Multifactorial analysis of the impact of different manufacturing processes on the marginal fit of zirconia copings

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This study evaluated the effect of different parameters on the marginal precision of CAD/CAM-fabricated zirconia copings. Specimens (n=60) were fabricated with two different scanners and two milling systems. The copings were evaluated with respect to their mean and average maximum marginal gaps. A two-way analysis of variance (ANOVA) (α=0.05) was used to evaluate the effect of different parameters (scanner, milling process) on marginal accuracy. The mean (averaged maximum) marginal gaps ranged from 57.9 (112.2 μm) to 71.0 (144.6 μm) in the "as machined" state. After manual adaptation, the respective values ranged from 54.6 (98.0 μm) to 59.9 (107.7 μm). The system and manual adaptation variables were found both to have multiple significant effects on the marginal gap size and to have a complex interaction. Thus, synchronized/validated processing chains should be preferentially used to guarantee optimal fitting accuracy for CAD/CAM zirconia restorations.

Keywords: Marginal fit, Zirconia coping, CAD/CAM system

INTRODUCTION

The introduction of yttria-stabilized zirconia significantly improved the flexural strength and fracture toughness of all-ceramic restorations compared to conventional glass or feldspathic ceramics. The clinical performance of zirconia-based restorations was previously investigated in fixed partial dentures and single crowns[1,2]. A recently published systematic review documented a framework survival rate for posterior fixed partial dentures of 99% after three years[3]. Additionally, the risk of a catastrophic failure of the zirconia framework the marginal accuracy is crucial for its clinical long-term success. An oversized gap between the crown and the prepared tooth promotes a washout of the luting material, micro-leakage, and plaque retention. This phenomenon can cause secondary caries, inflammation of the pulp, and periodontal tissues. This, in turn, can lead to a failure of the restoration[4,5]. There are variable definitions regarding what constitutes a clinically acceptable margin[6], and there is no concrete threshold for the maximum marginal discrepancy that is clinically acceptable. It has been reported that all-ceramic crowns show a mean marginal discrepancy that ranges from 19–160 μm[7-10]. The mean marginal gap for CAD/CAM-generated crowns is reported to be 23–110 μm[6,11-15].

Many authors accept the criterion established by McLean and von Fraunhofer (1971) who proposed after a 5-year examination of 1,000 restorations that 120 μm should be considered the maximum marginal gap[6,15-17]. To generate the best marginal accuracy of CAD/CAM-based restorations, most manufacturers' recommendations imply convergence angles of 6–8° for the preparation of the abutment. In *in vitro* studies of marginal adaptation, taper angles varied between 6 and 20°[15]. Previous *in vitro* studies revealed that the best marginal accuracies of zirconia copings produced by CAD/CAM systems occurred when the angles of the axial walls were prepared with a 12-degree axial taper[18,19]. Other studies have shown that the retention forces on abutments, especially for conventionally luted restorations, are significantly higher when the axial walls are prepared such that they are nearly parallel to each other (convergence angles≤5°)[20,21].

An increased axial taper of the preparation will decrease the retention characteristics. This can have a significant clinical impact because conventional luting may be associated with a higher risk of loss of retention with this type of preparation. Accordingly, recent clinical studies revealed cases of retention loss in conventionally luted zirconia restorations[22,23]. To avoid this clinical complication, adhesive luting procedures are recommended for a more conical preparation design. A dry working field is necessary for adhesive cementation. However, in many common clinical situations (*e.g.*, subgingival preparation borders, locations in the posterior mandible), this cannot be ensured[1]. Therefore, conventional luting is more practicable in these cases. Another parameter affecting the retention of full dental crowns is the axial height of the prepared abutment. Previous studies have demonstrated that separation forces are significantly increased on higher abutments[24,25]. This factor seems to be crucial, especially for the non-adhesive conventional luting of dental restorations[24,25]. To reduce the risk of retention loss, a more retentive preparation design with an axial taper

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of 4° (as applied in conventional metal ceramics) seems appropriate. However, this preparation design can only be recommended if the scanners available today can achieve a clinically acceptable fitting accuracy. The achieved fitting accuracy is determined by two main factors: the scanner system used for data collection and the milling systems. Regarding the milling systems, it can be distinguished between industrial fabrication and a milling center by providing the CAD data online[1,26]. To date, no study has been conducted to evaluate the impact of various factors within one production line.

The aim of the present study was to investigate the marginal precision of zirconia copings fabricated with different scanning and milling procedures to achieve a retentive preparation design (4-degree taper, appropriate axial height of 4–5 mm). As a working hypothesis, it was assumed that there would be significant differences in marginal fit in zirconia copings developed using different CAD/CAM processing routes.

MATERIALS AND METHODS

Sample preparation

An upper left second premolar acrylic tooth model (Frasaco, Tettnang, Germany) was prepared for a single crown using a conical rounded diamond instrument (8881.018.314, Gebr. Brasseler, Lemgo, Germany). The preparation had a 1.0-mm, 360° rounded shoulder. The occlusal reduction was at least 1.5 mm, and the resulting convergence angle was set at 2×2° (4-degree taper). Detailed preparation geometry is shown in Fig. 1. The prepared abutment was duplicated using a polysiloxane impression material (Adisil Rapid, Siladent, Dr. Boehme und Schoeps, Goslar, Germany). An autopolymerizing acrylic resin (GC Pattern Resin LS, GC Europe N.V., Leuven, Belgium) was poured into the impression. The acrylic pattern was used to cast a master die with a metal alloy (Palliag M, DeguDent, Hanau, Germany), which was used to represent a patient's abutment tooth. For the fabrication of the working dies (GC Fujirock EP, GC Europe N.V., Leuven, Belgium), a polyether (ImpregumPenta, 3M ESPE, Seefeld, Germany) with customized trays was used to take 40 individual impressions of the metallic master die. Forty "master casts" were made and divided into two groups: 20 samples per parameter were digitized with the Cercon eye (EYE) scanner (DeguDent, Hanau, Germany), while the other 20 specimens per parameter were digitized using the 3Shape D-700 scanner (3S) (DeguDent, Hanau, Germany). Both systems use a laser-based optical scanning method. However, in comparison, the 3S has a 3-axis movement system, allowing for a more individualized scanning position of the casts. The CAD process was performed with either the Cercon Art 3.1 software (working dies were scanned with the EYE) or the Dental Designer software (working dies were scanned with 3S) (both systems were from DeguDent, Hanau, Germany). All copings have a minimum thickness of 0.5 mm as mentioned in the manufacturer's recommendation. The copings of all sample series were made from the same presintered zirconia material (Cercon base, DeguDent, Hanau, Germany). All 20 data sets produced with the 3Shape system were fabricated in a centralized milling unit (Compartis, DeguDent, Hanau, Germany) after transmitting the data via a modem. From the 20 data sets produced with the EYE, frameworks were milled and sintered at the milling center (Compartis, COMP). From each data set, additional 20 frameworks were

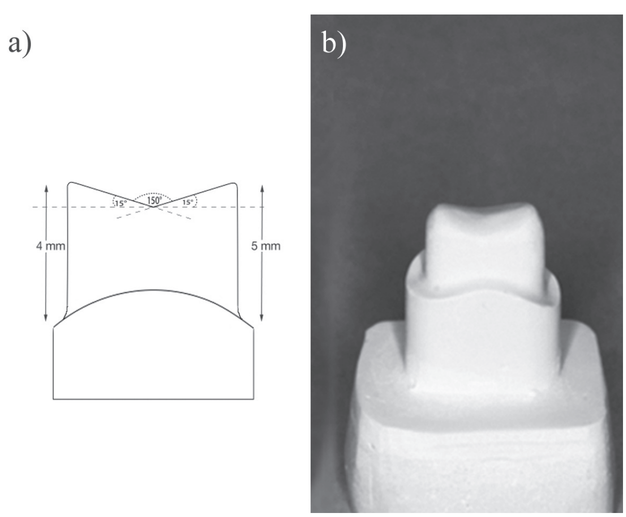


Fig. 1 The abutment preparation design.
(a) schematic representation; (b) stone cast.

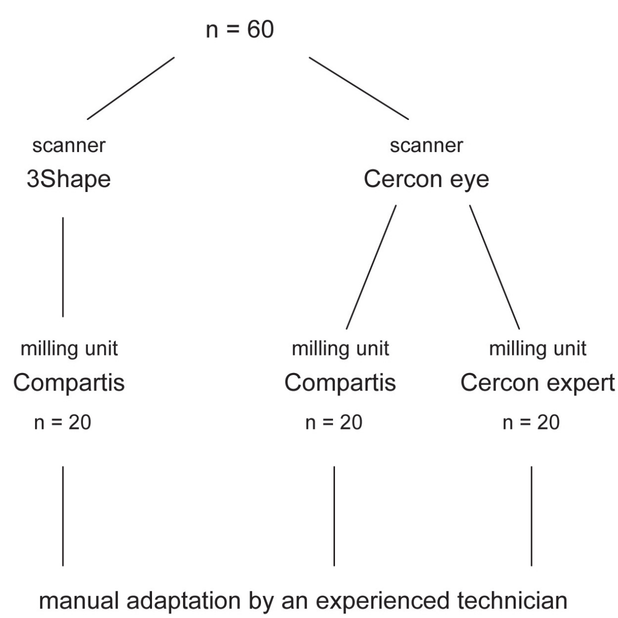


Fig. 2 Distribution of all specimens (n=60).

milled with a laboratory-based system (Cercon expert) (the distribution of all 60 specimens is shown in Fig. 2). Sintering for these specimens was done for 6 h at 1,350°C (Cercon heat, DeguDent, Hanau, Germany).

The conditions for the optimum seating for each production process chain were determined from a set of pre-study trials, namely 4 copings for each of the six sample series were fabricated with 4 different cement spaces each. The criteria for the "best possible fit" were chosen as demonstrated by Beuer *et al.*[27]. The cement space for all restorations (3Shape and Cercon eye) was set at 60 µm because specimens in pre-study trials with lower cement spaces partially couldn't be seated on the master die without manual adaptation. However, to minimize human influence on the evaluation, the marginal accuracy of all specimens was investigated "as machined", without manual adaptation by a technician. After completion of these evaluations, the three series were manually adapted by one experienced technician (under 8-fold magnification). Adaptation was performed according to the procedure described by Beuer *et al.*[27]. Areas that required correction were identified by applying occlusion spray (SD-Fit control, Servo-Dental, Hagen-Halden, Germany) on the master die, followed by coping's super-imposition on the die. Green spots that remained after removing the framework were detached with a diamond rotary cutting instrument (8801.014.314, Gebr. Brasseler, Lemgo, Germany) under water cooling.

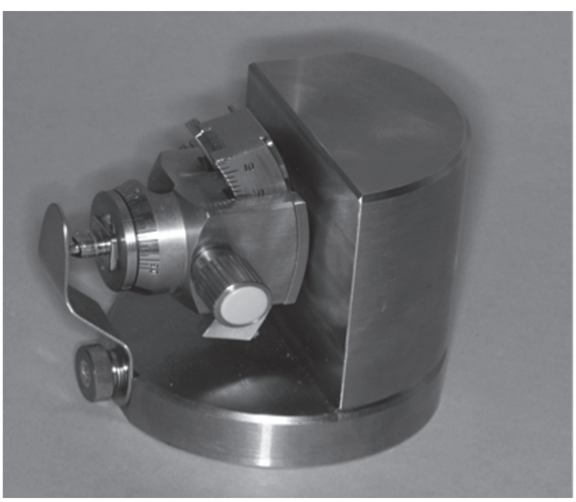
Evaluation of marginal fit

Marginal accuracy was assessed by measuring the absolute marginal discrepancy (AMD) on the metal master die (similar to clinical fitting) according to the criteria defined by Holmes *et al.*[28]. This could be ensured by the following two conditions: first, no over- or under-extended margins appeared; and second, a special custom spring-loaded device with a pivoted socket (Fig. 3) was used to guarantee that the maximum distance between the outer margin of the restoration and the preparation border of the die was perpendicular to the optical axis of the microscope at any single point. Twenty-four measurement points, staggered by 15°, were scaled around the master die (in accordance with the criteria established by Groten *et al.*[29]) to capture digital images for a computer-assisted survey of the marginal gap. Digital images (Fig. 4) were captured by a light microscope (Leica EZ4D, Leica Mikrosysteme, Wetzlar, Germany) with a magnification factor of 35× and an integrated camera, recorded on a computer (Mac OS X 10.5), and displayed on the monitor using image capture and processing software (Leica FireCam V.3.3.1, Leica Mikrosysteme, Wetzlar, Germany; Adobe Photoshop CS4, Adobe, San Jose, California, USA). The measurement of 24 AMDs per coping was performed with the tool "lineal" after calibration *via* a calibration slide (Motic-Europe, Barcelona, Spain).

Statistical analysis

All values of determined marginal gaps were exported to a spreadsheet (Microsoft Excel:mac 2007, Microsoft Corp., Redmond, Washington, USA). Evaluation of the mean marginal gaps (calculated by 20 copings per sample series ×24 measurement points per coping) was performed according to the literature[11,18,26,30] as well as by considering the averaged maximum marginal gap within one system or parameter (calculated only by the maximum values of each coping within one sample series). Data are expressed as means with standard

a)



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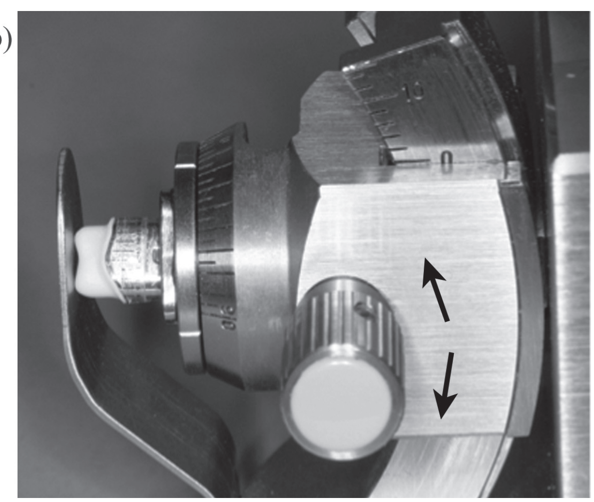

Fig. 3 (a) Metal device for marginal fit evaluation. (b) Detailed view of the pivoted socket used to ensure that the optical axis of the microscope was angled individually at 90° to the marginal gap width.

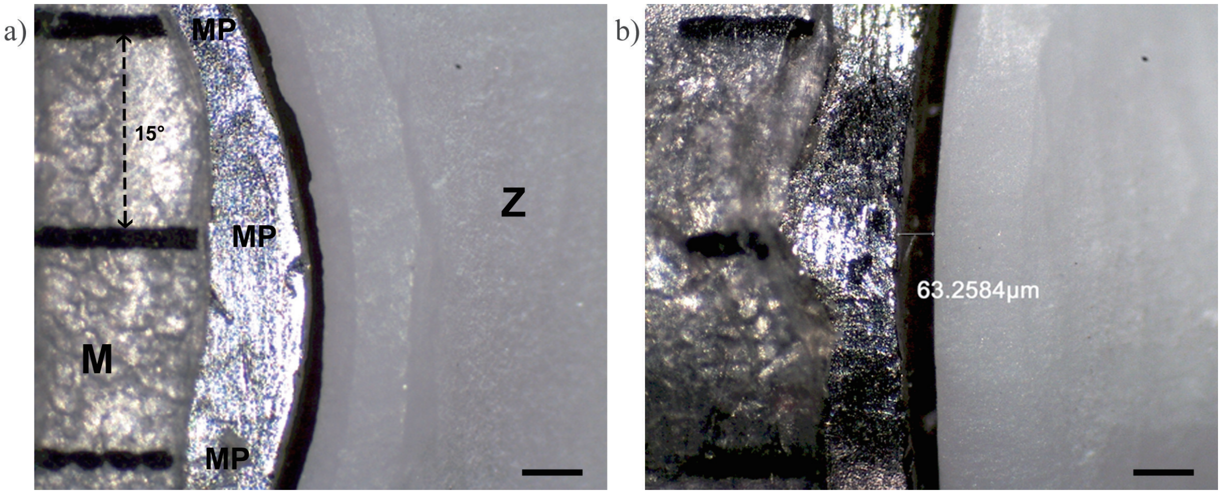

Fig. 4 (a) Marginal fit photograph (bar represents 100 µm) (M: metal master die; Z: zirconia coping; MP: measuring points). (b) Demonstration of a software-assisted evaluation of marginal gaps (bar represents 100 µm).

deviations and 95% confidence intervals. For both endpoints ("maximum marginal gap" and "mean marginal gap"), a normal distribution is a reasonable assumption; thus, two-way factorial ANOVAs were performed to investigate the influence of the systems (scanning and milling devices) and manual adaptation. All reported *p*-values are two-sided, and those smaller than 0.05 are considered to represent statistical significance. To adjust for multiple comparisons in post-hoc tests, the Tukey test was applied. All inferential analyses were carried out using SAS version 9.2 (SAS Institute Inc., Cary, North Carolina, USA).

RESULTS

Maximum marginal gaps
The mean values for the maximum marginal discrepancy ranged from 112.24±23.1 µm (EYE/COMP) to 144.6±30.5 µm (EYE/EXPERT). The means, standard deviations, and the corresponding 95% confidence intervals are shown in Table 1 and Fig. 5. A significant influence of the factor scanning or milling system was detected (p=0.0005). Pairwise comparisons (two-way factorial ANOVA) revealed lower marginal discrepancies when the centralized milling system (COMP) was used: differences of marginal gaps were −23.6 µm (p=0.01) for the 3S/COMP *vs.* EYE/EXPERT and −32.4 µm (p=0.001) for EYE/COMP *vs.* EYE/EXPERT (see Table 2).

Mean marginal gaps
Average values for the mean marginal discrepancies ranged from 57.9±6.49 µm (EYE/COMP) to 71.0±10.8 µm (3S/COMP). The means, standard deviations, and corresponding 95% confidence intervals are shown in Table 3. The corresponding ANOVA showed a significant interaction of the system (p=0.0032). A significant influence of the factor system was detected. Pairwise comparisons *via* two-way ANOVA were performed (Table 4): The scanners 3S *vs.* EYE (mean marginal gaps: +13.1 µm (p<0.0001)) as well as the milling systems COMP *vs.* EXPERT (mean marginal gaps: −11.3 µm (p=0.0005)) yielded differences in data. However, there were no significant differences in data when both system components (scanner and milling system) were changed simultaneously (p=0.86).

Maximum marginal gaps after manual adaptation
After manual adaptation, the resultant values for the maximum marginal gaps were as follows: 98.0±9.4 µm for 3S/COMP, 105.4±10.5 µm for series EYE/COMP, and 107.7±8.7 µm for series EYE/EXPERT. The means, standard deviations, and 95% confidence intervals are shown in Table 5 and Fig. 6. The corresponding two-way ANOVA showed a significant interaction between the processing form (adapted/machined) and the system (p=0.0032), indicating that the increase of marginal accuracy achieved by manual adaptation depends on the system. Thus, to investigate the influence of the processing form, on marginal accuracy the differences between the manual and machined adaptations were analyzed separately for each system. Significant differences were determined for 3S/COMP (−23.1 µm, p<0.0001) and EYE/EXPERT (−36.9 µm, p<0.0001) (Table 6). There were also reductions in the maximum marginal gaps of the adapted EYE/COMP series, although these reductions were not statistically significant (p=0.2342). Even though the increase achieved by manual adaptation was not consistent between the three systems, a second quality criterion was taken into account to demonstrate the advantage of manual adaptation. Figure 6 illustrates that the results after manual adaptation are more homogeneous than the results found without adaptation. This finding is verified by the observation that the confidence intervals

(as well as the standard deviations) are much smaller than for machined copings.

Mean marginal gaps after manual adaptation

The resultant values for the mean marginal gaps after manual optimization of the seating of the copings were as follows: 54.6±5.1 µm for EYE/COMP, 59.7±6.9 µm for series 3S/COMP, and 59.9±5.5 µm for series EYE/EXPERT. The different systems also showed significant differences independent of the form of processing (p<0.001; Table 1). Pairwise comparisons *via* two-way ANOVA showed again differences between 3S/COMP and EYE/COMP (about 9.1 µm, p<0.001) and between EYE/COMP and EYE/EXPERT (about 8.3 µm, p<0.001).

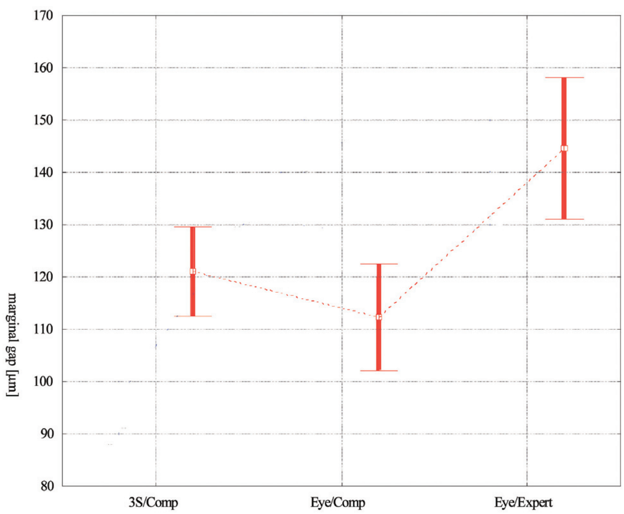

Fig. 5 Means of maximum marginal gaps with 95% confidence intervals.

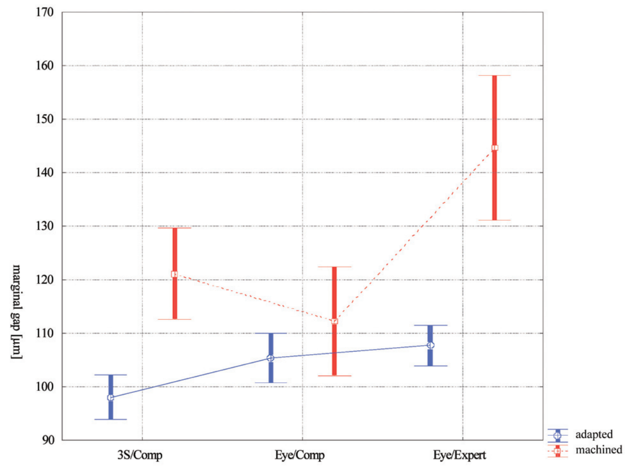

Fig. 6 Means of maximum marginal gaps with 95% confidence intervals; adapted *vs.* machined copings.

Table 1 Means, standard deviations, and 95% confidence intervals of the maximum marginal gaps

System	Mean (µm)	SD	Lower	Upper
3S/Comp	121.03	19.2	112.54	129.52
Eye/Comp	112.24	23.1	102.03	122.45
Eye/Expert	144.60	30.5	131.08	158.12

Table 2 Significant differences (bold) in maximum marginal gaps revealed by a post-hoc test performed after two-way factorial ANOVA for pairwise comparisons of the systems

System	Difference (µm)	p-value
3S/Comp *vs.* Eye/Comp	8.79	0.3949
3S/Comp *vs.* Eye/Expert	**−23.57**	**0.0135**
Eye/Comp *vs.* Eye/Expert	**−32.36**	**0.0011**

Table 3 Means, standard deviations, and 95% confidence intervals of the marginal gaps

System	Mean (µm)	SD	Lower	Upper
3S/Comp	71.01	10.8	66.20	75.81
Eye/Comp	57.94	6.5	55.07	60.81
Eye/Expert	69.22	10.7	64.47	73.98

Table 4 Significant differences (bold) in mean marginal gaps as revealed by a post-hoc test performed after two-way factorial ANOVA for pairwise comparisons of the systems

System	Difference	p-value
3S/Comp *vs.* Eye/Comp	**13.07**	**<0.0001**
3S/Comp *vs.* Eye/Expert	1.79	0.8603
Eye/Comp *vs.* Eye/Expert	**−11.28**	**0.0005**

Table 5 Means, standard deviations, and 95% confidence intervals of maximum marginal gaps: adapted and machined copings

Parameter	System	Mean (μm)	SD	Lower	Upper
Adapted	3S/Comp	97.95	9.4	93.77	102.13
	Eye/Comp	105.39	10.5	100.75	110.03
	Eye/Expert	107.68	8.7	103.84	111.53
Machined	3S/Comp	121.03	19.2	112.54	129.52
	Eye/Comp	112.24	23.1	102.03	122.45
	Eye/Expert	144.60	30.5	131.08	158.12

Table 7 Means, standard deviations, and 95% confidence intervals of marginal gaps: adapted and machined copings

Parameter	System	Mean (μm)	SD	Lower	Upper
Adapted	3S/Comp	59.70	6.9	56.64	62.77
	Eye/Comp	54.59	5.1	52.32	56.86
	Eye/Expert	59.89	5.5	57.45	62.32
Machined	3S/Comp	71.01	10.8	66.20	75.81
	Eye/Comp	57.94	6.5	55.07	60.81
	Eye/Expert	69.22	10.7	64.47	73.98

Table 6 Significant (bold) influence of manual adaptation on the maximum marginal gap revealed by a post-hoc test performed after two-way factorial ANOVA

System	Parameter	Difference	*p*-value
3S/Comp	**adapted *vs.* machined.**	**−23.08**	**<0.0001**
Eye/Comp	adapted *vs.* machined	−6.85	0.2342
Eye/Expert	**adapted *vs.* machined**	**−36.92**	**<0.0001**

However, there was no evidence of a difference between 3S/COMP and EYE/EXPERT (p=0.6849). Comparing standard deviations or lengths of confidence intervals also emphasizes the advantage of manual adaptation because both values are much smaller after such modification of the zirconia copings.

Summarizing effects and interactions

The different scanning as well as milling systems had an impact on the marginal accuracy of single zirconia copings. However, these effects are undirected in a non-homogeneous manner through the different combinations of CAD/CAM system components. The milling of zirconia copings in a centralized production center seemed to offer tendentially better marginal accuracy than the in-lab system. Manual adjustment granted a significant reduction of maximum marginal gaps of CAD/CAM-produced zirconia copings.

DISCUSSION

In accordance with all preceding studies regarding the marginal accuracy of dental CAD/CAM systems, the overall mean marginal gap per sample series was evaluated. Additionally, the maximum marginal gaps were evaluated, *i.e.*, the maximum value per coping was averaged for each series. It can be supposed that the point of maximum marginal gap (per coping) ultimately determine the clinical risk for marginal ditching and the associated marring phenomena, such as secondary caries or inflammation of the adjacent tissues.

In the present study, mean marginal gaps in the "as machined" state ranged from 57.9 to 71.0 µm, whereas single maximum marginal gaps of samples in the machined series ranged from 165.6 (3S/COMP) to 200.4 µm (EYE/EXPERT). For the manual adapted copings, the mean marginal gaps varied from 54 to 59.9 µm. This is in accordance with marginal gaps reported for CAD/CAM-generated zirconia copings in other studies, in which marginal gaps ranged from 24 to 110 µm[6,11,14,15,31]. The large variation in the reported mean values can be explained by a number of influencing factors, including CAD/CAM components and differences between pre-sintered and post-sintered milling of the zirconia blank. In *in vitro* studies using the same CAD/CAM system (Cercon) such as the present study, mean values for marginal openings were reported to range from 38 to 66 µm[11,27,31]. The variation in reported mean values of samples derived from the same CAD/CAM system can be explained by differences in study designs and measurement techniques, including evaluations of cemented or non-cemented crowns; various preparation designs of abutments; different types of microscope/magnifications used for the measurements; and the location and quantity of single measurements[6]. Moreover, changes in the hardware and software of the tested systems may affect the results of these *in vitro* studies.

A unique aspect of the present study is the analysis of the effects of multi-factorial interactions between different CAD/CAM components and the manual adaptation process on marginal accuracy.

This investigation revealed interactions of all variables in an undirected and non-homogenous manner, leading to significant differences in the marginal fit of zirconia copings.

This could be explained by the effects of the scanning and the milling system on the mean maximum and mean values of marginal discrepancies. The difference of the mean maximum values of 8.79 µm (S3/COMP: 121.03±19.2 µm; EYE/COMP: 112.2±23.1 µm), was statistically not significant (p=0.395) for different scanners. However, when the milling technique was changed, the difference was significant (32.4 µm, p=0.0011; EYE/COMP: 112.2±23.1 µm; EYE/EXPERT: 144.6±30.5 µm). This was also the case when both, scanner and milling systems, were changed simultaneously (23.6 µm, p=0.0135) (see Table 2). When mean marginal gaps were assessed, a change of the scanner as well as a change of the milling system induced significant differences (3S/COMP vs. EYE/COMP: 13.1 µm, p<0.0001; EYE/COMP vs. EYE/EXPERT: −11.28 µm, p=0.0005). The simultaneous change of both components revealed no significant differences (3S/COMP vs. EYE/EXPERT: 1.79 µm, p=0.8603) (see Table 4).

Therefore, the working hypothesis on the existence of significant differences in the marginal fit of zirconia copings that are based on different CAD/CAM processing routes could be fully confirmed. The scanner and the milling system influenced the marginal gap values in a statistically significant manner. These parameters interact in an undirected and complex way.

There have been few previous studies that have investigated the parameters that influence the marginal accuracy of CAD/CAM-fabricated crowns. Conflicting results have been reported regarding the effect of the milling system on the marginal accuracy of fabricated crowns. Beuer *et al.*[18] found no significant differences in the marginal fit of single zirconia copings manufactured by an in-laboratory milling unit relative to those manufactured by a milling center[18]. Kohorst *et al.* demonstrated a better marginal accuracy for FPD retainers produced in a milling center compared to restorations fabricated by a CAM process with manual modeling of the framework[26].

Additionally, the effect of the preparation angle has previously been evaluated *in vitro* using the same laboratory-based milling system and milling center as those used in the present study[18]. For both milling techniques, a significant influence of the milling technique was reported, with preparations developed using a 4-degree taper resulting in a significantly poorer fit than preparations with a 12-degree taper. However, to the authors' best knowledge, no investigation has been performed regarding the effect of the scanning process on marginal fit when using the same milling system.

Based on these findings, the marginal accuracy of CAD/CAM-fabricated zirconia frameworks is influenced by the scanner and the milling system. An optimum fitting accuracy can only be achieved if the process chain is validated and used in connection with a suitable preparation design.

At present, manufacturers intend to design so-called "open systems", which could lead to random data transfer between the various scanning and milling systems of different companies. However, the present study indicates that this non-synchronized ways of manufacturing might be a crucial factor for the achievable best marginal accuracy because every part of the manufacturing process manipulates the outcome in a complex and non-homogenous manner, particularly when retention-enhancing preparations are performed. It can therefore be strongly recommended that only validated process chains with synchronized operations should be used.

For the majority of CAD/CAM systems, an axial taper of 6–8° is recommended, which leads to a more conical and therefore less retentive preparation design. In some clinical situations, such as a reduced abutment height, this might lead to the need for adhesive luting. If the workspace offers a challenge with respect to moisture control (*i.e.*, subgingival preparation borders), conventional luting is more practicable than an adhesive cementation. However, this approach requires retention-enhancing factors such as nearly parallel-prepared walls or an adequate axial height[24,25]. Therefore, the axial taper in the present study was set at 4° (2×2°) in combination with an appropriate axial height (4–5 mm) to simulate suitable conditions for conventional luting. Previous studies have revealed that the best marginal fit of CAD/CAM-generated zirconia restorations is achieved with larger convergence angles such as 12°[18,19]. This could explain why, in the present study, larger values for marginal gaps were determined compared to those in earlier studies that used more conical preparation forms[18,30]. This observation is supported by another *in vitro* study that evaluated the influence of the marginal configuration (shoulder or chamfer) in 15 and 20° axial tapers, which determined that shoulder preparations exhibited statistically higher discrepancies when combined with steeper walls (15° total convergence angle)[32]. There is consensus between various authors that marginal openings less than 120 µm are clinically acceptable[6,15-17].

In the present study, none of the tested scanner and milling procedure combinations were able to produce copings for the retentive preparation design with a mean maximum value below the gap size threshold of 120 µm in the "as machined" state. The copings developed from all tested system combinations had to be adapted manually to generate restorations with a clinically acceptable fit. For all adapted copings, the mean maximum values could be decreased to a range between 98 and 107.7 µm. These values were well below the threshold level of 120 µm for clinically acceptable restorations. After implementing the manual adaptation process, the mean marginal gaps ranged from 54.6±5.1 to 59.9±5.5 µm, which are within the range of values, reported for other CAD/CAM systems. The effect of the manual adaptation procedures depends on the production technique applied. For two scanner/milling process combinations, the manual adaptation process led to a significant reduction of the mean marginal gaps

(3S/COMP: 23.08 μm, $p<0.0001$; EYE/EXPERT: 36.92 μm, $p<0.0001$). The remaining systems showed a non-significant reduction in the mean marginal gaps (6.85 μm; $p=0.234$). For the tested CAD/CAM components, the production of zirconia copings for a retentive preparation design (4-degree taper) requires an optimization of the fitting quality by manual adaptation.

Several limitations of this study must be mentioned. Clinically, the fit of all-ceramic restorations is influenced by factors that simulate oral conditions, such as the veneering technique, cementation methodology, and aging process, which have not been evaluated in the present study[33]. Furthermore, the preparations of the artificial abutments were idealized and thus do not reflect the conditions of daily clinical practice[14]. A disadvantage of the measurement of marginal gaps with a light microscope is the two-dimensional display format, which only allows for the detection of vertical discrepancies. However, misinterpretation is unlikely due to the use of a pivoted device for the fixation of the restoration and a sufficient exclusion of over- or under-extended margins and therefore of collateral horizontal discrepancies[18,26,34].

CONCLUSIONS

Considering the conditions and limitations of this *in vitro* study, the following conclusions can be drawn:

1. Regarding the mean maximum marginal gaps, the centralized milling system (Compartis) offers a better precision than the in-laboratory production (Cercon expert).
2. The complex interactions of the 3Shape and Cercon eye scanners with centralized (Compartis) and in-laboratory (Cercon expert) milling systems influencing the achievable marginal fit emphasize the importance of validated and synchronized process chains.
3. For a retentive preparation design with an axial taper of 4°, manual adjustment seems to be necessary for all systems tested to achieve maximum marginal gaps below the threshold of 120 μm.

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