Clin Oral Invest (2013) 17:851–857
DOI 10.1007/s00784-012-0749-6

ORIGINAL ARTICLE

Comparison of biogenerically reconstructed and waxed-up complete occlusal surfaces with respect to the original tooth morphology

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Received: 26 October 2011 / Accepted: 2 May 2012 / Published online: 13 May 2012

Abstract
Objectives Recently, it has become possible to reconstruct complete occlusal surfaces using the biogeneric tooth model. This study aimed to mathematically assess and compare the morphologic agreement between original morphology and CAD-reconstructed, waxed-up and CAM partial crowns.
Materials and methods Thirty-nine intact first permanent molars (39 participants) were included. Impressions, bite registrations and three gypsum replicas were made. Preparations for CAD/CAM partial crowns were performed and scanned. The restorations were biogenerically reconstructed (CEREC® v3.80) and milled. Wax-ups of these preparations were scanned as well as the milled restorations and original teeth. Discrepancies were evaluated by matching the scans with the original morphologies (Match3D, output: volume/area, *z* difference) and by contact patterns. The discrepancies were compared between CAD-reconstructions and either wax-ups or milled restorations (paired *t* test, α=0.025 for two multiple tests).
Results The mean differences between natural tooth morphology (triangular stabilisation 71.8 %) and biogeneric reconstructions, wax-ups and milled restorations (triangular stabilisation 87.2 %) were: 184±36 μm (volume/area), 187±41 μm (*z* difference); 263±40 μm (volume/area), 269±45 μm (*z* difference) and 182±40 μm (volume/area), 184±41 μm (*z* difference). Differences associated with biogeneric reconstructions were significantly less than those of wax-ups (volume/area and *z* difference, $p<0.0001$), but not significantly different than those of milled restorations ($p=0.423$ (volume/area), $p=0.110$ (*z* difference)).
Conclusions CAD software enables a closer reconstruction of teeth than do wax-ups, even when no cusps remain. The milling device is precise enough to transfer CAD into the final restoration.
Clinical relevance This study shows that state of the art CAD/CAM can effectively produce natural tooth morphology and may be ideal for fixed partial dentures.

Keywords CAD/CAM · Biogeneric tooth model · Cerec · Partial crown · Occlusal surface · Original tooth morphology

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Introduction

When restoring the occlusal surfaces of posterior teeth, clinicians largely agree that the task involves both harmonic intercuspidation and the restoration of natural looking morphology [1]. For indirect gold and pressed ceramic restorations, this aim is primarily addressed by the dental technician who waxes up the missing tooth parts by using an articulator. In contrast, computer-aided designed and manufactured (CAD/CAM) restorations accomplish this goal via different software systems and manual modifications.

In the past, the occlusal designs of CAD/CAM manufactured crowns or inlays were a challenging and time-consuming process, which required a great deal of knowledge and experience related to CAD software. In the past several years, many improved features with respect to occlusal design have been introduced. The first software systems were based on standard morphology, which needed individual adaptation [2–5], while newer systems use algorithms to adjust the occlusal surface to the bite registrations [6, 7]. A new approach involves the introduction of a "biogeneric tooth model" [8]. This biogeneric model is based on a mathematical description of teeth for which the information is obtained from a 3D data library comprising several hundred scans of caries-free and intact occlusal surfaces [9]. It is possible to mathematically construct a missing surface of a tooth by analysing the remaining tooth substance (CEREC® v3.00) [10, 11]. This allows the design of partial crowns and inlays with fitting occlusal dimensions in an acceptable time frame [12]. A new software update (v3.80) [13] now provides, for the first time, the chance to reconstruct a complete occlusal surface, even when the whole original occlusal surface has been lost. The necessary data for the biogeneric reconstruction are then gathered either from the tooth distal to the restoration, the antagonist, a bite registration or the contra-lateral tooth in the same arch.

The present study aimed to assess the mathematical match between the original occlusal surface and the biogenerically reconstructed occlusal surface with CAD, the occlusal surface waxed-up by a dental technician and the CAM ceramic restoration. In addition, the contact point situation of the original teeth and the milled restoration was evaluated descriptively. The following working hypotheses were tested: (1) the biogeneric reconstruction matches the original tooth surface better than does the waxed-up occlusal surface and (2) the biogeneric reconstruction matches the original tooth surface better than does the finally milled ceramic restoration because of compromised precision inherent in the milling process.

Materials and methods

Participants

The participants of this clinical study were selected from clinical students of dentistry at the Department of Restorative Dentistry, University of Munich. Participants were included when they had at least one quadrant with intact tooth morphologies without carious lesions and without missing teeth or spaces. Exclusion criteria were the presence of fillings, fissure sealants or unwillingness to participate in the study. Informed written consent was obtained from all participants. The study was granted approval by the Ethics Committee of the University of Munich (no. 022-10).

Models and preparation

If more than one quadrant met the inclusion criteria in an individual patient, only one quadrant was randomly selected by using a random selection program (SPSS, version 19, SPSS Inc., Chicago, IL, USA). A silicone impression (Aquasil, Dentsply DeTrey, Konstanz, Germany) was taken from the selected quadrant with a partial impression tray (Speiko, Münster, Germany). An alginate impression (Schuetz Dental, Rosbach, Germany) was taken from the antagonist quadrant. The impressions were poured out three times with type IV gypsum (MM Dental, Gummersbach, Germany). Saw-cut models were made from these gypsum replicas. To assign the gypsum replicas in the correct occlusal relation, two bite registrations were made. One registration was made with scannable material (CADbite, Ivoclar Vivadent, Schaan, Liechtenstein) for CAD reconstruction. The other registration was made with a silicone material (Futar D Fast, Kettenbach, Eschenburg, Germany) for use in a semi-adjustable articulator (Artex, AmmanGirrbach, Pforzheim, Germany). A quantification of occlusal contacts on the original gypsum cast was done with articulating paper. Additionally, it was evaluated if there was a triangular stabilisation on the respective teeth of the quadrant. The overall workflow is shown in Fig. 1. All materials were used according to the manufacturer's instructions.

The first molar of each quadrant was selected for preparation. The preparations for the all-ceramic partial crowns were performed by 39 students in their first clinical year after 2 weeks of full-time training in cavity preparations for CAD/CAM restorations. Each student performed one preparation. The preparations were done according to recommendations specific to CAD/CAM restorations [14]. Among other criteria, we specifically verified a minimum tooth removal of 1.5 mm in the occlusal and 2.0 mm in the proximal dimensions. To date, all cusps were removed. The preparation margin on the oral and buccal surface was set at the equator of the tooth. On the proximal surfaces the contact point was removed, avoiding subgingival preparation margins. During preparation we looked at the insertion axis of the planned restoration to be perpendicular to the occlusal surface plane and the equatorial line of the respective tooth and the distal adjacent tooth. Further, we looked at the preparation margin to include an angle of 90° in order to avoid any fractures of the ceramic restoration [14]. The preparation criteria were confirmed by a dentist with clinical expertise in CAD/CAM restorations.

Scanning and reconstruction procedures

The preparations were scanned by the same experienced dentist with CEREC® Bluecam (Sirona, Bensheim, Germany) according to the following protocol: the prepared tooth as well as the adjacent mesial and distal teeth were scanned as best as possible perpendicular to the occlusal plane. In addition, the scanning device was tilted 15° mesial, distal, oral or buccal to the described angle scanning all four sides in order to catch any undercuts of the scanned teeth.

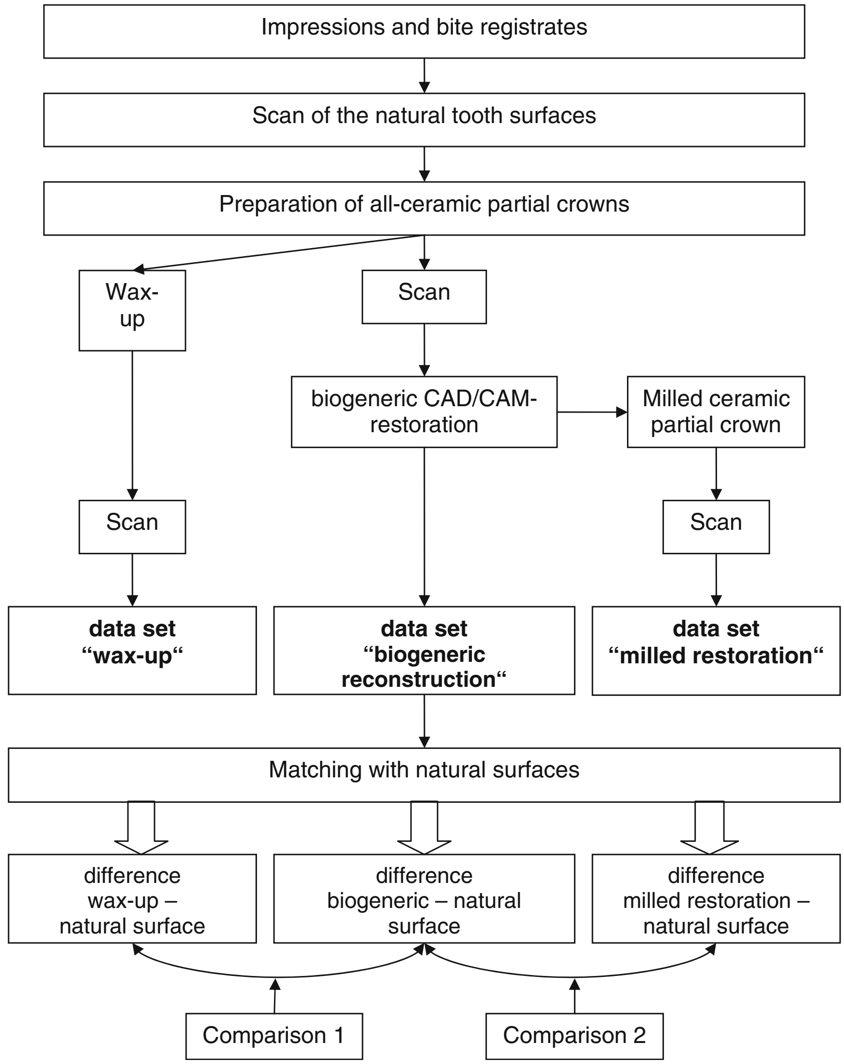

Fig. 1 Study workflow from the impressions to the data sets

Subsequently, the bite registration (CADbite) was trimmed as not to cover the adjacent teeth and placed on the preparation and scanned perpendicularly to the occlusal plane of the tooth. The result was an exact virtual 3D model of the preparation, including the mesially and distally adjacent original teeth and the occlusal shapes of the antagonist teeth (CEREC® v3.80). The unprepared tooth morphology from the second replica was scanned using the same protocol and the replica were mounted in an articulator by another bite registrate.

The 3D-model was virtually trimmed and the preparation margin was determined by the automatic preparation margin detector of the software. The margin was visually checked and manually corrected if necessary. The minimum occlusal thickness of the restoration of 1.5 mm was checked using the "blue cloud function" of the software, which provides a semi-transparent view of the preselected occlusal thickness. If there was not enough tooth substance removed, the preparation was adapted and checked again. The restoration was constructed using the software via the "biogeneric function" [12], which gains the information for biogeneric reconstruction of posterior teeth from the distal adjacent tooth. If necessary, manual adjustments of the biogeneric proposal were made on the oral/buccal and the proximal contact surfaces. Concerning the occlusal surface, adjustments were only made to achieve at least three occlusal contact points in the central fossa for triangular stabilisation. Afterwards, the restoration was milled with CEREC® inLab MC XL (serial number: 106645, Step Bur 12S, cylinder pointed bur 12S) using feldspathic ceramic blanks (Mark II, VITA Zahnfabrik, Bad Säckingen, Germany). The restoration was adapted to the preparation on the saw-cut models using diamond burs (Gebr. Brasseler, Lemgo, Germany). The approximal contacts were fitted between the adjacent teeth. The number of the occlusal contacts on the milled restorations after their adaptation to the saw-cut models as well as the number of triangular stabilising contact situations were counted as described before.

The gypsum replicas of the ceramic partial crowns placed on the preparations were scanned using CEREC® Bluecam with the same protocol as described above. Additionally, all partial crowns were modelled in wax on the same prepared teeth, creating at least three occlusal contact points as it was also demanded from the computer reconstruction. The modelling was done by a senior master dental technician with more than 30 years of experience. The wax-ups were also scanned using the previously described protocol. The scanned natural tooth surface, the preparation of the partial crown, the biogeneric reconstruction and scans of the wax-up and the final milled restoration are shown in Fig. 2.

Objectives

Hypothesis 1 was that the discrepancy between the natural tooth surface and the biogeneric reconstruction is less than the discrepancy between the original tooth surface and the professional wax-up.

Hypothesis 2 was that the difference between the natural tooth surface and the biogeneric restoration is less than the difference between the original tooth surface and the milled ceramic restoration due to the milling process.

Data processing

All data sets were decrypted into the stl-format and transformed to a high-field data format (.xv) for matching purposes (Dent Visual v3.00) [10]. Three data sets were generated. First, we assessed the difference between the original tooth surface and the biogeneric reconstruction. Second, the difference between the original tooth and the wax-up was evaluated. Third, the difference between the natural tooth and the milled restoration was determined. All of the respective pairs were matched.

As field of interest the occlusal surface of the first molar maximum 1.0 mm outboard the connection line of the cusps was selected. This selection was done to avoid any influence of possible oral/buccal adjustments. Next, an image was generated to show differences between the two matched surfaces, along with descriptive data (Match3D, v2.50) [15]. The discrepancy between the two surfaces was evaluated in two ways. A graphical view of the principles behind these two methods is shown in Fig. 3. First, we determined the complete volume between the two surfaces divided by the flat area of the selected field of view. Second, the difference between the two surfaces in the z-direction was calculated by the span between the 20 and 80 % quantiles according to the following formula [10]:

$$\Delta z = \frac{Q_{80\%} - Q_{20\%}}{2}$$

Statistical analysis

The statistical analysis of the data was performed using SPSS software (version 19). The mean and standard deviation (SD) of the described value differences were calculated across all cases. This was completed for both methods (volume/area, z difference). To confirm the normal distribution of the data, a Kolmogorov–Smirnov analysis was performed [16].

For both hypotheses, comparisons were made using the paired Student's t test (power 0.99, α level 0.05, and corrected according to Bonferroni adjustment to 0.025 for two multiple tests). Correlations between the two methods used

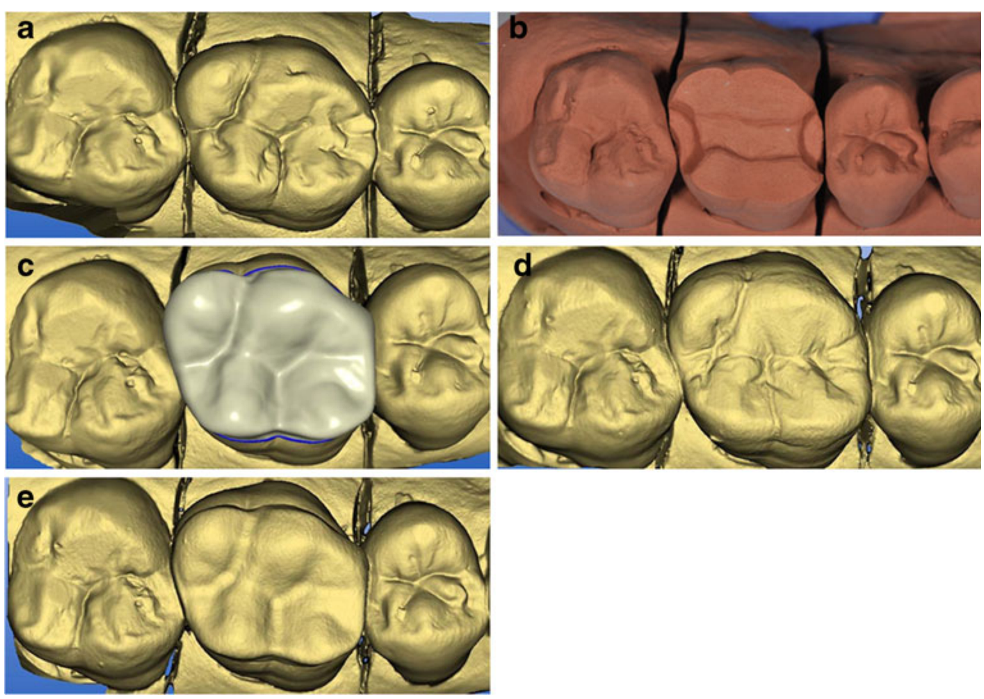

Fig. 2 Example showing one of the 39 cases for the **a** original tooth, **b** the preparation of the partial crown, replacing all cusps, **c** the biogeneric reconstruction, **d** the professional wax-up and **e** the scanned milled restoration

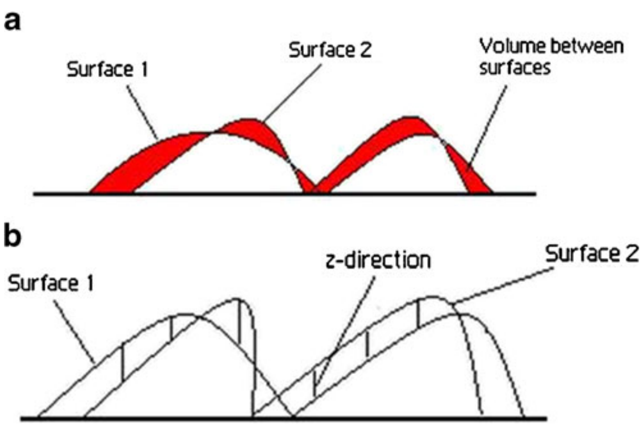

Fig. 3 Methods for determining the discrepancies between the two matched surfaces by **a** volume differences and **b** differences in z-direction

to describe the differences between the surfaces were later assessed using the Pearson product–moment correlation coefficient ($p \leq 0.01$).

The number of contact points (mean ± SD) and the percentage of triangular stabilised cases were given for the original teeth as well as the milled restorations.

Results

Thirty-nine participants (mean age 23.0±2.4 years) with 39 first molars (upper jaw $n=19$, lower jaw $n=20$; one tooth per person) were included in the study. The mean difference between the natural tooth surface and the biogeneric reconstruction was 184±36 µm (volume/area) and 187±41 µm (*z* difference). The mean difference between the natural tooth surface and the wax-up was 263±40 µm (volume/area) and 269±45 µm (*z* difference). Finally, the mean difference between the natural surface and the milled restoration was 182±40 µm (volume/area) and 184±41 µm (*z* difference). Images indicating the differences between these three pairs are shown in Fig. 4.

All different data sets showed normal distribution (Kolmogorov–Smirnov test, $p=0.432$, $p=0.950$, $p=0.162$, $p=0.745$, $p=0.522$, $p=0.599$).

Regarding the natural tooth surface, the biogeneric reconstruction was significantly more precise than the professional wax-up (*t* test, $p<0.0001$ by volume/area, $p<0.0001$ by *z* difference). Thus, hypothesis 1 was accepted. Also regarding the natural tooth surface, there was no significant difference between the milled restoration and the biogeneric reconstruction (*t* test, $p=0.423$ by volume, $p=0.110$ by *z* difference). Thus, hypothesis 2 was rejected. No loss of accuracy was noted during the milling process as values both before and after milling were nearly identical.

Based on the final data set, power calculation was performed (power=1 at the set significance level of 0.0025) [17].

The two different methods of determining differences between the surfaces showed correlation with statistical significance ($p \leq 0.01$, $r=0.965$ for the biogeneric reconstructions, $r=0.914$ for the wax-ups, and $r=0.952$ for the milled restorations).

On the original gypsum casts a mean of 2.8 (±0.7) occlusal contacts were found guaranteeing a triangular stabilisation of the respective tooth in 28 out of the 39 cases (71.8 %). Following the same protocol, a mean of 3.0 (±0.5) occlusal contacts were found on the milled restorations with a triangular stabilisation in 34 out of the 39 examined partial crowns (87.2 %).

Discussion

We evaluated discrepancies ranging from 182 to 187 µm between the natural tooth surfaces and the biogeneric reconstructions or milled restorations, respectively, with no significant differences. The discrepancies between the natural tooth surfaces and the wax-ups were significantly greater, at approximately 265 µm. To the best of our knowledge, there is no other study comparing complete occlusal reconstructions to their original morphologies. A deviation of 150 µm from the original morphology has been reported for inlay reconstructions with an earlier software version [10]. This is in the same range as our findings, considering that complete occlusal surfaces were reconstructed in our study. The significantly higher discrepancies of the wax-ups found in our

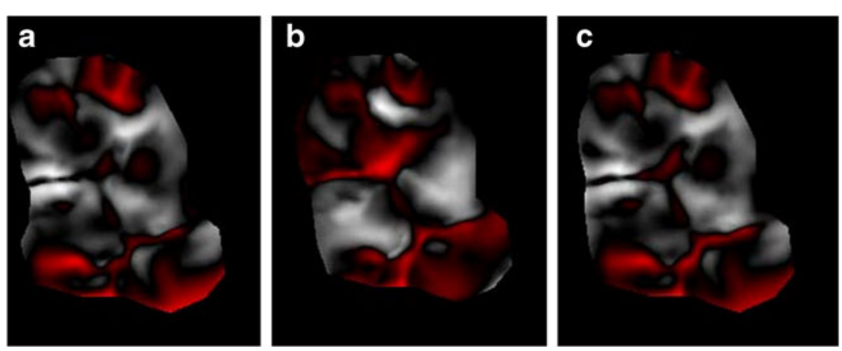

Fig. 4 Images showing differences between **a** natural surface and biogeneric reconstruction, **b** natural surface and professional wax-up and **c** natural surface and scanned milled restoration

study were also reported by a previous study [18]. We found no significant differences regarding CAD reconstruction and milled restorations, which is consistent with an earlier study that compared contact point patterns between virtual reconstruction (CEREC® 3D) and milled CAM restorations and showed high levels of agreement [7]. This suggests that there is only a minimal loss of information from the CAD reconstruction during the milling process. We did not make major adjustments to the occlusal design because we wanted to evaluate the agreement between the uninfluenced biogeneric software function and natural morphology.

When reporting the abovementioned discrepancies, one must take into account the critical steps involved in the manufacturing process, especially scanning and milling, which can cause a certain degree of imprecision. The used scanning device (CEREC® Bluecam) has been associated with an accuracy of 19–35 μm, depending on the size of the scanned region [19]. This is negligible compared to the presented discrepancies of 182–269 μm. The software acquires the data for the biogeneric reconstruction not only from the distal adjacent tooth, but it also takes the antagonist situation into account. The bite registrate, however, may be a possible factor of imprecision as the antagonist could show signs of erosion, abrasion or an insufficient restoration. In this study, we looked after intact original tooth morphology of the distal adjacent tooth as the main information for the biogeneric reconstruction is gathered from this tooth. Regarding the milling process, a milling device accuracy of 53–140 μm has been reported, but for an older milling unit type [20]. Although we measured the difference between CAM restorations and natural tooth morphologies, we obtained discrepancies ranging from 182 to 184 μm. While milling imprecision seems to be a considerable part of such discrepancies, they may be irrelevant because no significant differences were observed with the CAD reconstructions with respect to the original morphology.

When looking at the number of occlusal contacts, it can be stated that there is no loss of stabilisation of the restored teeth. We showed that it is possible to reconstruct a full triangular stabilisation with the biogeneric tooth model with minimal adjustments during the reconstruction, even when there was no such stabilisation in the original situation.

To date, many different methods have been described to assess the discrepancy between original tooth morphology and CAD reconstructions, wax-ups or final CAM all-ceramic restorations. Subjective questionnaires have been used to evaluate the naturalness of the biogeneric reconstructions versus conventional CAD reconstructions, favouring biogeneric function [12]. Many authors have also evaluated vertical increases in the incisal plate of the articulator as an indicator of the quality of the occlusal surface. This method has been used for the evaluation of conventional CAD reconstructions, with values between 480 and 999 μm and 460±190 μm for biogeneric reconstruction [12, 21, 22].

Another way to evaluate the quality of an occlusal surface reconstruction was reported recently. A dental technician rated the morphology of CAD crowns (CEREC® v2.80) regarding anatomical structure parameters, such as the location of the main fissure line, in comparison to conventional pressed all-ceramic crowns. The authors found no significant difference [23]. To describe the precision of CAD reconstructed occlusal surfaces, the same group compared the original contact point patterns to either the CAD reconstruction or conventionally manufactured IPS Empress crowns after occlusal adjustment. They found that the CAD reconstructed crowns showed 87 % agreement in contact patterns while the conventional pressed ceramic crowns showed a 95 % agreement, which was not statistically significant in difference [23]. Using a similar method, another study compared the contact point patterns and found a high level of agreement between milled crowns and CAD reconstructions. That study found a 78 % agreement regarding number, 76 % agreement regarding localisation and 65 % agreement regarding the size and shape of the contact points [7].

In contrast to most other studies in the literature, the current paper utilised a mathematical approach to assess discrepancies between the different occlusal surfaces. We used a matching software with an automatic matching routine, which superimposed the two data sets and guaranteed the same orientation of the compared surfaces via a least square fitting routine [15]. On the one hand, output was measured using volume differences between two matched occlusal surfaces, which was divided by the flat area of the selected field of interest (first molar). On the other hand, differences in z-direction were calculated for several ten thousand surface points dependent on the specific surface [15]. Information related to the z differences was shown as span between the 20 and 80 % quantiles [10, 18]. In comparison to giving only the mean and standard deviation, quantiles were used to avoid any overestimation of the z differences of steep peripheral surface areas. Both methods to describe the different images led to the same results and consequently showed a high level of correlation (>90 %) in our study. This mathematical approach was also used very recently in a clinical study [18], in which biogeneric reconstructions were compared with wax-ups in vivo, though without information regarding the intact, original tooth morphologies. However, the aim of our study was to assess the potential of biogeneric tooth models to create occlusal surfaces as close as possible to the original morphologies. This goal was achieved by first taking impressions of natural, unrestored and caries-free teeth, followed by preparations performed on gypsum replicas.

During the study, we missed a virtual articulator that was included into the software for the purpose of accounting for dynamic occlusal contacts during crown design. This may have been one potential source of compromised precision regarding the clinical use of the software. In particular, older individuals may have had teeth that were already restored or abraded, with little morphological details remaining. Consequently, the biogenerically reconstructed surfaces would have shown fewer relevant details.

Conclusion

Within the limits of the study, there was a high level of agreement between biogenerically reconstructed occlusal surfaces and the original tooth morphologies, even when all tooth cusps were replaced. Moreover, information regarding the surface pattern was not lost during the milling process. This enables a more natural morphology of the CAD/CAM restorations for state of the art clinical indications. Examples include biogeneric reconstructions of full crowns or fixed partial dentures using innovative materials such as lithium silicate ceramics [24], as well as fabrications of long-term provisional crowns made of new polymer materials, such as VITA CAD-Temp® for CEREC® [25].

Acknowledgements The authors would like to thank ZA Michael Nemecek, Dr. Christian Jauernig and the students enrolled in the preclinical course, Restorative Dentistry and Periodontology, in 2010 for their contributions to this study. We express our gratitude to the master dental technician, Robert Kollmuß, for doing the wax-ups. We thank Prof. Mehl for valuable discussion regarding the design of the study. We also thank the Sirona Company for allocating the data transformation program and VITA Zahnfabrik for providing us with the ceramic blanks.

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

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