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ORIGINAL ARTICLE

The clinical accuracy of single crowns exclusively fabricated by digital workflow—the comparison of two systems

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Abstract
Objectives The purpose of the study was to compare the accuracy of crowns exclusively fabricated by the digital workflow of two systems. The null hypothesis stated was: Both systems do not differ with respect to marginal and internal accuracy.
Materials and methods In 14 patients, 13 molars and 1 premolar were prepared. Each preparation was scanned intraorally with two different digital impression systems, Lava COS and Cerec AC. On the basis of these data, Lava DVS crowns [DVS] and Vita Rapid Layering Technique crowns [RLT] were fabricated, respectively. Both systems contained of a zirconia framework and a digitally fabricated silicate ceramic veneering. The marginal and internal fit of the crowns was documented by a replica technique. The replicas were examined under microscope with a magnification of ×200. The Wilcoxon signed rank test was applied in order to test if the values of the two systems showed significant differences at $p \leq 0.05$.
Results The results were as follows in micrometers (±standard deviation): at the marginal gap, 51 (±38) for [DVS] and 83 (±51) for [RLT]; mid-axial, 130 (±56) for [DVS] and 128 (±66) for [RLT]; axio-occlusal, 178 (±55) for [DVS] and 230 (±71) for [RLT]; and centro-occlusal, 181 (±41) for [DVS] and 297 (±76) for [RLT]. According to the Wilcoxon signed rank test, the results differed significantly at the marginal, axio-occlusal, and centro-occlusal gaps.
Conclusions The null hypothesis had to be rejected.
Clinical relevance The exclusively digital workflow on the basis of intraoral digital impressions delivered clinically satisfying results for single crowns with both systems.

Keywords Accuracy · Optical impression · Clinical · Single crowns · Ceramics · CAD/CAM

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Introduction

The term digital workflow in prosthetic dentistry comprises all coordinated computerized procedures that contribute to the fabrication of a restoration [1]. The first step of an entire digital workflow is the optical intraoral impression. Meanwhile, the rotatable three-dimensional (3D) display of the scanned intraoral surface is the standard presentation mode on the computer screen. This enables the user to immediately check the quality of the impression, including the abutment geometry and the finish line of the prepared teeth. If the dentist is not pleased with the result, the impression can be repeated within the same appointment. Therefore, it is claimed that intraoral optical scanners contribute to a "more efficient workflow in the dental office" [2]. In general, the usage of impression and tray material is avoided [2] and severe undercuts of nonprepared teeth do not have to be blocked out before impression taking. The prevention of tray and impression material may also be of an enhanced comfort for the patient. If the restorations are fabricated in cooperation with a dental laboratory, it is possible to discuss the result of the impression via Internet [3]. The design of a restoration on the computer screen (computer-assisted design [CAD]) and the computer-assisted manufacturing (CAM) are claimed to be more efficient than the application of conventional methods [2, 3]. Additionally, the CAD/CAM technology makes it possible to use materials, which are of

high homogeneous quality due to industrial prefabrication [4]—and the fabrication process can be faster than using conventional methods [5]. These facts may offer an economically priced, more affordable dentistry. Some materials like zirconia oxide can only be processed by means of the CAM technology. To check the final result of the restoration in the dental laboratory before try-in in the patient's mouth, most of the intraoral digital scanning systems facilitate the production of real tooth models on the basis of the digitally captured data by stereolithographic technique or by milling.

These models primarily serve as a checkup entity rather for the occlusal relationship and shape than for checking the accuracy of the marginal fit. It is possible to fabricate crowns based on zirconia frameworks exclusively using the digital workflow beginning with the optical impression and ending with the CAM production of the layering material. This is, e.g., possible with the Lava (3M Deutschland, Seefeld, Germany) [1] and with the Cerec/Inlab (Sirona, Bensheim, Germany) systems [6, 7]. Although the digital workflow seems to offer many advantages in terms of dentist, laboratory, and patient comfort, the basic criteria of good clinical practice for restorations have to be fulfilled as well. When the clinician tries in a full veneered crown, he checks the proximal contact, the fit, the static and dynamic occlusion, and the shape and esthetics of the restoration. The marginal fit of a restoration is decisive whether a restoration can be inserted or not. In the case of crown restorations, the margins are often located subgingival and thus a nonadhesive insertion technique, e.g., with GlasIonomer cement, is preferred. To avoid potential problems of increased dissolution of the cement, marginal gaps between 100 and 120 μm are required [8, 9]. McLean and von Fraunhofer even stated that gaps of up to 160 μm are clinically acceptable [10]. The clinical study of Sailer et al., investigating the prototype of a zirconia system, pointed out that the discussion of marginal fit is still important. During an observation period of 53.4 months, 21.1 % of 33 FDPs in 27 patients showed secondary caries due to poor marginal fit, although they were adhesively luted [11]. The internal fit has a practical impact as well. If there is an increased occlusal or incisal gap between the die and the inner crown surface, this space is needlessly sacrificed to the disadvantage of the framework and veneering thickness. There are only few clinical studies available that evaluate the internal and marginal fit of the entire digital workflow of all-ceramic systems. Therefore, the aim of the present study was to evaluate the fit of the complete digital workflow of two computerized all-ceramic systems by connected spot checks stating the hypothesis: There is no difference in terms of the internal and the marginal fit between crowns fabricated with the Lava (3M Deutschland, Seefeld, Germany) system, applying the Lava DVS technique [DVS], and the Cerec/Inlab system (Sirona, Bensheim, Germany), using the Vita Rapid Layering Technique (Vita Zahnfabrik, Bad Säckingen, Germany) [RLT].

Material and methods

Study group

Fourteen adult patients who showed the indication for a single crown in the posterior region (13 molars and 1 bicuspid) gave their consent after being informed about the aims of the study and the details of the treatment. The study protocol of this prospective clinical trial was approved by the ethics committee of the University of Aachen (application no. EK 234/10). Patients who showed signs of bruxism, poor oral hygiene, periodontal disease, or nonvital abutment teeth were not included in the study. The patient's treatments were carried out by two experienced dentists (5 and 17 years experience).

Prosthodontic procedures

The pretreatment of the abutment teeth includes caries excavation and adhesive built-ups (Adper Easy Bond and Filtek Supreme XT, 3M Espe, Seefeld, Germany). The preparation design for the all-ceramic crowns was similar to metal–ceramic crowns. As finish line, a distinct chamfer was provided. The location of the finishing line was oriented on the clinical conditions like the extension of the core subgingival, isogingival, or slightly supragingival. The circumferential reduction of the tooth substance was between 1.0 and 1.2 mm. The occlusal reduction was about 1.5–2.0 mm. The abutment height was at least 4 mm. All internal edges were rounded. For the preparation of the intraoral scan, retraction cords (Ultrapak, Ultradent Products, South Jordan, UT, USA) were placed, applying the double-layer technique. The upper retraction cord was removed before scanning. In order to achieve scannable surfaces, the intraoral areas were covered with Lava Chairside Oral Scanner C. O. S. Powder (3M Deutschland, Seefeld, Germany) or Cerec Optispray (Sirona, Bensheim, Germany). The quadrant of the prepared tooth, the antagonists, and the buccal bite in maximum intercuspation were optically scanned with both intraoral scanning systems—Lava COS (3M Deutschland) and Cerec AC using the Cerec Connect software (Sirona). The sequence of the system that was used first was randomly selected for each patient. The optical impression captured by Cerec Connect was based on the strip light projection principle [12–14]. The captured data were sent online via the Cerec Connect portal directly to the dental laboratory responsible for the manufacturing of the crowns. The dental laboratory e-

mailed a purchase order for a stereolithographic upper and lower model to infiniDent Services (Darmstadt, Germany). The Lava COS used the principle of active wavefront sampling in order to acquire the intraoral 3D situation on the computer screen [15]. The Lava data were sent to the Lava data processing center (Lexington, MA, USA) for digital post-processing. The scans were checked for artifacts and the data density of areas, which were scanned several times, were reduced in order to obtain a manageable data amount. The data were forwarded to two dental laboratories in Germany and to a model fabrication center for stereolithographic model production. The prepared teeth were temporarily provided with crowns made of Luxatemp (DMG, Hamburg, Germany) and placed with eugenol-free temporary cement (TempBond NE, Kerr, Rastatt, Germany).

Laboratory procedures

Fourteen all-ceramic single crowns were manufactured by the use of each CAD/CAM system. The [DVS] crowns were manufactured on the basis of the Lava COS scans, while the [RLT] crowns were produced using the 3D model data which were captured with the Cerec AC. The stereolithographic models exclusively served for checking the proximal contacts and occlusion of the crowns. Both the [DVS] and the [RLT] restorations were first designed as full contoured virtual crowns using the Lava and the Cerec Inlab software, respectively. Then, the full anatomical datasets were split into two different data records. One contained the anatomically shaped framework and one the veneering structure. As framework materials, presintered zirconia blanks were used. For [RLT], Vita In-Ceram YZ blanks (Vita Zahnfabrik, Bad Säckingen, Germany) and, for [DVS], Lava Frame blanks (3M Deutschland, Seefeld, Germany) were applied. The spacer settings for Cerec and Lava were −40 and 30 μm, respectively. The densely sintered frameworks were first tried in using a fit check (Fit Test C&B, Voco, Cuxhaven, Germany). If necessary, the fit was corrected with a red ring handpiece and a fine cylindrical burr with rounded edges under water cooling. The final wall thicknesses were checked using a caliper, if the recommended framework wall thickness of at least 0.5 mm was kept. The frameworks were then joined together with the veneering structure. In the case of [DVS], the veneering material consisted of presintered glass–ceramic blocks, which were connected with the zirconia cores by firing. For [RLT], silicate ceramic blocks were used (Vitablocks Triluxe Forte, Vita Zahnfabrik). They were luted to the framework material using a self-adhesive composite resin (RelyX Unicem, 3M Deutschland). The restorations were tried in and both proximal contacts and the static and dynamic occlusion were checked and adjusted if necessary.

Replica technique

In order to document the marginal and the internal discrepancies, silicone replicas were fabricated. In total, 28 samples on the 14 prepared abutments were produced (14 [DVS] and 14 [RLT]). After removing the provisional crowns, the preparations were thoroughly cleaned with pumice. The crowns were filled with a light body silicone (President Light Body Green, Colténe, Konstanz, Germany) and placed on the abutment teeth, applying a force of 20 N, which was checked by a dynamometer. During load application, a cotton roll was placed between the lever of the dynamometer and the occlusal crown surface. The thin silicone layer represented the gap width between the inner surface (inclusively the crown margin) of the crown and the surface of the abutment tooth. After setting of the light body silicone, the crown was removed from the abutment. The thin green-colored silicone film in the abutment crowns was stabilized by injecting a heavy orange-colored body silicone (President Heavy Body Brown, Colténe, Konstanz, Germany). The replicas were removed and segmented with a razor blade. The molar replicas were segmented once in the mesiodistal direction and three times in the bucco-oral direction, so that eight fragments per abutment were obtained (Fig. 1). The premolar replicas were segmented into six fragments by cutting them once in the mesiodistal direction and twice in the bucco-oral direction.

Gap measurement

Two calibrated examiners, who were not involved in the clinical treatment, carried out the measuring procedure.

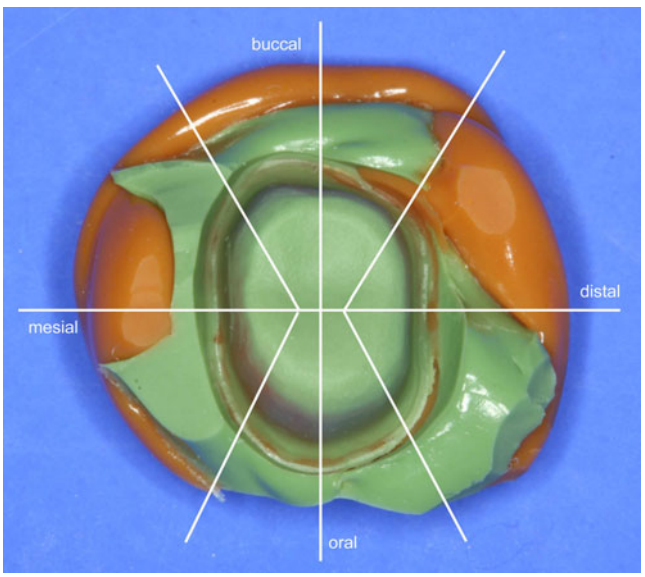

Fig. 1 Replica sample of a molar: the *lines* indicate the intersections of the sample preparation for microscopic investigation

The cross-sections were adjusted horizontally on modeling clay in order to obtain a parallel orientation to the microscope's plate and to achieve a rectangular observation angle. The green-colored silicone layer, which represented the discrepancy between the die and the inner surface of the restoration, was examined at 200-fold magnification using a light microscope with corresponding digital camera and software (Axio Image M2m, AxioCam MRC, AxioVision 4.8, Zeiss, Oberkochen, Germany). At each cross-section, the following four landmarks were measured (Fig. 2):

LM1: the marginal discrepancy, which represented the marginal gap according to Holmes et al. [8]. The width was measured as the perpendicular distance from the internal surface at the margin of the restoration to the preparation.

LM2: the mid-axial discrepancy, which represented the distance between the die and the inner surface of the crown at the middle of the axial wall.

LM3: the axio-occlusal transition discrepancy, which was defined as the bisector of the angle, defined between the straight line attached to the occlusal plateau and the straight line applied to the axial wall.

LM4: the centro-occlusal discrepancy plateau.

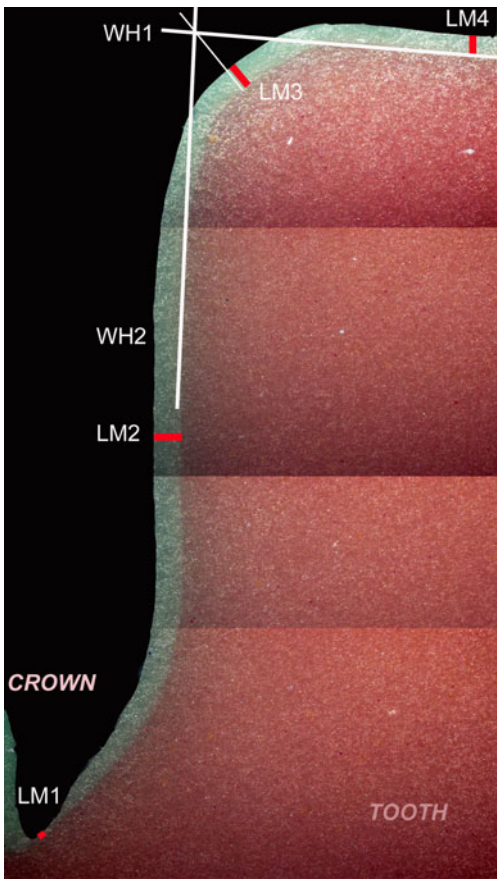

Fig. 2 Example of a cross-section of a replica. Locations of the discrepancy measurements at LM1 to LM4: *LM1* marginal gap, *LM2* mid-axial gap, *LM3* axio-occlusal transition (LM3 is defined by the intersection of the axial (*WH2*) and occlusal (*WH1*) lines), *LM4* centro-occlusal gap

Statistical procedures

The statistical analysis was done with PASW Statistic, version 18.0 (SPSS, Chicago, IL, USA). For each distance, the measurements of both calibrated examiners were documented and the mean value was calculated.

For each system, the mean value, the standard deviation (SD), the median, the minimum, the maximum, and the 95 % confidence interval of all available measurements for each landmark were determined. The data of the two systems were tested for statistically significant differences at $p \leq 0.05$ applying the Wilcoxon signed rank test.

Results

The mean value at LM1 (marginal gap) amounted to 51 μm (SD, ±38 μm) for [DVS] and 83 μm (SD, ±51 μm) for [RLT]. At LM2 (mid-axial), mean gap widths of 130 μm (SD, ±56 μm) for [DVS] and of 129 μm (SD, ±66 μm) for [RLT] were measured. At LM3 (transition from the axial wall to the occlusal plateau), means of 178 μm (SD, ±55 μm) for [DVS] and of 230 μm (SD, ±71 μm) for [RLT] were revealed. At LM4 (centro-occlusal), the replicas showed a mean thickness of 181 μm (SD, ±41 μm) for [DVS] and of 297 μm (SD, ±76 μm) for [RLT]. Table 1 shows the medians, the SD, the minima, the maxima, and the 95 % confidence intervals for all landmarks. The box plot diagram (Fig. 3) shows the median values, both the 25 and 75 % quartile and the outliers of the two systems at the different landmarks. The values at LM1, LM3, and LM4 of [DVS] differed significantly from the measurements of [RLT] at $p \leq 0.05$ (Wilcoxon signed rank test).

Discussion

The aim of the present study was not to measure the accuracy of two different intraoral scanning systems. The purpose was to evaluate the accuracy of the entire process chain under clinical conditions. Therefore, the fit of the completely finished crowns was evaluated, inclusive of the layering structure of both [DVS] and [RLT]. As a matter of principle, in both cases, there is the risk of causing impurities on the intaglio surface of the crown when the coping is connected with the veneering. This fact should have been tested as well.

Two zirconia-based digital veneering systems were chosen because the preparation guidelines allow a little less

Table 1 The means, medians, SD, 95 % confidence intervals, minimum, and maximum values of the gap widths of 14 [DVS] and [RLT] crowns at 4 different landmarks are displayed

Landmark	[DVS]							[RLT]						
	Median [µm]	Mean [µm]	SD [µm]	Min [µm]	Max [µm]	95 % confidence interval		95 % confidence interval		Max [µm]	Min [µm]	SD [µm]	Mean [µm]	Median [µm]
						Upper bound [µm]	Lower bound [µm]	Lower bound [µm]	Upper bound [µm]					
LM1	42	51	38	0	213	58	44	73	93	236	4	51	83	71
LM2	126	130	56	30	257	140	119	116	141	314	23	66	129	121
LM3	162	178	55	87	414	188	167	216	243	552	57	71	230	227
LM4	188	181	41	60	269	189	173	283	312	527	193	76	297	279

LM1 the marginal discrepancy, *LM2* the mid-axial discrepancy, *LM3* the axio-occlusal transition discrepancy, *LM4* the centro-occlusal discrepancy

pronounced chamfer finish line than, e.g., for lithium disilicate crowns where a chamfer preparation of at least 1 mm is recommended. This is advantageous in the case of deeply decayed teeth when the finish line is sited subgingival and a ferrule design for the built-ups has to be accomplished.

To the authors' knowledge, the present study was the first one which directly compares two CAD/CAM systems which offer the opportunity to fabricate restoration exclusively based on intraoral data scanning. Of course, the 3D data captured with the scanning systems provide the basis for further processing. If these data lead to inaccuracies, it is unlikely that the quality of the restoration is satisfying. Both optical systems, which were used clinically in this study, were compared in vitro and revealed similar results [16]. In clinical practice, aspects like tooth position, location of the finish line, sulcus bleeding, and patient compliance are

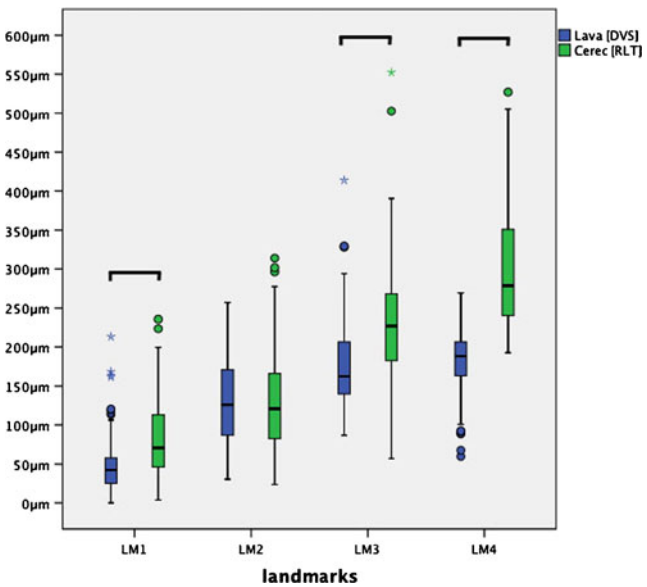

Fig. 3 Box plot diagram of [DVS] and [RLT] values at LM1, LM2, LM3, and LM4 for $N=14$ each. Significant differences are connected by the *horizontal lines* (Wilcoxon signed rank test)

important factors that may influence the outcome of an impression. In order to create identical and comparable conditions for both systems, each abutment was scanned with the Lava COS and the Cerec AC as data basis for the [DVS] and [RLT] crowns, respectively. The fit of the restorations was further decisively influenced by the quality of the design program, by the translation of the design code into the numerically controlled milling process, and by the quality of the milling devices themselves. It is evident that the processing route and the tuning of each part of the process chain are important for the final result [17]. Often, identified systematic shortcomings of one compartment of the system are compensated by other parts of the process chain. Therefore, it is reasonable to evaluate the final output of a CAD/CAM system by analyzing clinically important criteria.

Of course, the additional comparison with a conventional workflow based on an analogous impression technique would have been interesting. However, this procedure would have raised the inconvenience for the patients decisively not only with respect to time aspects. In order to keep the study set up with connected spot checks, three different impressions per crowns would have been necessary. If the random generator indicated to do the conventional impression at first or at second, the replacement of the retraction cords would have been necessary because, when removing the conventional impression, the cords are often displaced or removed.

One major parameter for clinical success is the fit of a restoration. In order to document the internal and marginal accuracy, the replica technique is accepted as a reliable and noninvasive method [10, 18–23]. Shortcomings of this method are the two-dimensional display of a marginal gap and the impossibility of a circumferential analysis of the fit. In some cases, the interpretation of the marginal gap is not possible, especially if a finish line is located subgingival [22].

It would be desirable to apply nondestructive 3D fit assessment protocols for accuracy measurement like those

also described by Luthardt et al. and Holst et al. for in vivo studies [24, 25], but there is always the drawback that the intraorally scanned digital die is never really identical to the original die in the oral cavity. This fact is not only based on technical inaccuracies but rather on clinical shortcomings like the intraoral conditions during impression taking. On the other hand, the replica method shows the discrepancy between digitally produced restoration and the original intraoral die. Therefore, it could be a complementary test set up for the future to accomplish a 3D scan of the replicas for accuracy measurement.

From the practical point of view, the fit of a crown could be influenced by too tight proximal contacts. This factor was excluded in this study by checking the proximal mesial and distal contacts carefully with a 50-μm thick metal matrix band. The contact was adjusted as long as the matrix band could be inserted completely in the contact area with resistance.

Although the values of [DVS] and [RLT] at LM1 differ significantly, the relevance of the difference is debatable due to the fact that both means and their corresponding confidence intervals are below the commonly accepted threshold of 120 μm [10]. The maxima of the gaps, which are important for clinical aspects, are nearly similar for [DVS] and [RLT] with 213 and 236 μm, respectively (Table 1). The maximum width for [DVS] might be caused by a little too much peripheral misinterpretation of the virtual finish line at the disto-buccal localization of a lower right first molar. In the case of the maximum value for [RLT], there was no irregularity identifiable.

All the descriptive marginal values are comparable to other clinical studies that applied similar replica techniques for single crowns [20, 22, 26]. Thus, the results based on the optical impressions in this study and the CAD/CAM fabrication method showed completely satisfying fit and proved that this kind of process chain is applicable for adequate patient treatment in the case of single crowns. The study confirmed the results for [DVS] revealed by Syrek et al. [27] and by Scotti et al. [28]. The latter study also found increasing widths from LM1 to LM4. The differences at LM3 and LM4 are of importance because large variations of the cement gap may lead to a weakening of reconstruction [29]; and the larger the gap, the more tooth substance has to be removed in order to gain the minimum thickness of the restoration. In general, the values of the [RLT] crowns tend to be larger than those of [DVS]. As Ender and Mehl showed in vitro, both optical systems revealed similar accuracy values and even slightly greater deviations in precision for [DVS] [16]. One reason for smaller gaps for [DVS] than for [RLT] in the present study may be the more stable execution of the Lava milling unit, the use of smaller burr diameters and a higher degree of freedom of the milling axis.

Overall, for both systems, an increase of the gap widths from LM1 to LM4 of both systems is obvious. If in the case of the Cerec system in the parameter menu a default spacer setting of zero was shown, it was in reality +100 μm (Inlab software versions 3.x) because this presetting of +100 μm was defined by the manufacturer as zero. In consequence, a spacer setting of −40 μm was +60 μm in reality. This phenomenon was confirmed by Moldovan et al. who applied a spacer setting of −100 μm for the Cerec milling unit in order to get a mean internal fit of 60–70 μm in an in vitro investigation of the internal fit of a grinding system and a milling system [30]. In the present study, it would not have been sensible to decrease the spacer settings below the chosen value because the values at LM2 were sufficient—a further reduction would have increased the probability of primary inner wall contacts at that landmark.

Conclusion

Within the limitations of the present study, it can be concluded that all-ceramic single crowns which were exclusively fabricated by digital means with the Lava and Cerec AC/Inlab system revealed satisfying marginal and internal fit.

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Conflict of interest During the years, the authors SW and SR have held oral presentations and/or courses receiving a separate and appropriate honorarium each from at least one of the companies 3M Deutschland, Sirona, and Vita Zahnfabrik that supported the present study.

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