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ORIGINAL ARTICLE

Computer-aided evaluation of preparations for CAD/CAM-fabricated all-ceramic crowns

Jan-Frederik Güth · Jan Wallbach · Michael Stimmelmayr · Wolfgang Gernet · Florian Beuer · Daniel Edelhoff

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Abstract
Objective The aim of this study was the evaluation of preparations from general dental practitioners for zirconia crowns and their correlation with clinical recommendations using a digital approach.
Material and method Seventy-five datasets of left first upper molars (FDI 16) prepared for single zirconia crowns by general dental practitioners were analyzed using a computer-aided design software (LAVA™ Design; 3M ESPE, Seefeld, Germany) and a 3D-inspection software (COMETinspect®plus version 4.5; Steinbichler Optotechnik, Neubeuern, Germany). Evaluated parameters were convergence angle, undercuts, interocclusal reduction, abutment height, and design of preparation margin.
Results The mean convergence angle was determined to be 26.7°. The convergence angle in the mesiobuccal to distopalatal dimension was significantly the highest (31.7°), and the abutment height showed a mean value of 4.1 mm. Convergence angle and abutment height showed a negative correlation. Seventy-three percent of the evaluated locations revealed a margin design conforming to ceramic restorations. In over 30 % of the cases, the interocclusal reduction was insufficient. Generally, no preparation fulfilled all recommendations. Five (6.66 %) of the preparations fulfilled four criteria, 16 (21.33 %) preparations fulfilled three criteria, 31 (41.33 %) fulfilled two criteria, 17 (22.66 %) preparations fulfilled one criterion, and 6 (8 %) fulfilled no criterion.
Conclusions Within the limitations of this study, most general dental practitioners seem to have difficulties fulfilling all clinical recommendations given for the preparation of zirconia crowns. The presented digital approach seems to be a useful method to evaluate the preparation geometry.
Clinical relevance The correct preparation geometry represents an important prerequisite for the success of all-ceramic full crowns. As preparations clearly need to be improved, the approach presented could be the basis of a future tool to increase preparation quality in practice and education by direct objective feedback.

Keywords Preparation geometry · All-ceramic crowns · CAD/CAM · Zirconia · Digital evaluation

J.-F. Güth (✉) · M. Stimmelmayr · W. Gernet · F. Beuer · D. Edelhoff
Department of Prosthodontics, Dental School, Ludwig-Maximilians University Munich, Goethestraße 70, 80336 Munich, Germany
e-mail: jan_frederik.gueth@med.uni-muenchen.de

J. Wallbach
Grünauer Allee 49, 82008 Unterhaching, Germany

Introduction

Performing a preparation is a common procedure in general dental practice, as a necessary prerequisite for the fabrication of fixed prosthetic restorations, and influences the success of a restoration substantially. During preparation, biological and technical necessities often oppose each other and therefore sometimes make it a difficult procedure for the dentist [1].

A ration of parameters divide sufficient from insufficient preparations, including (1) total occlusal taper, (2) abutment height, (3) ratio of abutment height to faciolingual dimension, (4) circumferential morphology, (5) finish line location, (6) finish line form and depth, (7) axial and incisal/occlusal reduction depth, (8) line angle form, and (9) surface texture [2]. However, such distinctions seem to remain theoretical, since single parameters influence each other in daily practice.

Among the above-mentioned parameters, the convergence angle, defined as the angle between the opposite axial surfaces of teeth prepared for artificial crowns, plays an important role [3, 4]. It influences retention, resistance, fit, and decision for the luting mode of crowns [5–8]. Retention is defined as the potential to oppose the removal of the restoration along its path of placement, whereas resistance means the capacity to prevent dislodgment of the crown by forces directed in lateral or oblique directions [9]. Both retention and resistance have been reported to be approximately linear and inversely proportional to taper or convergence angle [7, 10, 11]. Furthermore, the variation of the preparation design regarding wall height and margin design influences the stress distribution occurring in dental restorations [12, 13].

For the stability of dental restorations, the luting mode plays a key role and is dependent on the preparation geometry [14]. Thus, a retentive preparation geometry is considered to be a prerequisite, for a conventional cementation [15]. Goodacre et al. suggest a total occlusal convergence angle of 10–20° and a minimal abutment height of 4 mm for molars and 3 mm for other teeth when conventional cementation is applied [2]. In another in vitro study, the slope of a graph of cycles to dislodgement as a function of taper changed abruptly at a convergence taper of 12° [16]. In addition, a shoulder or pronounced deep chamfer preparation is highly recommended for all-ceramic crowns. Furthermore, the preparation design affects the marginal and internal fit as well as the fracture resistance of single crown zirconia frameworks [5, 6].

A number of studies have evaluated different parameters of single crown preparations using different approaches, such as Tool Maker Microscope mechanical digitizing overhead projectors, or 2D printouts from virtual models [3, 17–19]. Summarized, these studies show mesiodistal and buccolingual convergence tapers with values of 22.2–28.5° and 16.8–35.7°, respectively.

Overall, preparation design plays a decisive role in the success of single all-ceramic crowns. However, there are doubts that the scientifically based clinical recommendations can be transferred into clinical application.

This study evaluates whether general dental practitioners can meet the clinical recommendations defined for this study for posterior all-ceramic zirconia crowns, quantified as convergence angle, undercuts, interocclusal reduction, abutment height, and design of preparation margin, using a new digital approach based on the analysis of digital surface tessellation language (STL) data. The null hypothesis was that the clinical recommendations for the preparation were met in daily clinical routine.

Material and methods

The study was based on 75 STL datasets of left upper first molars (FDI 26) which showed preparations for full-ceramic crowns. The datasets arose from preparations that were previously carried out by 75 different general dental practitioners in their offices during daily routine. These general dental practitioners had sent the gypsum models to a centralized milling center (Corona Lava™ Milling Center, Starnberg, Germany), where they were digitized using the optical scanner Lava ScanST (3M ESPE, Seefeld, Germany). Subsequently, the datasets were allocated anonymously and transferred to the Department of Prosthodontics of the LMU Munich.

The evaluation was conducted using two software programs. The parameters "undercuts" and "interocclusal space" were assessed by Lava Design Software (3M ESPE, Seefeld, Germany), whereas "marginal preparation design," "convergence angle," and "abutment height" were analyzed with the inspection software COMETinspect®plus (version 4.5, Steinbichler Optotechnik, Neubeuern, Germany), which was used in several studies before [20, 21].

As there are no universally valid scientific guidelines, for this study, the authors defined some clinical recommendations on the basis of literature, manufacturers' recommendations, and scientifically based experiences, for this study [2, 14, 22].

For the parameters undercuts, interocclusal reduction, convergence preparation angle, and marginal design, clinical recommendations were defined in this study like this:

> Undercuts—preparations should not contain any undercuts.
> Interocclusal reduction—between 1.5 and 2 mm.
> Convergence angle—between 6° and 15°.
> Marginal design—chamfer preparation or rounded shoulder preparation.
> Abutment height—above 4 mm.

1. Undercuts

   After importing the dataset into the Lava Design Software, the insertion axis of the crown was automatically optimized and undercuts could be detected. The evaluation followed as a yes/no decision for each tooth.
2. Interocclusal reduction

   The parameter interocclusal reduction was assessed with the help of different virtual copings constructed by the Lava Design Software for each stump. The virtual copings exhibited a parallel surface to the surface of the prepared tooth and different thicknesses of 1, 1.5, and 2 mm. By analyzing which coping virtually crossed the dataset of the antagonist first, the dimension of each interocclusal reduction could be estimated and classified into one of four groups: (a) occlusal reduction ≤1.0 mm, (b) occlusal reduction >1.0≤1.5 mm, (c) occlusal

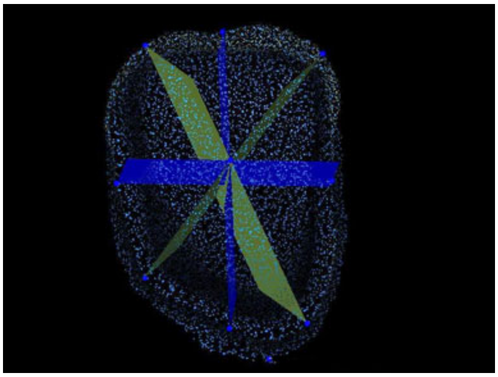

Fig. 1 STL dataset with four virtually constructed planes: A, B, C, and D

reduction >1.5≤2.0 mm, and (d) occlusal reduction >2.0 mm. Furthermore, it was assessed in which areas of the occlusal surface (center, central fissure, cross fissure, mesiobuccal cusp, distobuccal cusp, mesiopalatal cusp, distopalatal cusp) the coping crossed the dataset of the antagonist. If crossings occurred simultaneously in more than one area, these areas were recorded.

3. Convergence angle

The STL datasets were imported into the inspection software COMETinspect®plus. For the assessment of the convergence taper, four virtually vertical planes in the (A) mesiodistal (m–d), (B) mesiobuccal–distopalatinal (mb–dp), (C) buccopalatinal (b–p), and (D) distobuccal–mesiopalatinal (db–mp) directions crossing one central point (*Z*) and forming horizontal tapers of 45° under each other were manually constructed (Figs. 1 and 2). Using the inspection software, the convergence angles were determined by analyzing the taper between two opposing surfaces of all four planes (Fig. 3). Consequently, 300 values (4×75) were measured. The mean values for each plane and one overall taper were calculated.

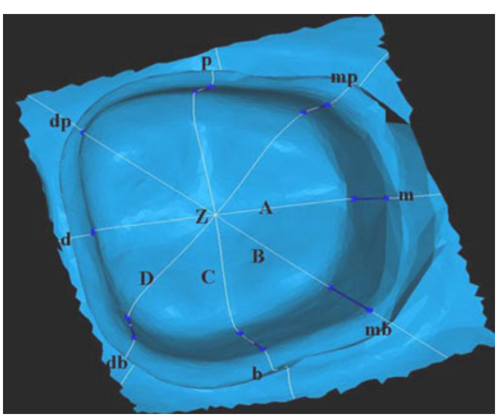

Fig. 2 STL dataset with definition of measurement locations: mesial (*m*), mesiobuccal (*mb*), buccal (*b*), distobuccal (*db*), distal (*d*), distopalatal (*dp*), palatal (*p*), mesiopalatal (*mp*)

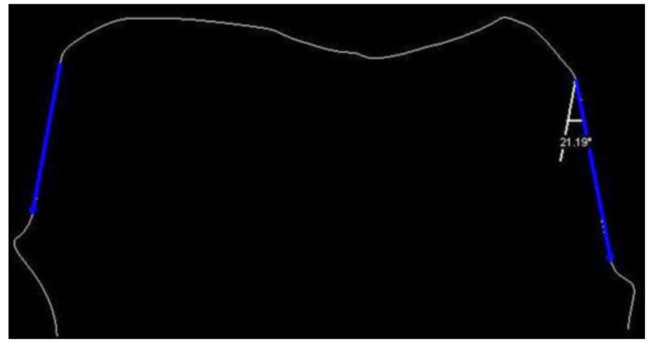

Fig. 3 Determination of convergence angle in one of the planes

A pilot study was carried out previously to the study to calibrate the investigator and to test the reproducibility of the method. The investigator carried out the process as described above, 15 times for one single tooth. The results of the pilot tests showed a SD of 0.37° for the convergence angle within one plane.

4. Margin design

The evaluation of the preparation margin design was conducted using planes A, B, C, and D. According to the defined measurement points, the margin design was evaluated (m, mb, b, db, d, dp, p, mp) and classified into seven groups:

(a) Chamfer
(b) Shoulder with round inner edge
(c) Shoulder with sharp inner edge
(d) Beveled shoulder
(e) Shoulderless preparation
(f) Reverse bevel
(g) Indefinable margin

The classification was made by a single observer, who was calibrated during several pilot tests to guarantee sufficient objectivity. In most cases, the classification of the margins into groups using the sectional images was obvious.

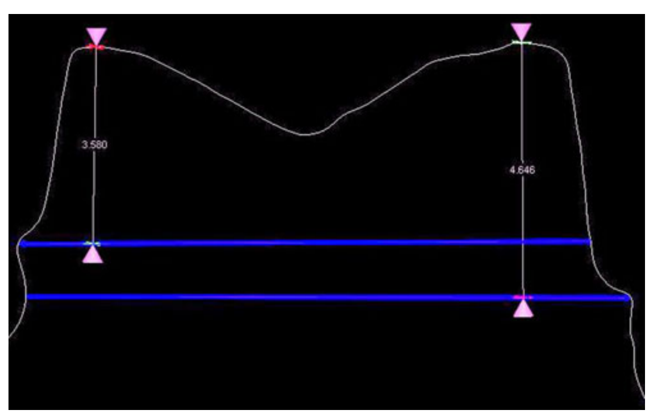

Fig. 4 Evaluation of abutment height as the distance between the highest cuspal tips and the cervical line

Table 1 Interocclusal dimension: quantity and percentage distribution of interocclusal dimension (N=75)

	mb-cusp	db-cusp	mp-cusp	dp-cusp	Central fissure	Cross fissure	Center	Overall
≤1 mm	1	1	1	1	0	0	1	3 (4.0 %)
>1.0 to ≤1.5 mm	19	6	1	3	2	2	3	23 (30.7 %)
>1.5 to ≤2.0 mm	11	6	5	2	6	3	4	25 (33.3 %)
>2.0 mm	24							24 (32.0 %)

In cases when the virtual coping crossed the antagonist in more than one area, all affected areas were recorded

5. Abutment height

   The abutment height (occlusiocevical dimension) was measured in planes A, B, C, and D, respectively. The abutment height was registered as the distance on the imaginary coronal axis between the highest cuspal tips and the cervical lines at the same locations (Fig. 4). A mean value for each plane, plus one overall average value from all 600 measured values at all locations, was calculated. A previously conducted pilot study, in which one tooth was evaluated 15 times, showed a SD for the abutment height of 0.1 mm within a single measurement location.

   Statistical analysis was carried out using SPSS 12.0. (SPSS Inc., Chicago, USA). For the analysis of the different locations under each other, regarding the parameter convergence angle, the Kolmogorov–Smirnov test on normal distribution was assessed, followed by the Mann–Whitney U test to compare data, as the data were not normally distributed. To analyze the correlation between abutment height (cervico-occlusal dimension) and convergence angle, the Kolmogorov–Smirnov test, followed by Spearman correlation, was conducted. The level of significance was set at 5 %.

Results

Undercuts were detected in 30.7 % of the examined preparations, whereas 69.3 % showed no undercuts. Three of 75 preparations showed an interocclusal reduction of less than 1 mm, and 23 showed one between 1 and 1.5 mm. The values of these two groups correlate to a percentage value of 34.7 %. In the range between 1.5 and 2 mm, 25 preparations (33.3 %) were found. Twenty-four preparations (32 %) showed greater than 2 mm of interocclusal space. The area around the mesiobuccal cusp showed the least interocclusal space, followed by the distobuccal cusp (Table 1).

The 300 measured angles revealed an overall angle of 26.7°. Using the Mann–Whitney U test, angle B (mb–dp) showed the statistically significant highest value of 31.7°, representing the most conical taper compared to other locations, followed by A (26.3°), C (24.6°), and D (24.4°), which were not statistically significantly different from each other (p=.05). Table 2 shows the results. Only ten preparations (13.33 %) revealed an overall convergence angle between 6° and 15°. Of the preparations, 86.66 % showed greater values.

Margin design was evaluated at eight locations on each tooth, obtaining 600 measurements in total. Three hundred forty-seven measurement points exhibited a chamfer design, followed by 119 with a shoulderless preparation and 92 with a rounded shoulder. A chamfer preparation was found most frequently in the mesiobuccal location (52), followed by distobuccal (48) and buccal (46). Of the preparations, 25.3 % (19 preparations) showed a ceramic-conforming marginal design, as chamfer or rounded shoulder preparation, at all measurement locations. Table 3 displays the margin designs pending on the measurement locations.

At the same locations as the marginal design, the abutment height was evaluated. The mean value of 600 measured locations was 4.09 mm. The greatest height (4.84 mm) was found at the buccal localization, followed by mesiobuccal (4.65 mm) and distobuccal (4.40 mm). The smallest average abutment height was found mesial, with 3.15 mm. Forty-one (54.66 %) preparations showed an average abutment height of more than 4 mm. Table 4 gives the values for the abutment height for each location.

Table 2 Mean values for convergence angles at different locations

	N	Mean	Median	Standard deviation	Minimum	Maximum
Overall angle	75	18.2°	18.3°	6.4°	5.08°	36.15°
Angle A	75	17.3°	17.3°	6.2°	3.98°	38.55°
Angle B	75	19.2°	19.3°	7.7°	3.02°	35.56°
Angle C	75	18.6°	18.6°	8.7°	3.16°	37.72°
Angle D	75	17.7°	17.6°	7.5°	3.71°	40.78°

Table 3 Margin design divided into classes on different locations

Class/location	Mesial	Mesiobuccal	Buccal	Distobuccal	Distal	Distopalatal	Palatal	Mesiopalatal	Total
Chamfer	40	52	46	48	36	43	40	42	347 (57.8 %)
Rounded shoulder	7	13	11	10	11	17	15	8	92 (15.3 %)
Unrounded shoulder	0	0	3	0	0	0	0	1	4 (0.7 %)
Beveled shoulder	0	0	0	0	0	0	0	0	0 (0.0 %)
Shoulderless	20	10	12	11	19	9	17	21	119 (19.8 %)
Reverse bevel	0	0	0	3	4	6	0	1	14 (2.3 %)
Indefineable margin	8	0	3	3	5	0	3	2	24 (4.0 %)

Generally, no preparation fulfilled all parameters. Five (6.66 %) of the preparations fulfilled four criteria, 16 (21.33 %) preparations fulfilled three criteria, 31 (41.33 %) fulfilled two criteria, 17 (22.66 %) preparations fulfilled one criterion, and 6 (8 %) fulfilled no criterion.

Discussion

Regarding the results and their comparison to previous studies using different methods, the digital evaluation method based on STL data seems to be a useful tool for the evaluation of dental preparations. However, every test setup underlies several factors of influence, which have to be revealed and evaluated.

Initially, the reproducibility of the new approach has to be discussed. To prove reproducibility, a single tooth was evaluated 15 times using the new method in advance of the actual study. These pilot tests showed good reproducibility (SD) for the parameters measured using the manually constructed planes. Consequently, it can be assumed that the computer-aided evaluation offers sufficient reproducibility, when carried out by a calibrated observer.

Regarding the marginal design, it can be argued that the assignments to the individual groups were made subjectively. In addition, the transition between one preparation form and another can occasionally be fluid. Therefore, the classification allowed a certain room for interpretation. However, as all evaluations were done by the same observer and several pilot tests were conducted prior to the study, a certain calibration of the observer can be assumed.

Different in vitro investigations have shown considerable influence on fit, retention, resistance, and therefore longevity of fixed prosthodontic restorations [6, 7, 23]. There is a close relation between convergence angle, diameter, abutment height, and the resistance of crowns [2, 23, 24]. In contrast to the convergence angle, the parameters of abutment height and diameter are given by anatomy and therefore are difficult to affect.

As there are no universally valid scientific guidelines, some clinical recommendations were defined on the basis of literature, manufacturers' recommendations, and personal scientifically based experiences, for this study. Not even one of the evaluated preparations could meet the clinical recommendations for zirconia crown preparations defined for this study. This means the null hypothesis has to be rejected.

Since in the presented study only 13.33 % of the preparations revealed a convergence angle between 6° and 15°, this clinical transfer was identified to be the most difficult task. In contrast, the majority of preparations (69.33 %) showed no undercuts.

Table 4 Average value and mean value of abutment height for each location

	N	Mean (mm)	Median (mm)	Standard deviation (mm)	Minimum (mm)	Maximum (mm)
Overall average	600	4.1	4.1	0.74	2.79	6.4
Mesial	75	3.1	3.1	0.98	1.24	5.85
Mesiobuccal	75	4.6	4.6	1.01	2.77	7.98
Buccal	75	4.8	4.6	0.88	3.06	7.09
Distobuccal	75	4.4	4.4	0.89	2.45	7.14
Distal	75	3.6	3.5	1.07	1.02	6.68
Distopalatal	75	3.8	3.8	1.11	1.23	6.21
Palatal	75	4.3	4.4	1.07	1.65	6.79
Mesiopalatal	75	4	4	0.9	1.86	6.35

In this study, a significant negative correlation between cervico-occlusal dimension and convergence angle was found (Spearman correlation, $r=-0{,}046$). In practice, this means shorter abutments correlated with more conical preparations. This result confirms Al-Omari et al. and Sato, but stands in contrast with general recommendations and reflections [17, 25]. Especially in the decision for luting mode, the individual abutment height and convergence taper play an important role [14].

Compared to the suggested recommendations of Goodacre, a mean abutment height of 4.09 mm on molars presented in this study would allow conventional cementation [2]. Nevertheless, regarding the mean convergence angle of 26.74°, adhesive luting appears to be the more reliable alternative. Thus, adhesively seated crowns with taller convergence angle showed higher retention than conventionally cemented crowns on less tapered preparations [26, 27]. However, Sarafianou and Kafandaris could not find a difference between these two luting methods for convergence angles less than 10° [28]. Additionally, adhesive luting increases the loadability of all-ceramic crowns significantly [29–31].

The values of convergence angle obtained in this study are in accordance with values in the literature [3, 17, 18, 32]. On the one hand, a taller convergence angle reduces retention and resistance; on the other hand, it leads to superior internal and marginal fit [5, 6, 26, 33, 34].

Regarding the results for angle B, it can be assumed that dental practitioners have difficulties estimating the correct taper, especially in the mesiovestibular to distopalatal directions. An explanation could be the difficult view to the distopalatal corner of upper molars during preparation.

The optimal preparation taper is possible to achieve under clinical circumstances, and its acceptability for long-term retention and prognosis has been intensely discussed in the literature. In this context, Parker et al. postulated a “limiting taper” by a mathematical approach based on a height-to-base ratio. The calculated values were 29–33° for incisors and canines, 10° for premolars, and 8° for molars [35, 36].

Regarding that divergence from the parallel has to be greater than 12° to be observed as converging surfaces under clinical circumstances, it seems difficult to meet the clinical recommendations for convergence angle on molars intraorally [37, 38].

For all-ceramic crowns, the interocclusal dimension should be between 1.5 and 2 mm, due to sufficient material thicknesses. Taking this as a reference, one third of the preparations showed an interocclusal dimension that was too small. In most cases, the deficits were observed at the inner slope of the mesiobuccal cusp.

The recommendations for chamfer or shoulder preparation with rounded inner edge mainly have a material background. Chamfer and shoulder preparations create surfaces almost perpendicular to loading direction [39]. In this study, appropriate marginal designs were found in 73.2 % of measurement locations. Therefore, 26.8 % of the evaluated margin locations did not exhibit a ceramic-compatible margin design. Only 25.33 % of the preparations showed a ceramic-conforming marginal design in all measured locations.

The results of this study give a hint that general practitioners seem to have difficulties to fulfill all aspects of the here defined specific clinical recommendations for preparations for full-ceramic crowns. However, as a sample size of 75 is rather small to generate generalized statements, further studies with a greater sample size should be conducted in the future.

As STL data form the basis of most CAD/CAM systems, digital methods for the evaluation of preparations could be integrated into systems for direct data capture in the future. Further automatization of the method could give direct feedback to the general dental practitioner about the quality of preparations and potential mistakes. This direct feedback could therefore enhance the preparation quality. Besides this, the method could be a valuable tool for dental education, to visualize mistakes and provide fair judgment of preparations.

Conclusion

Within the limitations of this study, it can be concluded that:

1. General dental practitioners seem to have difficulties to fulfill all criteria of clinical recommendations for the preparation of all-ceramic crowns.
2. The presented digital approach based on STL datasets seems to be a useful method to evaluate preparation geometry. In the future, direct feedback based on digital evaluation could help to increase preparation quality in practice and education.

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

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