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ORIGINAL ARTICLE

Fully automatic CAD design of the occlusal morphology of partial crowns compared to dental technicians' design

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Abstract
Objectives The aim of this study was to compare the occlusal morphology of partial crown reconstructions made by dental technicians with reconstructions made by a fully automatic software process (biogeneric tooth model) in relation to the original natural tooth shape.
Material and methods Stone replicas of natural teeth were measured three-dimensionally before preparing inlay and onlay cavities for ceramic restorations (n=5). For each preparation, five reconstructions (in total n=25) were made by five dental technicians. Additionally, reconstructions were calculated automatically by a software based on the biogeneric tooth model (Cerec 3D). In order to compare the two different kinds of reconstruction, an objective metrical similarity measure (shape similarity value, SSV) based on calculated volumes between compared datasets was used.
Results In 22 of 25 cases, the reconstructions made by the CAD software were closer to the original situation than the reconstructions made by the technicians. Mean average SSV of reconstructions made by the technicians (310.2±78.8 μm) was significantly higher (p<0.05) than mean SSV of CAD reconstructions (biogeneric model) (222.0±47.7 μm).
Conclusions In the design of naturally shaped occlusal inlay/onlay surfaces, a fully automatic CAD system can be at least as good as conventional wax-ups by dental technicians.
Clinical relevance The adjustment of a dental restoration to fit the morphology of surrounding tooth structures, still presents challenges for the dentist.

Keywords Similarity measure · CAD/CAM · Biogeneric tooth model · Occlusal morphology

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Introduction

A fundamental consideration in restorative dentistry is the design of occlusal surfaces [1]. This is not only the key for mastication but also for the stability of the entire stomatognathic system. Designed occlusal surfaces should correspond to the natural tooth shape, with functional fissures and cusps, and adapt to the anatomical shape of the adjacent teeth and antagonists. Concepts of occlusal design reflect current biomechanical ideas and paradigms concerning the functioning of an occlusal surface [1–3].

At the moment, there is a gradual change in restorative dentistry from manual towards computerized fabrication, by means of computer-aided design (CAD) and computer-aided manufacturing (CAM) devices [4–6]. However, the design of functional occlusal surfaces still requires considerable interaction with, and the experience of, a human operator [7, 8]. More advanced CAD software systems try to reduce this demanding and time-consuming interaction between the dentist and the CAD/CAM device. To this end, algorithms to fit the occlusion to static or dynamic bite registration are used [9–11].

But there remains a desire for a CAD system with fully automatic occlusal surface generations. Therefore, a mathematical representation of tooth surfaces and their natural variations called the "biogeneric tooth model" was introduced [12, 13]. Based on a 3D data library of hundreds of scans of intact unrestored posterior human teeth, this model is capable of deducing an entire occlusal surface from the residual substance of a partially destroyed tooth [13, 14]. The biogeneric tooth model is already implemented in current CAD software (Cerec 3D, Sirona, Bensheim) and promises to make fully automated design of partial crowns possible [15]. Compared to conventional CAD software, this mathematical model already proved its efficiency in generating CAD/CAM partial crowns with natural tooth morphology [16]. However, the question remains, whether this software can compete with well-trained dental technicians concerning the design of natural occlusal surfaces.

The aim of this study was to compare the occlusal morphology of reconstructions made by dental technicians with reconstructions made by the biogeneric tooth model. The different reconstructions were set in relation to the original tooth shape before simulating an inlay/onlay preparation. Morphological comparisons were performed with the aid of a 3D-similarity measure.

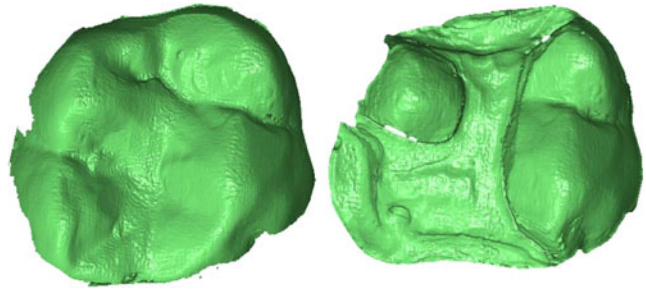

Fig. 1 Scan of an original (*left*) and preparated (*right*) tooth surface

Material and methods

Original occlusal surface

For this study, five subjects were randomly selected from a pool of young adults with completely intact tooth surfaces, no tooth restorations, and no caries. All subjects agreed to participate in the study by informed consent. The average age was 25 years (range from 21 to 33 years). Polyether impressions (Impregum, 3 M Espe, Seefeld, Germany) of both jaws were made, and subsequently, stone replicas (Fuji Superstone, white; GC Corp, Tokyo, Japan) were fabricated. The occlusal surfaces of the molars were measured with a 3D scanning device (Scan 3D Pro, Willitec, Munich, Germany) [17]. The resolution of the measuring process was 30×30 μm (*x*, *y*), yielding approximately 100,000 surface points per tooth. The accuracy in height direction (*z*) was approximately 10 μm.

Designing the reconstruction

Preparations for adhesive inlays/onlays were simulated on the stone replicas (Fig. 1). For this, one molar tooth was randomly chosen in each subject. For each preparation, at least one cusp was left untreated. The casts of the upper and lower jaw were saw-cut and fixed in an articulator (SAM Präzisionstechnik GmbH, Munich, Germany). Bite registrations of the antagonists were taken with a scanable vinyl polysiloxane registration material (Metal-Bite, R-dental, Hamburg, Germany). The treated teeth and the antagonist registrant were scanned with an opto-electronic intraoral camera (CEREC-3D, Sirona, Bensheim, Germany). Using Cerec 3D CAD software v3.00, based on the biogeneric tooth model [13, 18], models were virtually trimmed, and preparation margins were set. Fully automatic reconstructions were performed in the inlay/partial crown modus with no interaction through the operator. Reconstruction data were saved and converted into STL-format and xv-format files (DentVisual, software developed by A. Mehl). Additionally, five well-trained dental technicians (all of them at least with 7 years of experience) were instructed to wax up the original tooth form in the resulting inlay/onlay cavities at the best of their ability. The technicians had no time limit. They were instructed to reconstruct occlusal surfaces, which should correspond to a natural morphology, as well as adapt to the shape of the adjacent teeth and antagonists. No especial guidelines or wax-up concepts were recommended. Each wax-up model was scanned with the above-mentioned 3D scanning device (Scan 3D Pro) and the data were saved and converted in the same way as described before.

3D similarity measure

All reconstructions (computer-based reconstructions and conventional reconstructions made by the technicians) were superimposed with their original surface according to a best-fit method by the program Match3D 2.5 [19]. Figure 2 presents a scan of an original tooth surface, a virtual CAD reconstruction, and scans of wax-up models by dental technicians. Difference images, displaying color-marked local 3D distances (Figs. 3 and 4), were calculated between the datasets by evaluating distances point by point in z-direction (perpendicular to the occlusal surface, about 100,000 surface points (*k*)) [19]. The "shape similarity" value (SSV) was defined as the sum of the positive volumetric deviation and the absolute

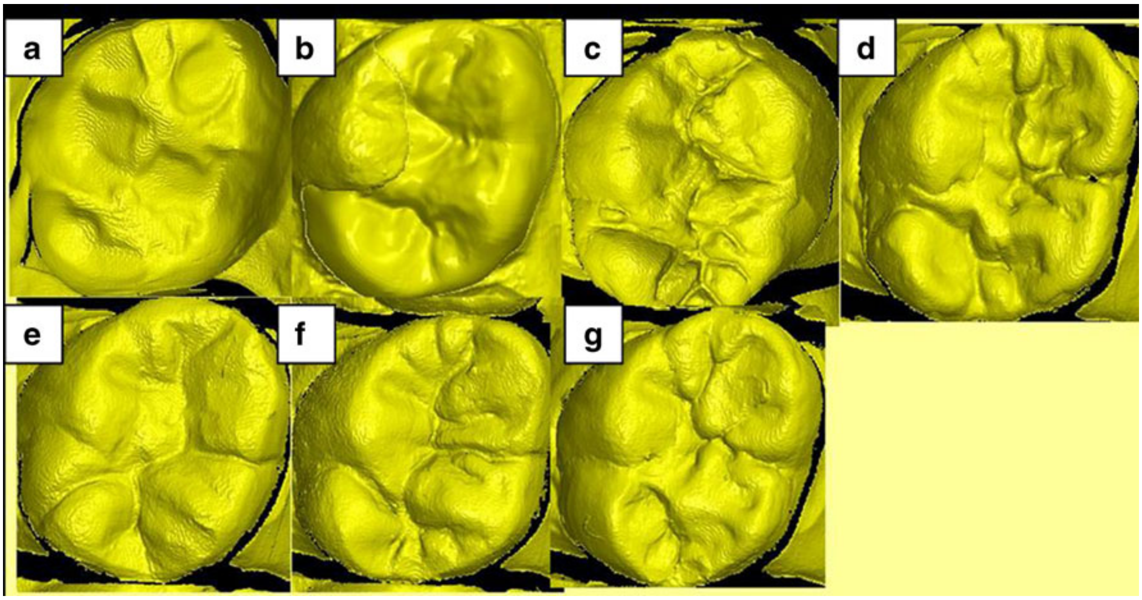

Fig. 2 Case 4. **a** Scan of original tooth surface. **b** Virtual CAD reconstruction. **c–g** Scans of wax-up models by dental technicians

negative volumetric deviation, divided by the surface area of the difference image:

$$\text{Shape similarity value} = \frac{Vol_{\text{pos}} + \text{abs}(Vol_{\text{neg}})}{A_{\text{tooth}}} \quad (1)$$

In mathematical theory, this value corresponds to a l_1-distance metric in k-dimensional vector space by $\left\| \vec{v}_{tooth1} - \vec{v}_{tooth2} \right\|_{l_1} / k$. Superimposed surfaces, which are more dissimilar, come along with higher volumetric deviations resulting in a high SSV and vice versa. With

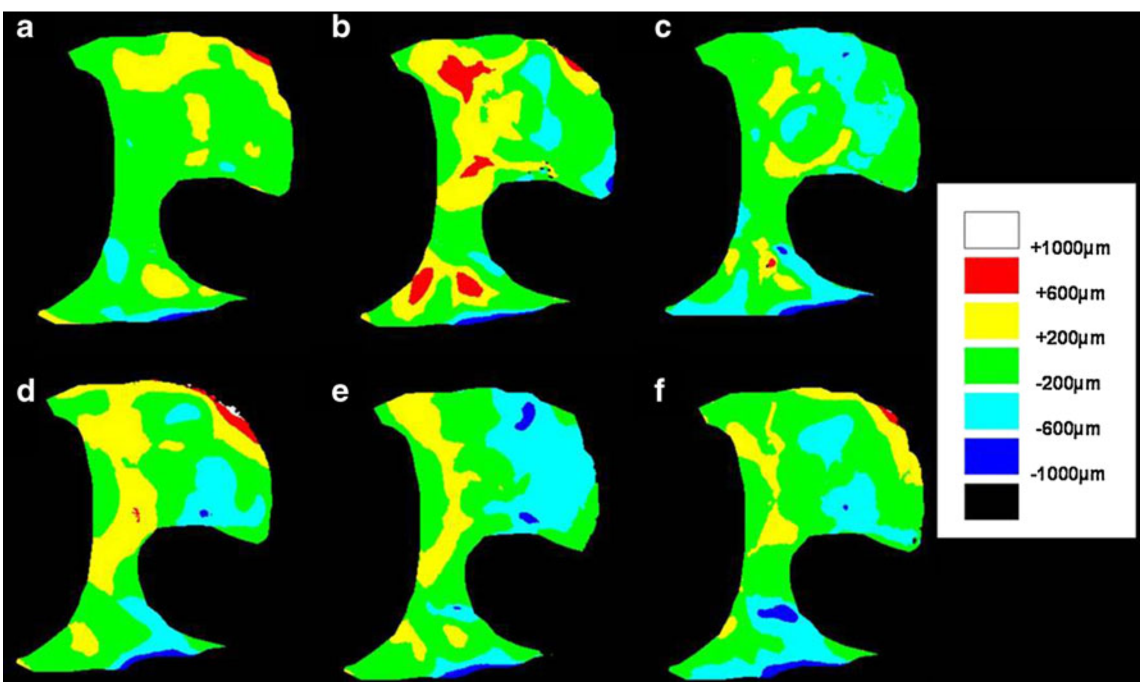

Fig. 3 Case 4: difference images displaying color-marked local 3D-distances. **a** Between original surface and virtual CAD reconstruction and **b–f** original surface and wax-up by dental technicians; *green* = low differences, *red*, or *blue* = high differences

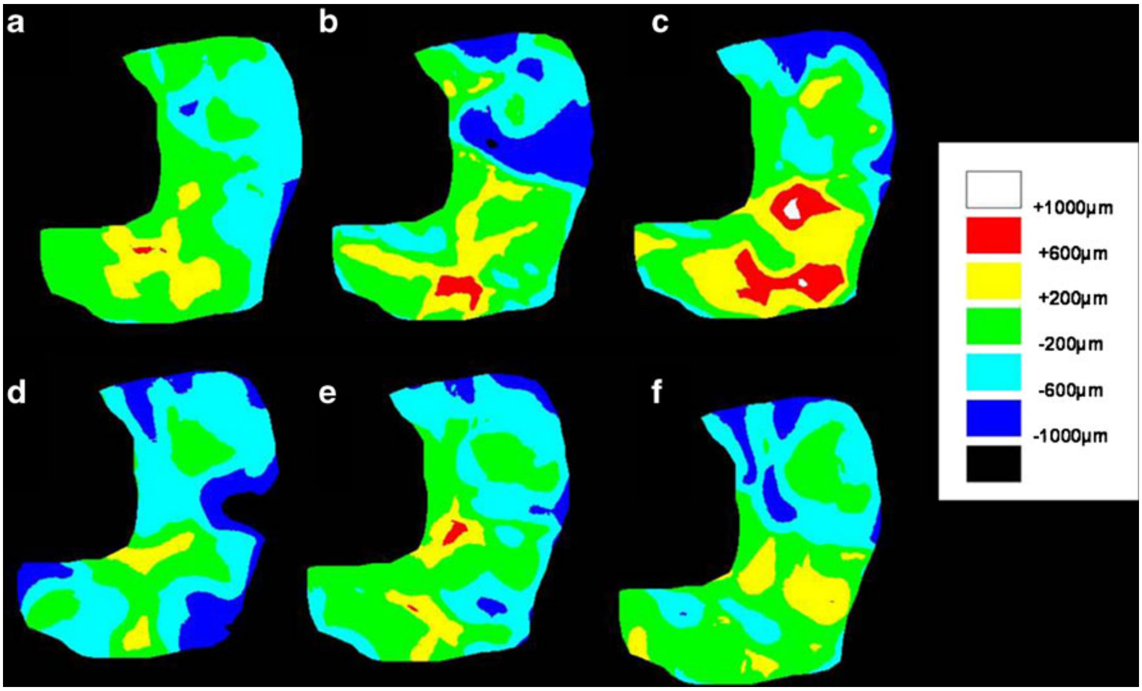

Fig. 4 Case 2: difference images displaying color-marked local 3D-distances. **a** Between original surface and virtual CAD reconstruction and **b–f** original surface and wax-up by dental technicians; *green* = low differences, *red*, or *blue* = high differences

this measure, (a) similarities between computer-based reconstructions and corresponding natural tooth forms (n=5, group A, subgroup 1) and (b) similarities between reconstructions made by the technicians and corresponding natural tooth forms (n=25, group B or n=5 for each technician, subgroups 2–6) were calculated.

Statistical analysis

Statistical analysis was performed with SPSS 14.0 unless otherwise stated. All significant differences were detected at a 95 % confidence level. The following null hypothesis was to be tested by student t test: there is no statistically significant difference concerning the shape similarity measure between samples group A (computer-based reconstructions matched to natural teeth) and group B (dental technician-based reconstructions matched to natural teeth). Before starting the experiments, power analysis was done with G*Power Version 3.1.0 computer program [20]. Data about relevant difference between the two sample groups A and B and about estimated standard deviations were drawn from a preliminary study [21]. Setting the α level at 5 %, five samples in group A and 25 samples in group B were needed to have at least an 80 % statistical power. Subgroup SSV means of CAD-reconstructed surfaces (subgroup 1) and surfaces reconstructed by each single technician (subgroups 2–6) were analyzed by one-way ANOVA with post hoc LSD test.

Results

At first view, it is obvious that reconstructions based on the same original surface considerably differ from each other (Fig. 2). Figures 3 and 4 show the difference images for two cases.

The mean shape similarity value of reconstructions made by the technicians was 310.2 (±78.8) µm. The mean shape similarity value of the CAD reconstructions (biogeneric model) was 222.0 (±47.7) µm (Fig. 5). Only in three of 25

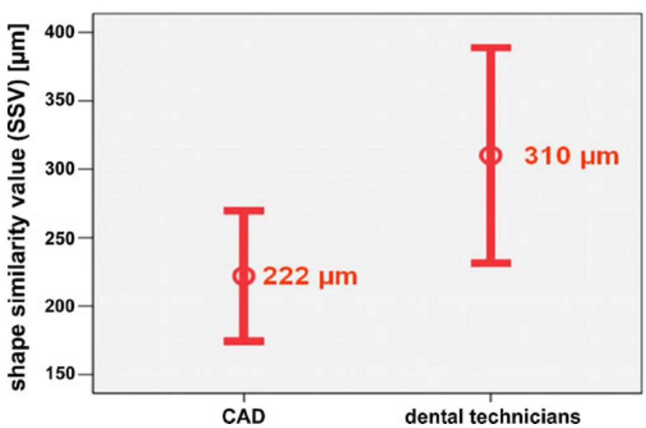

Fig. 5 *Error bars* displaying mean shape similarity value (micometer) and standard deviation of comparisons. **a** Between original surfaces and corresponding virtual CAD reconstructions. **b** Between original surfaces and wax-up models by dental technicians

samples of the reconstruction made by the technicians showed a lower value of the SSV than the reconstruction made by the CAD software (Fig. 6). In case 2, technician number 3, and in case 5, technician number 2 and 4 were able to design more natural tooth morphology according to the SSV. Calculated values of the volume between two compared surfaces are shown in the graph (Fig. 6).

Based on the 95 % confidence level, the null hypothesis was rejected. Hence, based on the SSV, computer-based reconstructions were considered to be significantly more similar to the original occlusal surface than the reconstructions made by the technicians ($p<0.05$). Mean SSV difference was 88.16 μm, and 95 % confidence interval of the difference was 12.72 μm and 163.60 μm in particular. Comparing the different single group means of SSV, a higher diversity was shown: CAD reconstructions were significantly more similar to the original morphology than conventional reconstructions made by dental technicians 1 and 3. However, technician numbers 2, 4, and 5 showed no significant difference compared to the CAD group.

Discussion

Length measurement and descriptive characterization are the only references for comparing the morphology of occlusal surfaces [22–26]. However, linear metrical parameters are not suitable for the comparison of complex 3-dimensional structures like teeth. Other literature dealing with occlusal morphology or wax-up techniques are solely descriptions of occlusal surface features with different weighting of these features [27–29]. A visual comparison of manufactured tooth surfaces is therefore highly dependent upon our experience and imagination, thus leading to irreproducible evaluations. Hence, an objective measure that is able to display similarities/dissimilarities of different occlusal surfaces was required for this study. By means of the SSV, no reference points have to be set. This way of comparing tooth forms is technically robust and allows standardized and reproducible morphological comparisons. Contrary to calculating the standard deviation [14], the SSV includes the deviations in a linear way and therefore does not overestimate outliers with quadratic terms. This reduces errors, which may arise from differences on steep inclines or measurement errors made by optical scanners. A limitation of the measure is the problem that only an average value is calculated. This measure does not metrically indicate, which areas of two surfaces are coincident or different.

The final results of this study, based on the used similarity measure SSV, approved our alternative hypothesis. In case of an inlay/onlay situation, the fully automatic biogeneric tooth model was able to reconstruct missing areas of the occlusal morphology more naturally than well-trained dental technicians. This means that one of the key points in oral rehabilitation, the adaptation of a dental restoration to the surrounding tooth structures, can be achieved by a fully automatic dental CAD program. Higher SSV variances of the occlusal surfaces waxed up by the dental technicians reflect the individuality of wax-up patterns. Nevertheless, in some single cases, it is certainly possible that a conventional reconstruction can produce a more natural tooth form.

The tested biogeneric CAD program is obviously able to provide fully automatic design for the manufacturing of partial crowns with a natural occlusal morphology. This confirms a recent study of Ender et al. [16], which assessed the naturalness of fully automated occlusal design by subjective visual ratings of dental experts. These ratings are based on a detailed questionnaire, asking for certain features of tooth morphology like fissures and cusps. In contrast, by means of an objective similarity measure, this study compares each reconstruction with the original tooth surface in pairwise comparisons. Additionally, complete groups of CAD reconstructions and conventional reconstructions were compared as well. As a result, this study contributes objective and reproducible metric data to the debate about the effectiveness of fully automated occlusal

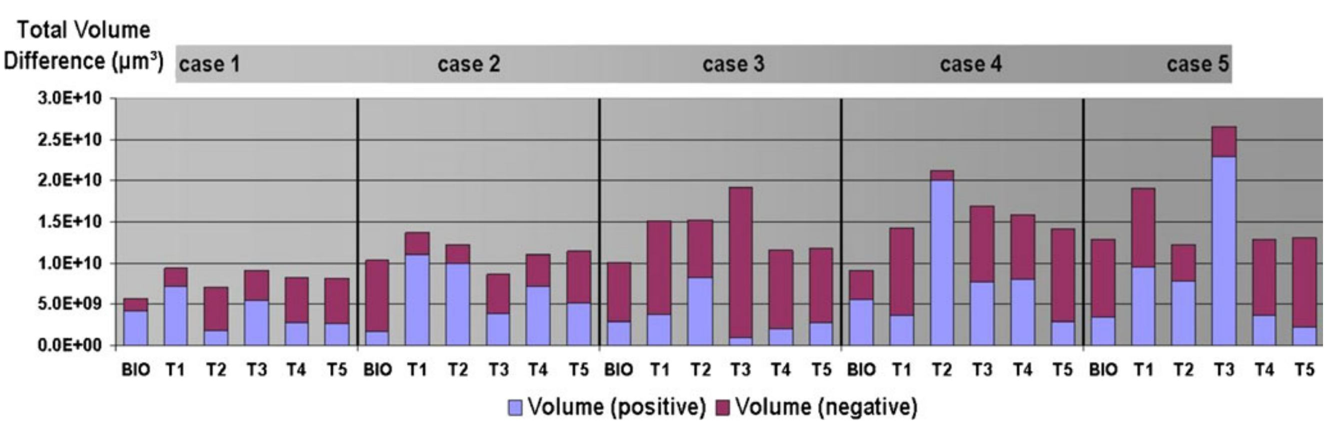

Fig. 6 *Cases 1–5* volumetric deviations in comparisons of original surfaces with corresponding virtual CAD reconstructions (biogeneric model, *BIO*) and wax-up models by dental technicians 1–5 (*T1–5*)

design. However, direct information on the esthetical fit of the reconstructed crowns as demanded by experts [16, 30] is not provided. A further limitation of this study is that proximal, buccal, and oral surfaces were not taken into consideration. Besides this, a point of critique could be that functional aspects are not explicitly assessed.

A recent study of Ellerbrock and Kordaß [31] also analyzed whether computer-generated occlusal surfaces are equivalent with those waxed up by experienced dental technicians. Similar methods (similarity measure) for comparing occlusal surfaces were utilized. It was concluded that comparable occlusal surfaces can be achieved by computer-aided design. Nevertheless, the occlusal surfaces generated in that study were not referenced to the original surface.

In conclusion, it could be demonstrated that, within the limitations of this study, a fully automatic CAD system can be at least as good as conventional wax-ups made by dental technicians with regard to the design of naturally shaped occlusal inlay/onlay surfaces. In the future, the automatic design of complete single and multiple tooth restorations could become possible. Algorithms that can derive the morphology of a tooth from the shape of its neighboring and antagonistic teeth are necessary. Numerous benefits associated with CAD/CAM-generated dental restorations, such as cost-effective production and increase in quality and reproducibility [5, 6], may also be transferred to even larger reconstructions.

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

References

1. Türp JC, Greene CS, Strub JR (2008) Dental occlusion: a critical reflection on past, present and future concepts. J Oral Rehabil 35:446–453
2. Neff P (1995) Trauma from occlusion. Restorative concerns. Dent Clin N Am 39:335–354
3. Wiskott HW, Belser UC (1995) A rationale for a simplified occlusal design in restorative dentistry: historical review and clinical guidelines. J Prosthet Dent 73:169–183
4. Tinschert J, Natt G, Hassenpflug S, Spiekermann H (2004) Status of current CAD/CAM technology in dental medicine. Int J Comput Dent 7:25–45
5. Strub JR, Rekow ED, Witkowski S (2006) Computer-aided design and fabrication of dental restorations: current systems and future possibilities. J Am Dent Assoc 137:1289–1296
6. Beuer F, Schweiger J, Edelhoff D (2008) Digital dentistry: an overview of recent developments for CAD/CAM generated restorations. Br Dent J204:505–511
7. Jedynakiewicz NM, Martin N (2001) Functionally generated pathway theory, application and development in Cerec restorations. Int J Comput Dent 4:25–36
8. Fasbinder DJ (2006) Clinical performance of chairside Cad/Cam restorations. J Am Dent Assoc 137(Suppl):22S–31S
9. Reich S, Troeltzsch M, Denekas WM (2004) Generation of functional Cerec 3D occlusal surfaces: a comparison of two production methods relevant in practice. Int J Comput Dent 7:229–238
10. Reich S, Wichmann M, Burgel P (2005) The self-adjusting crown (Sac). Int J Comput Dent 8:47–58
11. Hartung F, Kordass B (2006) Comparison of the contact surface pattern between virtual and milled Cerec 3D full-ceramic crowns. Int J Comput Dent 9:129–136
12. Mehl A, Blanz V, Hickel R (2005) A new mathematical process for the calculation of average forms of teeth. J Prosthet Dent 94:561–566
13. Mehl A, Blanz V, Hickel R (2005) Biogeneric tooth: a new mathematical representation for tooth morphology in lower first molars. Eur J Oral Sci 113:333–340
14. Richter J, Mehl A (2006) Evaluation for the fully automatic inlay reconstruction by means of the biogeneric tooth model. Int J Comput Dent 9:101–111
15. Dunn M (2007) Biogeneric and user-friendly: the Cerec 3D software upgrade V3.00. Int J Comput Dent 10:109–117
16. Ender A, Mörmann WH, Mehl A (2011) Efficiency of a mathematical model in generating CAD/CAM-partial crowns with natural tooth morphology. Clin Oral Investig 15:283–289
17. Mehl A, Gloger W, Hickel R (1997) Erzeugung von CAD-Datensätzen für Inlays und Kronen mit funktionellen Kauflächen. Dtsch Zahnärztl Z 52:520–524
18. Reiss B (2007) Cerec standard 3-D occlusal contouring in comparison with the new biogeneric occlusal morphing: a case report. Int J Comput Dent 10:69–75
19. Mehl A, Gloger W, Kunzelmann KH, Hickel R (1997) A new optical 3-D device for the detection of wear. J Dent Res 76:1799–1807
20. Faul F, Erdfelder E, Lang A-G, Buchner A (2007) G*Power 3: a flexible statistical power analysis for the social, behavioral, and biomedical sciences. Behav Res Methods 39:175–191
21. Litzenburger A (2007) Parametrisierung unbekannter Zahnoberflächen mittels des biogenerischen Zahnmodells, Dissertation, University of Munich (LMU)
22. Kieser JA (1990) Measurement of tooth size. In: Kieser JA (ed) Human adult odontometrics. Cambridge University Press, Cambridge, pp 4–14
23. Ash MM (1993) Wheeler's dental anatomy, physiology and occlusion. W.B. Saunders Co., Philadelphia
24. Hattab FN, Al-Khateeb S, Sultan I (1996) Mesiodistal crown diameters of permanent teeth in Jordanians. Arch Oral Biol 41:641–645
25. Otuyemi OD, Noar JH (1996) A comparison of crown size dimensions of the permanent teeth in a Nigerian and a British population. Eur J Orthod 18:623–628
26. Ferrario VF, Sforza C, Tartaglia GM, Colombo A, Serrao G (1999) Size and shape of human first permanent molar: a Fourier analysis of the occlusal and equatorial outlines. Am J Phys Anthropol 108:281–294
27. Kitagawa Y, Manabe Y, Oyamada J, Rokutanda A (1996) Morphological and anthropological aspects of human triangular deciduous lower first molar teeth. Arch Oral Biol 141:387–391
28. Scott GR, Turner CG (2000) The anthropology of modern human teeth: dental morphology and its variation in recent human populations. Cambridge University Press, Cambridge
29. Harris EF, Potter RH, Lin J (2001) Secular trend in tooth size in urban Chinese assessed from two-generation family data. Am J Phys Anthropol 115:312–318
30. Probst FA, Mehl A (2008) CAD reconstruction using contralateral mirrored anterior teeth: a 3-dimensional metric and visual evaluation. Int J Prosthodont 21:521–523
31. Ellerbrock C, Kordass B (2011) Comparison of computer generated occlusal surfaces with functionally waxed-on surfaces. Int J Comput Dent 14:23–31