, clinical studies have showed low failure rates for Y-TZP restorations, i.e., about 2% to 6% after three to five years. The main causes of these clinical failures are secondary caries, loss of retention and chipping of the porcelain veneer.^{12,13} For this reason, restoration fit is an important factor for restoration prognosis, insofar as poor marginal adaptation results in dissolution of the luting agent and favors microleakage of bacteria and their byproducts, thus increasing tooth susceptibility to inflammation of the vital pulp, secondary caries, and marginal discoloration.¹⁴⁻¹⁶

The CAD-CAM technique uses a series of processing steps, such as scanning, software designing, milling and sintering, which may interfere with the precision of fit of the restoration. Although the sintering shrinkage of restorations obtained from partially sintered blocks can be compensated by milling enlarged restorations, it is not as yet clear whether this compensation is effective for the production of FPDs with long spans.^{4,17} In addition, previous studies reported that the internal adaptation of CAD-CAM restorations is poorer, compared with marginal adaptation.^{3,5,17} This finding represents a relevant clinical problem, insofar as wide internal gaps have been associated with decreased fracture strength and loss of retention of the restoration.¹⁸

There is no standard methodology to measure the marginal and internal adaptation of indirect restorations. Different techniques and tools are available to evaluate the restoration adaptation.¹⁹⁻²² Recently, a methodology involving micro-computed

tomography (micro-CT) was proposed as a reliable and non-destructive technique to evaluate the internal and marginal adaptation of dental restorations. However, there are only few studies that use this methodology for this purpose in the dental field.^{5,23,24}

The objective of this study was to measure the marginal and internal fit of zirconia-based all-ceramic three-unit FPDs, using a novel methodology based on micro-CT technology. The study hypothesis was that the gap width is similar at all measuring points.

Methodology

Fixed partial denture

A stainless steel model simulating prepared abutment teeth was constructed with the following characteristics:

- 4.5 mm height,
- 6° taper and
- 120° chamfer as the finish line.^{5,7}

The distance between the centers of the dies was 16 mm, corresponding to the distance between a lower second premolar and a lower second molar (10 mm span). An artificial gingiva was produced with acrylic resin (JET, Clássico, São Paulo, Brazil), and a polyvinyl siloxane impression of the model was taken (Aquasil™, Dentsply, Petrópolis, Brazil) using the double impression technique. A working die was made with type IV special CAD/CAM stone (CAM-base, Dentona AG, Dortmund, Germany).

The stone die was digitized by the Lava™ Scan non-contact, optical scanning system, and the FPD framework was designed by LAVA™ Scan ST Design System (3M ESPE, St. Paul, USA). A uniform 20 µm cement spacer was used. The frameworks were milled with the LAVA™ CNC 500 Milling Machine using LAVA Zirconia Frame pre-sintered Y-TZP material (Y-TZP - 3M ESPE, St. Paul, USA). The frameworks were sintered using the LAVA™ Furnace 200 (3M ESPE, St. Paul, USA). Ten frameworks were produced with 9 mm² connector cross-sections (Figure 1).

After milling, a bonding agent (Effect Bonder, Vita Zahnfabrik, Bad Sackingen, Germany) was ap-

plied to the framework and sintered according to the cycle recommended by the manufacturer. Vita VM9 porcelain (Vita Zahnfabrik, Bad Sackingen, Germany) was used to veneer the frameworks with a uniform thickness of approximately 1.2 mm around the crowns and pontic, and 0.6 mm around the connectors. The porcelain thickness was ascertained at 7 pre-determined points using a digital caliper, and polishing burs were used to ensure uniform thickness. A final porcelain glaze cycle was performed according to the instructions of the manufacturer.

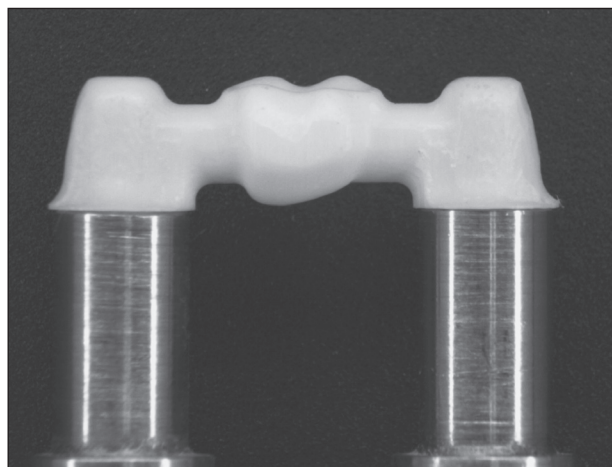


Figure 1 - Zirconia framework on the metal dies.

Micro-CT scanning

Each FPD was seated on the original stainless steel model and scanned by the SkyScan 1172 micro-CT system equipped with a 10 megapixel camera (Skyscan, Aartselaar, Belgium). The scanning parameters were:

- accelerating voltage of 100 kV,
- current of 100 μ A,
- exposure time of 2950 ms per frame,
- Al + Cu filter, and
- rotation step at 0.4° (180° rotation).

The x-ray beam was irradiated perpendicular to the preparation long axis, and the image pixel size was 17 μ m. The x-ray projections were reconstructed using SkyScan's volumetric reconstruction software (Nrecon). Reconstructed slices were saved as a stack of BMP-type files. Beam hardening correction of 80% and ring artifact correction of 7 were used for the reconstruction. The scanning procedure was performed without cementation of the FPDs.

Gap measurements

CTAn software (Skyscan, Aartselaar, Belgium) was used to obtain cross-sectional images through the center of the die (x-axis), in the mesiodistal and buccolingual directions (Figure 2). This software

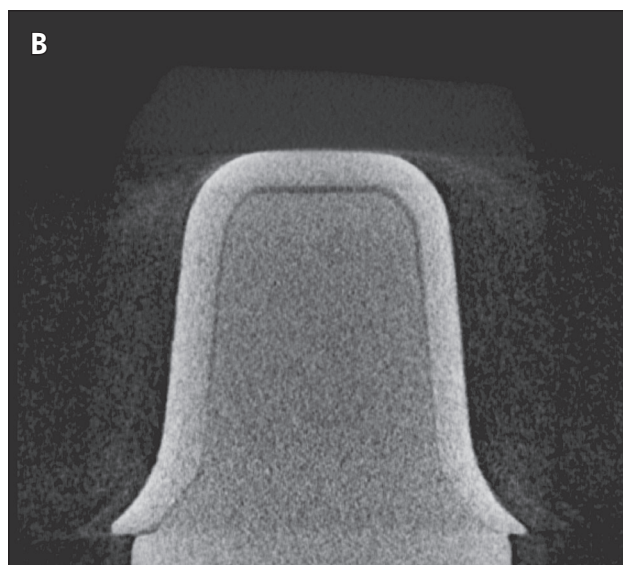
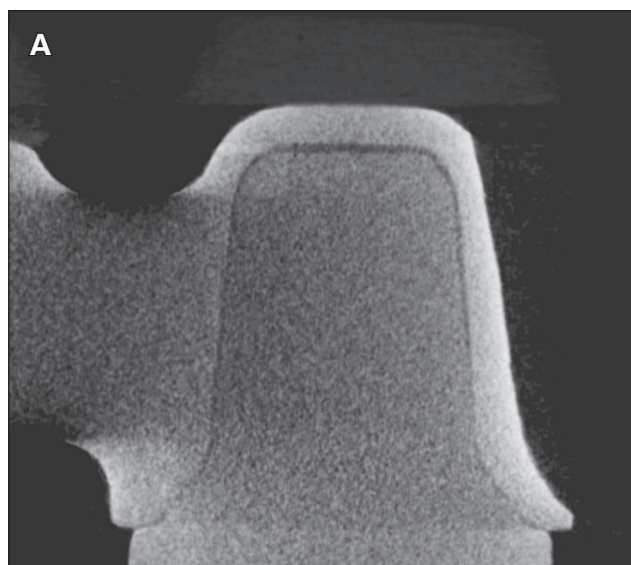


Figure 2 - Cross-sectional images through the center of the die (x-axis), in the mesiodistal (A) and buccolingual directions (B).

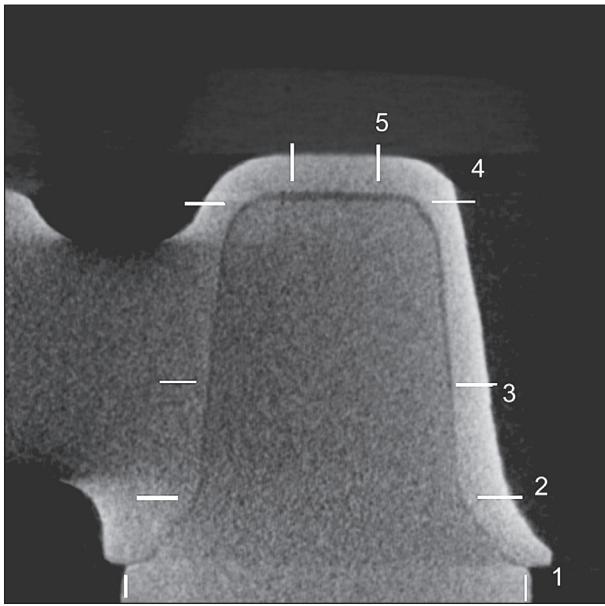


Figure 3 - Measuring locations: (1) MG; (2) CA; (3) AW; (4) AOT; (5) OA.

made it possible to choose a region of interest (ROI) and the desired number of slices for the region selected. As a result, the number of slices could be standardized for all specimens, and the same slice—corresponding to the center of the crown, in both buccolingual and mesiodistal directions—was analyzed for each crown. These images were transferred to Adobe Photoshop software to delimit the internal space between the die and the crown, and Image J software was used to perform the measurements. All measurements were performed by a single examiner. The presence of small radiographic artifacts precluded the use of any automatic tool. Therefore, all measurements were taken manually, and the measuring points were standardized to minimize errors.

Five measuring points were selected⁵ (Figure 3):

- **MG - marginal gap:** perpendicular measurement from the internal surface of the crown to the margin of the die;²⁵
- **CA - chamfer area:** 800 μm occlusal to the margin of the die;
- **AW - axial wall:** internal adaptation at the midpoint of the axial wall;
- **AOT - axio-occlusal transition area:** transition from the occlusal plateau to the axial wall;

Table 1 - Mean, median, minimum, maximum and standard deviation (SD) values of gap width for the measurement points (μm), and coefficient of variation (CV).

Location	Mean	Median*	Min	Max	SD	CV (%)
1. MG	47	42 ^d	21	99	16	35
2. CA	69	66 ^c	30	147	21	30
3. AW	65	65 ^c	25	107	16	25
4. AOT	104	105 ^b	33	188	30	29
5. OA	133	125 ^a	75	226	35	26

*Values followed by the same small letter in the column are statistically similar ($p \geq 0.05$).

- **OA - occlusal area:** 500 μm from the axio-occlusal angle in the direction of the center of the occlusal plateau.

Results from different measuring points were analyzed statistically using Kruskal-Wallis one-way analysis of variance on ranks and Tukey's test, at a significance level of 5%, since data failed the normality test.

Results

Mean, median, minimum, maximum and standard deviation values (all in μm), as well as coefficient of variation (%) of the gap width for the different measuring points, are shown in Table 1. There were significant differences between gap dimensions obtained for the different measurement points ($p < 0.001$). MG showed the smallest median gap width. OA had the highest median gap dimension followed by the AOT point. The OA dimension was three times larger than that of the MG. CA and AW gap width values were statistically similar. The coefficient of variation values showed a small variation when different measuring points were compared, suggesting similar variability. This could be related to the reproducibility of the CAD-CAM technology, and also to the accuracy of the measuring methodology. Figure 4 shows the boxplot representing the gap width median and quartiles at each measurement point.

No internal adjustment was made in the crowns. In addition, although the manufacturer recommends performing manual finishing before sintering

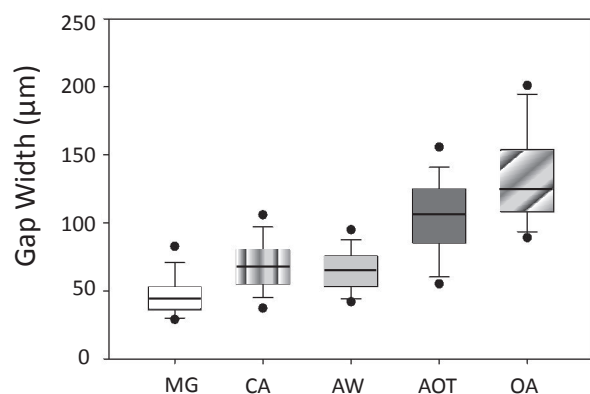


Figure 4 - Boxplot of the gap width values at each measuring point (μm).

takes place, no external finishing was conducted in the frameworks, thus explaining the slightly overextended margins observed in the cross-sectional images (Figure 2 and 3).

Discussion

In the present study, different levels of adaptation were observed for the FPDs at the different measuring points. Thus, the study hypothesis was rejected, and it was demonstrated that the CAD-CAM technique used was unable to create a homogeneous gap width along the tooth preparation, even though a uniform 20 μm cement spacer setting was used to produce the FPDs. This finding is in agreement with other studies that investigated the adaptation of Y-TZP FPDs produced with LAVA and other current CAD-CAM systems.^{3,5,17,20} An investigation also found significantly different mean gap values as a function of measurement location.³ The study reported that the occlusal gap width of LAVA three-unit framework was six times larger than the marginal gap width. Furthermore, a study that measured the gap width of all-ceramic FPDs produced with three different CAD-CAM systems (Digident, Cerec InLab and LAVA) also observed an increase in values from the marginal gap to the central measuring location.¹⁷ These differences in the adaptation level as a function of the location could be related to the quality of acquisition and processing of the digital data, and the diameter and shape of the milling instruments, as discussed below.^{3,26}

The LAVA scanner acquires its optical impres-

sion by means of striation projection, which is susceptible to a few errors that could partially explain internal inaccuracies. First, the finite scanning resolution of the measuring system may result in slightly rounded edges, leading to premature contacts at the occlusal edges. To overcome this problem, the CAD-CAM manufacturer created a spacer parameter that can be applied to the restoration design with different thicknesses, allowing the customization of the internal gaps. Second, a physical phenomenon called “overshooters,” which simulates virtual peaks near the edges, may also contribute to the increased internal discrepancy.^{17,26}

In the present study, the marginal gap was the area of the FPD retainer that showed the best adaptation in comparison with all the other internal measurement points. There is a consensus between a series of studies that a marginal opening below 120 μm is clinically acceptable.^{3,27,28} In this study, a mean marginal gap of 47 μm was found, which is well below the clinical threshold. This is an important finding since the marginal adaptation is an important criterion for the success of all-ceramic restorations in the long term. A poor marginal adaptation may increase plaque retention and change the distribution of the microflora, which may induce the development of periodontal diseases. A large marginal gap is also related to a more rapid rate of cement dissolution, which is conducive to the percolation of food, oral debris and other substances that are potential irritants to the vital pulp.¹⁴⁻¹⁶ On the other hand, wider gaps are currently more accepted, in view of the evolution of adhesive luting materials and protocols.

Although there was an increase in the gap width from the margin to the occlusal area, the values observed for the internal regions of the retainers were still relatively low and were within the clinically acceptable limit. A study reported that a mean axial wall gap dimension of 122 μm could reduce the fracture strength of the crowns.¹⁸ In the present study, not only the axial wall but also the chamfer and axio-occlusal transition areas showed mean gap values below this threshold. It is important to produce restorations with a uniform cement space so as not to compromise the retention and resistance

forms, especially for all-ceramic restorations that have a brittle behavior.²⁹

Metal-ceramic restorations are the gold standard for prosthetic restorations, and there is a concern regarding the ability of CAD-CAM technology to produce restorations with such precision of adaptation. Studies that measured the marginal gap of three-unit metal-ceramic FPDs *in vivo* reported values between 67 to 85 μm .^{17,30} These values are slightly higher than the mean marginal gap value of the zirconia-based FPD investigated in the present study. This difference may also be related to differences in the gap measurement methodology and to the fact that the present study was carried out in the laboratory. However, the similarity between these marginal gap values suggested that CAD-CAM technology is able to produce high precision restorations, and all-ceramic FPDs may show comparable quality of adaptation in relation to metal-ceramic FPDs. The greater accuracy observed for the CAD-CAM systems in recent years may be attributed to improvements in technologies, software and milling strategies.³ Even when pre-sintered blocks are used, the sintering shrinkage is effectively compensated during the grinding process, which ensures an accurate final result.⁵

The micro-CT technique allows 2D and 3D investigation of the marginal and internal gaps within the range of a few micrometers.^{23,24} The asymmetric geometry of the FPD and the atomic elements present in the composition of the ceramic framework (zirconium) produced small artifacts in the cross-sectional images that precluded 3D analysis of the cement space. However, 2D analysis enabled accurate visualization of the all-ceramic FPD marginal and internal adaptation. The results obtained in the present study are in agreement with previous stud-

ies.^{3,17,20} The gap width values are within the values reported in the literature for LAVA CAD-CAM system FPDs, and small differences, such as those observed between the gap widths at different measuring points, could be detected. Thus, the micro-CT technology seems to be a reliable tool to evaluate FPD fit. Studies that applied the micro-CT technique to evaluate the adaptation of ceramic crowns also suggested that this method may be recommended as a useful tool for the evaluation of dental restorations.^{23,24}

Conclusion

In the present study, different levels of adaptation were observed within the FPD, at different measuring points, thus rejecting the study hypothesis. The marginal gap had the smallest dimension and the occlusal area gap had the largest. Nevertheless, the adaptation values were within the clinically acceptable. In addition, micro-CT technology seems to be a reliable tool to evaluate the fit of dental restorations.

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