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ORIGINAL ARTICLE

# Different CAD/CAM-processing routes for zirconia restorations: influence on fitting accuracy

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**Abstract** The aim of the present in vitro study was to evaluate the influence of different processing routes on the fitting accuracy of four-unit zirconia fixed dental prostheses (FDPs) fabricated by computer-aided design/computer-aided manufacturing (CAD/CAM). Three groups of zirconia frameworks with ten specimens each were fabricated. Frameworks of one group (CerconCAM) were produced by means of a laboratory CAM-only system. The other frameworks were made with different CAD/CAM systems; on the one hand by in-laboratory production (CerconCAD/CAM) and on the other hand by centralized production in a milling center (Compartis) after forwarding geometrical data. Frameworks were then veneered with the recommended ceramics, and marginal accuracy was determined using a replica technique. Horizontal marginal discrepancy, vertical marginal discrepancy, absolute marginal discrepancy, and marginal gap were evaluated. Statistical analyses were performed by one-way analysis of variance (ANOVA), with the level of significance chosen at 0.05. Mean horizontal discrepancies ranged between 22 μm (CerconCAM) and 58 μm (Compartis), vertical discrepancies ranged between 63 μm (CerconCAD/CAM) and 162 μm (CerconCAM), and absolute marginal discrepancies ranged between 94 μm (CerconCAD/CAM) and 181 μm (CerconCAM). The marginal gap varied between 72 μm (CerconCAD/CAM) and 112 μm (CerconCAM, Compartis). Statistical analysis revealed that, with all measurements, the marginal accuracy of the zirconia FDPs was significantly influenced by the processing route used ($p<0.05$). Within the limitations of this study, all restorations showed a clinically acceptable marginal accuracy; however, the results suggest that the CAD/CAM systems are more precise than the CAM-only system for the manufacture of four-unit FDPs.

**Keywords** CAD/CAM · Processing route · Zirconia · FDP · Fitting accuracy

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## Introduction

In recent years, yttria-stabilized polycrystalline tetragonal zirconia (Y-TZP) has been increasingly applied to the manufacture of all-ceramic restorations. This zirconia material, once only used in engineering, combines high esthetics, excellent biocompatibility, low plaque accumulation, and low thermal conductivity with high strength—attributes of crucial importance for dental application. The high strength of zirconia (due to the structural reinforcement during the tetragonal-to-monoclinic transformation) [1] even permits utilization of all-ceramic restorations in the posterior region [2, 3]. Nowadays, subtractive milling techniques by means of computer-aided design/computer-aided manufacturing (CAD/CAM) systems are most commonly used for the processing of Y-TZP. Because of its high strength and hardness, which are detrimental to milling times, and the attrition of milling tools [4], Y-TZP is usually not machined in a densely sintered state, but in a presintered porous state. However, to achieve maximum strength, these Y-TZP ceramics must be sintered after milling, which is accompanied by shrinkage of 25–30% and has to be taken into account before milling the workpieces [4–6]. In recent years, further innovative technologies that facilitate the transformation of superfine dispersed ceramic powders into high-density and high-purity ceramic restorations by a direct shaping process have been developed [7].

One of three different processing routes is now usually used for the fabrication of zirconia restorations by means of subtractive milling techniques. Firstly, restorations may be manufactured with different manual or electronic copy milling systems. With the manual systems, a coping or framework is manually fabricated in wax or composite, and then the pattern is placed into a pantographic machine. The copying arms of these machines trace the wax pattern, while the cutting arm, which has a carbide cutter, mills a selected presintered zirconia blank [8]. The final shape of the restoration is enlarged, in order to account for shrinkage during the sintering phase. The electronic copy milling systems, referred to as CAM-only systems, also require a wax-up of the framework, which is then scanned by means of a laser beam without any contact and converted to a digital design. On the basis of these data, the framework is then milled in a CAM unit and then sintered in a furnace [9]. Secondly, zirconia frameworks can be made by means of in-laboratory CAD/CAM production. In this process, a stone cast of the prepared teeth is optically or mechanically scanned and digitized into geometrical data. Then, the framework is virtually designed using a CAD program. Based on the resulting data set, the restoration is milled in a CAM unit and sintered to its final density. Thirdly, the scan of the stone cast can be performed in the dental laboratory. After optimization of the geometric shape with the aid of the CAD system, the restoration data are sent to a milling center for centralized production under the most exacting quality standards. The dental laboratory normally returns the finished framework by parcel post within 72 h for further processing.

One of the most crucial aspects for the long-term clinical success of fixed dental restorations is their fitting accuracy, especially in the marginal area. Marginal discrepancies may cause the exposure of luting material to the oral environment. Glass-ionomer cements or zinc phosphate cements are mostly used for the fixation of zirconia-based restorations on the abutment teeth. The solubility of these dental cements results in a space between restorations and the prepared teeth. In this defective area, plaque retention increases, accompanied by secondary caries and a change in bacterial diversity, which can induce the onset of periodontal diseases [10–13]. Furthermore, microleakage from the oral cavity can initiate endodontic inflammations [14]. Besides biological aspects, fitting accuracy is also relevant to mechanical reliability under functional loading. Rekow and Thompson [15] demonstrated that an excessive cement layer may cause stress concentrations on the tensile surface, due to viscoelastic deformation of the cement material under cyclic loading. These increased tensile stresses damage the veneering porcelain and initiate chipping of the veneering layer. Chipping appears to be one of the major reasons for failure of zirconia-based restorations [10, 16–18].

Various studies have examined the marginal accuracy of all-ceramic fixed dental prostheses (FDPs)—both in vitro and in vivo [19–30]. However, to the best of our knowledge, there are no published investigations evaluating the marginal accuracy of complex zirconia restorations fabricated by means of different processing routes provided by an individual company. Therefore, the objective of the present in vitro study was to determine the marginal accuracy of CAD/CAM-fabricated posterior four-unit zirconia FDPs generated by means of the three processing routes described above and provided by one and the same company (DeguDent, Hanau, Germany). The null hypothesis to be tested was that the fitting accuracy significantly depends on the processing route used.

## Materials and methods

### Preparation of a master model

First premolar and second molar of an upper jaw typodont resin model (Frasaco OK 119, A-3 T, Franz Sachs & Co., Tettnang, Germany) were prepared to accommodate an all-ceramic FDP. The model was prepared by adjusting a 1.0-mm circumferential chamfer, an occlusal reduction of 2.0 mm, and a 5° convergence angle. The area of the resin model including the prepared teeth was then duplicated as an abrasion-resistant master model made of nickel–chromium alloy (Wiron 99, Bego, Bremen, Germany). Based on 20 individual impressions (Silagum, DMG, Hamburg, Germany) of this master model, 20 casts in class IV stone (Fuji Rock, GC, Leuven, Belgium) were made and subsequently used as a basis for fabricating the Y-TZP frameworks.

### Fabrication of FDPs with Y-TZP frameworks

Three groups of FDPs, with ten specimens each, were manufactured by means of different processing routes for each test group. All frameworks were made from the same presintered zirconia material (Cercon base, DeguDent). The dimensions of all series of frameworks were practically the same, with the connector width and height differing by less than 0.2 mm between series. Connector cross-sectional areas (from mesial to distal) were 12.5, 15.6, and 11.6 mm$^2$, respectively; the wall thickness of the abutment crowns was 0.6 mm.

Frameworks of one test group (CerconCAM) were fabricated by means of a CAM-only system. Ten individual wax-ups were made on ten stone casts, which were manually provided with spacer (Cercon spacer, DeguDent) in the range of the prepared abutment teeth, beginning 1.5 mm above the preparation margin. The homogeneous dimensioning of all wax-ups was guaranteed by use of various silicone templates, which were prepared in advance with the first wax-up made. Then, the frameworks were fabricated by scanning (laser scanning method) and copying each wax-up in a CAM unit (Cercon brain, DeguDent) with subsequent sintering of the presintered zirconia restorations (Cercon base, DeguDent) in the system oven (Cercon heat, DeguDent) for 6 h at 1350°C.

To manufacture the frameworks in the second test group (CerconCAD/CAM), ten stone casts of the master model were optically scanned, using a laser method (Cercon eye, DeguDent). After digitization of the geometrical data of each stone cast, CAD design was performed for the ten individual situations (Cercon art, DeguDent). Based on the generated data sets, frameworks were milled (Cercon brain, DeguDent) of presintered zirconia (Cercon base, DeguDent) in the dental laboratory. Cement space of the retainers was virtually adjusted to 30 µm. Terminal sintering was performed in the furnace (Cercon heat, DeguDent) for 6 h at 1350°C.

With the third test group (Compartis), geometrical data of identical frameworks generated in the CerconCAD/CAM-group were sent to the DeguDent milling center and ten restorations were fabricated (Compartis, DeguDent) from presintered zirconia blanks (Cercon base, DeguDent). Finally, restorations were returned to the laboratory for further processing.

In the next step, all frameworks were examined for deformity and debris and steam cleaned. Next, the FDPs were adapted to the nickel–chromium master model until the best possible fit was achieved. The adaptation was conducted by an experienced dental technician under ×4 magnification. Inner areas of the retainers that needed correction were detected using a permanent marker. The marker was applied to the abutment teeth of the master model, and the frameworks were placed onto the die without force. If necessary, the colored spots remaining inside the retainers were removed by a fine bur, using water cooling and light pressure. This procedure was repeated until the retainers achieved uniform contact with the abutment teeth and retention would be lost if further adjustment were made. Afterwards, a dental technician and a dentist decided if further correction might improve the fit of the framework.

To simulate clinical conditions as accurately as possible, frameworks were veneered according to the manufacturer's instructions with the recommended ceramics (Cercon ceram kiss, DeguDent), using a slurry technique (Fig. 1). To prevent contamination of the frameworks' margins and retainers' inner surfaces, the veneering porcelain was not applied to an annular area extending approximately 0.5 mm from the cervical margin rim of the FDP retainers. The homogeneous dimensioning of the veneering layer with layer thickness between 0.5 and 1.2 mm (according to position) was guaranteed by use of various silicone templates that were prepared in advance with a wax-up.

## Analysis of fitting accuracy

To determine the fitting accuracy, the retainers of the FDPs were filled with light-body silicone (Dimension Garant L, 3M ESPE, Seefeld, Germany). Then, the FDPs were placed onto the abutment teeth of the master model and loaded with a force of 50 N in the occlusal direction. After the light-body silicone had set, the restorations were removed from the master model while the thin silicone films representing the space between abutment teeth and retainers remained on the abutment teeth (Fig. 2). The silicone films were then stabilized by a contrasting heavy-body silicone (Detaseal bite, Detax, Ettlingen, Germany), using a customized impression tray. The resulting replicas of premolar and molar were placed in a setting jig and segmented with a razor blade—once in the mesio-distal and once in the bucco-palatal direction, so that, per abutment, four measuring locations (mesial, distal, buccal, and palatal) were used (Fig. 3).

The quartered replicas were photographed using a light-optical microscope (Orthoplan, Leitz, Wetzlar, Germany) at a magnification of ×51.2, and the software CorelDraw 10 (Corel, Ottawa, Canada) was used to measure marginal distances. Overall, four different measurements per measuring location were made. The

**Fig. 1** FDP with zirconia framework after the veneering process

**Fig. 2** Silicone films representing the space between abutment teeth and retainers

horizontal marginal discrepancy (*x*), the vertical marginal discrepancy (*y*), the absolute marginal discrepancy (*z*), and the marginal gap (*w*) were evaluated (Fig. 4), as defined by Holmes et al. [31]. The horizontal marginal discrepancy is defined as the horizontal misfit between the outermost portions of the retainer's margin and the preparation edge of the abutment teeth, measured perpendicularly to the path of draw of the restoration. The vertical marginal discrepancy is defined as the vertical misfit between the outermost portions of the retainer's margin and the preparation edge of the abutment teeth, measured parallel to the path of draw of the restoration. The vectorial sum of these two distances (*x* and *y*) defines the absolute marginal discrepancy (*z*). Hence, the absolute marginal discrepancy is the hypotenuse of a right triangle, the sides of which are the horizontal and the vertical marginal discrepancy. The perpendicular measurement from the surface of the abutment to the retainer's margin is called the marginal gap (Fig. 4).

**Fig. 3** Stabilized replica after segmentation in the mesio-distal and bucco-palatal directions

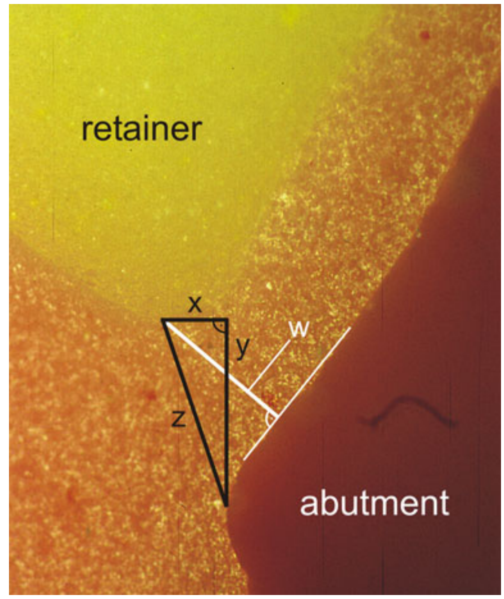


**Fig. 4** Microscopic cross-sectional photograph of a replica. Definition of measuring distances for marginal accuracy. *x* horizontal marginal discrepancy, *y* vertical marginal discrepancy, *z* absolute marginal discrepancy, *w* marginal gap

### Statistical analysis

Statistical analysis was performed using SPSS for Windows, version 16.0 (SPSS Software, Munich, Germany). The normal distribution of data and homogeneity of variance were checked using the Kolmogorov–Smirnov and Levene tests, respectively. In order to detect whether different processing routes had a significant influence on marginal accuracy, one-way analysis of variance was used, with the level of significance set at 0.05. Differences between groups were checked for significance with the post hoc Scheffé test or, alternatively, the post hoc Tamhane test, if variances were not homogeneous. Furthermore, to determine whether dimensions of the FDPs were extended or shortened in the direction of the longitudinal axis, horizontal marginal discrepancies (*x*) at the mesial and at the distal measurement locations of each abutment were statistically compared by means of Student's *t* test. The level of significance was also set at 0.05.

## Results

Table 1 and Fig. 5 show detailed results for each measurement with the different processing routes. Medians, mean values, standard deviations, minima, and maxima are given in this table, and significant differences for each measurement are denoted there. The mean differences between all systems ranged within their standard deviations. One-way ANOVA reveals that the processing route

**Table 1** Results for marginal accuracy of FDPs fabricated by means of different processing routes

| | Horizontal discrepancy, $x$ (μm) | | | | | Vertical discrepancy, $y$ (μm) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Group | MD | MV | SD | Min | Max | MD | MV | SD | Min | Max |
| CerconCAM | 18.4 | $21.7^{a}$ | 69.9 | −124.7 | 205.0 | 151.4 | $162.1^{c}$ | 84.3 | −40.8 | 364.7 |
| CerconCAD/CAM | 50.2 | $49.4^{b}$ | 42.0 | −41.8 | 177.3 | 47.6 | $62.8^{a}$ | 47.7 | −9.6 | 207.5 |
| Compartis | 51.6 | $57.6^{b}$ | 53.7 | −59.4 | 198.5 | 109.8 | $119.6^{b}$ | 64.7 | 16.1 | 326.4 |
| | Absolute marginal discrepancy, $z$ (μm) | | | | | Marginal gap, $w$ (μm) | | | | |
| Group | MD | MV | SD | Min | Max | MD | MV | SD | Min | Max |
| CerconCAM | 173.7 | $180.9^{c}$ | 77.3 | 32.5 | 375.6 | 103.1 | $111.9^{b}$ | 55.3 | 25.7 | 321.5 |
| CerconCAD/CAM | 85.7 | $94.3^{a}$ | 38.8 | 22.3 | 208.0 | 70.4 | $72.1^{a}$ | 34.3 | 7.0 | 182.3 |
| Compartis | 150.6 | $145.5^{b}$ | 58.9 | 39.9 | 351.3 | 114.8 | $112.0^{b}$ | 52.2 | 15.1 | 289.8 |

Values denoted by the same index do not differ with statistical significance

*MD* median, *MV* mean value, *SD* standard deviation, *Min* minima, *Max* maxima

used has a statistically significant influence on each measurement ($p<0.05$). Hence, the hypothesis that the fitting accuracy of zirconia FDPs depends on the processing route used could be accepted. FDPs of the group CerconCAM, fabricated by means of the laboratory CAM-only system, showed the lowest mean values for horizontal marginal discrepancy. For all other measurements (vertical marginal discrepancy, absolute marginal discrepancy, and marginal gap), the lowest mean values were achieved by in-laboratory CAD/CAM production (CerconCAD/CAM). Furthermore, values of this test group exhibit the least standard deviation with each individual measurement.

Results of the statistical analysis of the restorations' dimensions in the direction of the longitudinal axis are shown in Table 2. With the exception of the premolar retainer in the test group CerconCAD/CAM, the horizontal marginal discrepancies ($x$) at the mesial and the distal measurement locations of each retainer differ with statistical significance in all test groups. With each retainer, considerably higher values of horizontal marginal discrepancy were found at the pontic sides than at the non-pontic side.

## Discussion

The results of the present study showed that the route of CAD/CAM processing used for the fabrication of zirconia FDPs has a significant influence on the restorations' fitting accuracy. Restorations fabricated with CAD/CAM by means of in-laboratory production showed the best marginal accuracy of the systems studied here. To the authors' knowledge, there are no investigations in the literature evaluating the marginal accuracy of zirconia restorations fabricated on different processing routes provided by an individual company. For three-unit posterior FDPs, Beuer et al. [20] also investigated the same routes of CAD/CAM processing with respect to their influence on marginal and

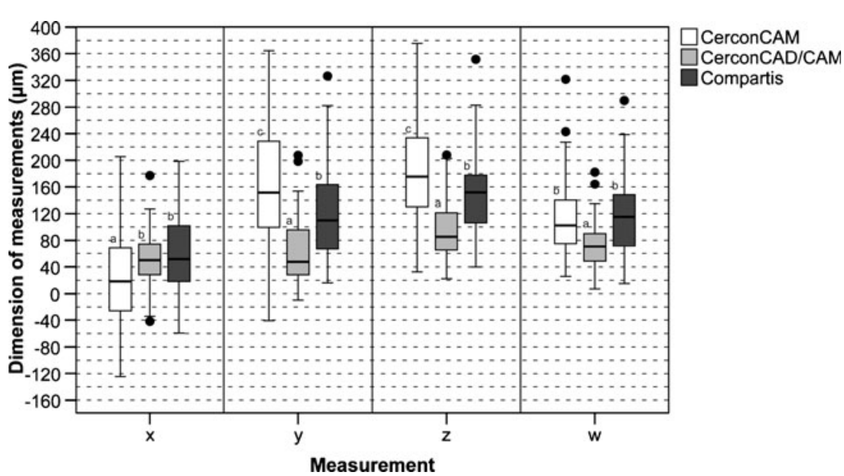


**Fig. 5** Box plots representing dimensions of different measurements versus processing route used. Medians, quartiles, and extremes are given. Within each column ($x$, $y$, $z$, $w$), groups denoted with the same index do not differ with statistical significance

**Table 2** Horizontal marginal discrepancies on the pontic side and on the non-pontic side of the premolar (P) and the molar (M) abutments, respectively

| System | Abutment | mesial | distal | p |
|---|---|---|---|---|
| CerconCAM | P | 25.6 (55.4) | 92.9 (51.4) | p=0.011 |
| CerconCAM | M | 105.6 (59.9) | -2.4 (56.5) | p=0.0006 |
| CerconCAD/CAM | P | 60.2 (26.8) | 87.1 (32.5) | p=0.059 |
| CerconCAD/CAM | M | 93.2 (35.4) | 27.2 (28.3) | p=0.0002 |
| Compartis | P | 22.1 (68.7) | 117.9 (43.1) | p=0.002 |
| Compartis | M | 100.7 (30.5) | 27.1 (36.4) | p=0.0001 |

*p* values for the statistical comparison between the two sides of each abutment are denoted

internal fit, but they compared systems provided by different companies. In their survey, restorations exhibited mean marginal gaps between 8 and 60 µm, which are obviously lower values than presented in the current study (72–112 µm). This could be explained if the frameworks shrank to different degrees due to the sintering process. Inaccuracies in the computer-aided calculation process or in the sintering procedure may have a more marked influence on the restorations' fit with more extensive FDPs [32]. Notwithstanding these differences, Beuer et al. [20] reported that the processing route significantly affected the fitting accuracy—as was found in the present study. However, restorations fabricated in a milling center showed the best precision of fit, closely followed by the FDPs made with the aid of an in-laboratory CAD/CAM system; the CAM-only system exhibited the worst fitting accuracy [20]. For the CAM-only system, these findings are in accordance with the present study. In particular, the absolute marginal discrepancy, which is considered to be the most suitable parameter to reflect the general fit in the marginal area [31], was significantly larger than that with the other systems (Table 1; Fig. 5). Reflecting this poor fit, a clinical study of posterior FDPs fabricated by the evaluated CAM-only system recorded 21% secondary caries after 5 years [10]. The large number of different fabrication steps and the variability in manual fabrication required in the CAM-only system might cause the differences in the mean marginal accuracy. The standard deviation, which is higher than that with the CAD/CAM systems for all measurements, could be considered as a further indication of the variability in the manufacturing procedure (Table 1). The first step in the processing route is that all the abutment teeth have to be manually provided with spacer. A wax-up of the restoration's framework is then prepared by hand. The resulting wax pattern is removed from the die and then fixed into a scanning frame. Removal of the wax pattern from the die may cause distortions, negatively affecting the marginal accuracy. In addition, the scanner of the CAM-only system has to scan the internal aspects, including the thin margin of the wax pattern, in order to generate geometrical data; this is much more complex than the scanning of the die. Hence, it becomes apparent that there are two main factors to consider in the accuracy of restorations fabricated by CAM-only systems: on the one hand, the skill of the dental technician, and, on the other hand, the precision of the scanning procedure.

In contrast, the scanning procedure in our study could be ruled out as responsible for differences between the two investigated CAD/CAM systems. In both groups, the same ten data sets based on the scanning of ten different stone casts were used for further production of the zirconia frameworks with each processing route. Therefore, strictly speaking, this investigation does not evaluate the entire CAD/CAM process, but only the influence of the milling and sintering procedure on the fitting accuracy. However, the influence of the scanning procedure could also be disregarded for routine clinical application, as identical scanner and CAD software are used for both routes of CAD/CAM processing. Consequently, the significant differences in marginal accuracy between the in-laboratory and the centralized CAD/CAM production are most likely caused by differences in the manufacturing process, as different milling machines and sintering furnaces are used for the two processing routes. Furthermore, it should be noted that default settings were used with both systems and that fitting accuracy may have been optimized by adjusting these settings. With the in-laboratory CAD/CAM processing route, the same milling machine and the same sintering furnace are used as with the CAM-only system. This could be considered as a further indication that the manual fabrication and handling of the wax pattern, together with the scanning procedure, are the reasons for the inferior fitting accuracy of the restorations fabricated by the CAM-only system.

Further aspects that might influence the marginal fitting of the restorations on the master model are errors due to impression and fabrication of the stone replicas. These processing steps were performed using a vinyl polysiloxane and a type IV stone under most reliable in vitro conditions. In a recent investigation, Persson et al. [33] found high accuracy for both dental impressions and corresponding stone replicas—using the same materials under comparable conditions. It therefore appears that, in the present study, fitting accuracy of the FPDs was not significantly affected by either processing step.

Another factor influencing the differences between several processing routes might be the adaptation of the frameworks on the master model by the dental technician. All frameworks were adjusted by the same technician and revised by two calibrated examiners to the best possible fit in their opinion. This influence can therefore be regarded as the minimal unavoidable degree of error inherent to the system. This procedure also reflects the fabrication process in the dental laboratory as well as the clinical try-in procedure and has been reported by other authors [20, 34].

Few studies that investigate the marginal accuracy of four-unit FDPs made from Y-TZP are available in the literature. With posterior restorations made by means of different CAD/CAM systems, Kohorst et al. [28] reported mean horizontal marginal discrepancies between 38 and 116 µm, mean vertical marginal discrepancies between 24 and 197 µm, and mean absolute marginal discrepancies between 58 and 206 µm. For the same kind of restorations, Tinschert et al. [22] found a mean horizontal marginal discrepancy of 59 µm, a mean vertical marginal discrepancy of 48 µm, a mean absolute marginal discrepancy of 71 µm, and a mean marginal gap of 46 µm. With anterior FDPs, Komine et al. [35] measured absolute marginal discrepancies between 87 and 113 µm, and Vigolo et al. [29] determined vertical marginal discrepancies between 46 and 63 µm, depending on the CAD/CAM system used. Reich et al. evaluated a mean absolute marginal discrepancy of 91 µm with four-unit FDPs within a clinical trial [19]. All these findings are in good accordance with the results of the present study. More evidence concerning marginal accuracy is available for three-unit zirconia FDPs. Different in vitro studies found values for the mean marginal gap ranging between 9 and 86 µm [20, 21, 25–27, 30]. Mean values for restorations evaluated in vivo ranged between 77 and 190 µm [23, 24]. As could be anticipated, three-unit FDPs exhibited slightly smaller marginal discrepancies than four-unit restorations. Some of the aforementioned investigations also evaluated the influence of various CAD/CAM systems processing presintered zirconia on marginal gap. In all these studies, significant differences between the systems were found [20, 25, 26, 29, 30, 35], whereas major misfits were determined with CAM-only systems according to the results in the current investigation.

As a further aspect of this study, differences in horizontal marginal discrepancy between the pontic and the non-pontic side of the retainers were determined to detect distortions (extended or shortened dimensions) towards the longitudinal axis of the restorations due to the fabrication process. The analyses revealed that, with almost all retainers, the horizontal marginal discrepancies on the pontic side were significantly larger than those on the non-pontic side, irrespective of the processing route used. This fact indicates that the FDPs were too short in the direction of the longitudinal axis; distortion directed towards the pontic side occurred due to the fabrication process in all test groups. An analogous observation was made by Wettstein et al. [24] investigating the clinical fit of zirconia FDPs. Considering that the observed distortions are not a consequence of the scanning procedure, the processing of the geometrical data, or the milling process, only the sintering of the frameworks and the veneering process may be the reasons for the phenomenon. Dittmer et al. found a significant influence of the veneering process on marginal accuracy of zirconia-based FDPs [36]. Similar to the present results, major distortions in the marginal area, induced due to the veneering process, were found along the longitudinal axis of the restorations. However, these distortions were reported to be directed towards the center axis of the FDP retainers on both the pontic side and the non-pontic side. Moreover, values of distortions due to the veneering process were considerably lower than the differences between the horizontal marginal discrepancies of the pontic and of the non-pontic sites of measurement in the present study. These considerations suggest that the determined distortions were mainly not caused by the veneering process but were most likely due to post-machining sintering of the zirconia restorations. This is confirmed by findings of Kunii et al. [32], who also reported significantly greater marginal inaccuracies on the pontic side than on the non-pontic side of four-unit zirconia frameworks. They stated that these differences had arisen from the sintering shrinkage of the pontic and distortion of the framework during post-machining sintering. Furthermore, they found that the sintering shrinkage in the center axis of the retainers was smaller than that in the horizontal axis. To prevent this detrimental shrinkage, either more homogenous zirconia blanks need to be prepared or the fabrication process (machining/sintering) need to be adjusted to rectify the anisotropic shrinkage of the blanks.

Various techniques for determination of fitting accuracy have been described in the literature, e.g., cross-section technique [20, 21, 25], direct microscopic measurement [26, 29], replica technique [22, 37, 38], and computer-aided 3-D evaluation [39, 40]. In the current investigation, a replica technique was used to evaluate the marginal accuracy of zirconia restorations. This method has been used by numerous authors to investigate the accuracy of crowns and FDPs in vivo [19, 23, 24, 37] as well as in vitro [22, 38] and offers the advantage that neither restoration nor abutment has to be destroyed during the survey [41]. Many authors consider the method to be highly reliable and valid [42, 43]. Rahme et al. did not find significant differences for marginal gap dimensions, whether the measurement was conducted with a replica technique or directly with a light-optical microscope at sectioned specimens [42, 43]. This was also confirmed by the authors in a former survey [28]: repeated manufacture of replicas followed by measurement of a specific distance could be performed with an uncertainty of ±13.6 µm (standard deviation), and repeated measurement of the same distance could be performed with an uncertainty of ±2.8 µm (standard deviation). However, a disadvantage of the technique is the two-dimensional-only display format. Furthermore, due to the sectioning of the replicas, the marginal accuracy was just measured at eight defined locations for each FDP, which might not represent the complete fit. Nonetheless, several studies have used the same cross-section replica technique with a similar number of sites of measurement [19, 23, 24, 27, 37, 38]. In contrast, Groten et al. [44] stated that approximately 50 measurements along the margin of a restoration yield clinically relevant information and a consistent estimation for the gap size. They performed a direct measurement of the vertical misfit with the aid of scanning electron microscopy. This technique indeed allows the measurement at numerous positions on the cervical margin but provides information about the marginal accuracy only in the vertical but not in the horizontal dimension, as is possible with the replica technique. Because measuring just a single distance lacks significance and does not allow the estimation of actual marginal conditions [31], four different marginal distances were evaluated in the present investigation by means of the replica technique, in order to win detailed information about marginal accuracy. A further limitation of the current study was that all restorations were placed onto the abutment teeth of the master model after their retainers had been filled with a light-body silicone, representing the space between abutment teeth and retainers. Therefore, the marginal accuracy could have been influenced by this procedure, due to incomplete seating of the FDPs on the master model. However, when the occlusal force is applied during placement of the FDPs, the silicone flows like conventional luting cements [41]. It appears that the cement space, adjusted during modeling of the restorations, allowed accurate seating of the retainers.

## Conclusions

The objective of the present study was to prove the hypothesis that the marginal accuracy of four-unit zirconia FDPs significantly depends on the processing route used. With the three investigated processing routes provided by one manufacturer, restorations made by CAM/CAM production showed significantly better marginal accuracy than restorations fabricated by means of a CAM-only system. FDPs made by the in-laboratory CAD/CAM system showed the best mean marginal accuracy of all investigated processing routes.

Furthermore, it was found that distortions of the zirconia frameworks due to the sintering process may influence the fitting accuracy. However, this effect was found for all restorations, irrespective of the processing route used. Further research should be carried out to obtain more detailed information about the effects during the sintering of zirconia restorations.

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**Conflict of interest** The authors declare that they have no conflict of interest.

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