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Different Aspects of the Digital Workflow

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High-accuracy digital model design for full crown tooth preparation

Abstract

Aim: Precise tooth preparation is necessary for successful restorative treatments. In the narrow oral space, achieving such precision with traditional manual operation is impeded by visual deviation, human eye blind zones, and hand-orientation errors. To overcome these drawbacks, a mini-robotic system for tooth preparation was developed to manipulate an ultra-short-pulse laser beam for the automatic shaping of a target tooth into a prepared tooth. Automatic tooth preparation is based on three-dimensional (3D) data. The present study was conducted to investigate the basic principles for digitally designing full crown tooth preparations and to quantitatively evaluate the associated design precision.

Materials and methods: Cone beam computed tomography (CBCT) and dental model surface scan data were obtained from 20 volunteers. Using these data, a complete and systematic process for the digital design of full crown tooth preparations was conducted. The study included 40 cases with two design types. Software-derived measurements of prepared occlusal thickness, shoulder width, and axial convergence angle were compared with the design preparation data.

Results: The design precision for shoulder width exceeded that for occlusal ablation depth, which exceeded that for axial convergence angle. One-way ANOVA analysis results confirmed no significant differences in the design precision of full crown preparations with different tooth morphologies, and the independent samples *t* test results showed no significant difference among the design standards. The mean errors for occlusal ablation depth, shoulder width, and axial convergence angle were 0.0096 ± 0.0108 mm, 0.0006 ± 0.0004 mm, and 0.1201 ± 0.1288 degrees, respectively.

Conclusion: The design route of the full crown computer-aided design (CAD) software reported on in this article is highly feasible and accurate.

Keywords: *digital model, computer-aided design, accuracy evaluation, restorative treatment, teeth morphologies, tooth preparation*

Introduction

Dental defects are common in dentistry. The traditional restoration of dental defects requires tooth preparation, which is a destructive treatment process that requires the grinding of dental hard tissue using various high-speed turbine-driven drills with diamond or tungsten steel burs. This allows the defective tooth to be shaped into a prepared tooth with specific morphology.[1] Precise tooth preparation is necessary for the success of restorative treatments as it not only facilitates the appropriate three-dimensional (3D) space to accommodate different fillings and restorations in the dental hard tissue, but also satisfies the mechanical, retentive, supportive, and esthetic requirements of the treatment. Thus, it fundamentally reduces the probability of secondary iatrogenic diseases, including secondary caries, tooth fracture, gingival and periodontal injury, and even tooth removal.[2]

Two methods are currently typically used in clinical tooth preparation, namely grinding using turbine-driven drills, and ablation by erbium-doped yttrium aluminum garnet (Er:YAG) or erbium and chromium-doped yttrium scandium gallium garnet (Er,Cr:YSGG) handheld laser systems. These two methods not only have poor accuracy and efficiency but also generate mechanical and thermal stress as well as create microcracks of several tens of micrometers in the enamel.[3,4] Therefore, in order to overcome the drawbacks of these traditional tooth preparation methods, a mini-robotic system for tooth preparation was developed that can manipulate an ultra-short-pulse laser beam to shape a target tooth for preparation. Compared with the methods currently used in dental clinics, the advantages of this method include higher precision and efficiency as well as less mechanical and thermal damage. In addition, the surfaces are better prepared without significant traces of melting, deformation or cracking.[5]

Precise tooth preparation design is crucial and is the first step in the process of automated tooth preparation. Tooth preparation should follow some basic design principles. First, the tooth preparation design determines the amount of tooth structure removal. Conservation of sound tooth structure helps to preserve tooth vitality and reduce complex dentin-pulp injury. Edelhoff and Sorenson[6,7] introduced a comprehensive classification system for tooth preparation design to quantify the amount of tooth structure removed during both innovative and conventional preparations in order to maximize the preservation of sound tooth structure. Second, tooth preparation design plays an important role in the stability and fracture resistance of some artificial restorations.[6,7] El Salam Shakal et al[8] indicated that tooth preparation design strongly influenced the bonding strength of resin-bonded fixed partial dentures. In an *in vitro* study, it was reported that a 0.5-mm axial chamfer tooth preparation was equivalent to a 1-mm preparation with regard to the stability and fracture resistance of posterior metal-free Artglass crowns.[9] Third, the design of the tooth preparation convergence angle had a significant effect on the applicability of restorations. Corazza et al[10] performed finite element analysis (FEA) to analyze the influence of convergence angle design on the stress distribution of all-ceramic full crowns, conducted compressive testing to register the load to fracture, and reported that crown performances were best when the mesiodistal convergence angle was 20 degrees. The applicability of restorations also includes their retention properties. Chan et al[11] studied the relationship between retention and the marginal seating discrepancy of complete veneer crowns with various preparation convergence designs. These authors concluded that the optimal retention and minimum discrepancy of a complete veneer crown can be obtained with tooth preparation convergence angles between 2 and 20 degrees. In summary, tooth preparation design has an important impact on the retention and stability of the prosthesis and the health of the natural teeth. To this end, some researchers have assessed the design of tooth preparations for different types of dental restorations. Goodacre et al[12] developed nine scientific principles of tooth preparation to ensure the mechanical, biological, and esthetic success of tooth preparations for full crown restorations.

Tooth preparation design is currently performed by dentists, who devise the 3D shape of the tooth preparation themselves based on prosthodontics textbooks, clinical experience, and theoretical knowledge. However, in this approach, the intended tooth preparation design in the dentist's mind cannot be used as input data for an automated tooth preparation system. Computer-aided design (CAD) of tooth preparations can solve this problem by providing the precise 3D data required for creating a tooth preparation. It may simultaneously promote communication between patients and dentists or between dental technicians and dentists. Furthermore, increasing numbers of educators are training dental interns and students. CAD tooth preparation will help to establish an evaluation standard for use during training.

Based on the above considerations, two commercial reverse engineering software packages, Geomagic Studio (3D Systems Inc., Rock Hill, SC, USA) and Imageware (Siemens PLM Software, Berlin, Germany), were used to preliminarily explore the CAD method for tooth preparation.[13] On this basis, a set of CAD software was developed by the present authors for full crown tooth preparation. In the current study, the principles and processes involved in the digital design of full crown tooth preparation were investigated and its design accuracy quantitatively evaluated.

Materials and methods

Experimental subject selection

Twenty subjects with complete mandibular dentition and complete tooth crowns were selected to participate in the study from July 2016 to January 2017. The study was approved by the Bioethics Committee of the Stomatological Hospital of Peking University (Beijing, China; No. PKUSSIRB-201627042; Date: 27/06/2016). All of the experimental protocols and procedures were approved by the licensing committee and performed in accordance with the approved guidelines and regulations. The subjects were informed of the objective of the study, and informed consent was obtained from all of the subjects.

Acquisition of cone beam computed tomography 3D reconstruction and dental model scan data

Polyether impression material (3M Impregum; Minnesota, USA) was used to obtain the participants' maxillary and mandibular impressions. Superhard plaster (Heraeus Kulzer, Hanau, Germany) was injected to form the plaster cast. A dental model 3D scanner (Smart Optics Activity 880; Ruhrgebiet, Germany) was selected to acquire 3D data from the maxillary and mandibular plaster casts of the 20 volunteers. The data were stored as stereolithography (STL) files. Cone beam computed tomography (CBCT) (NewTom VG, Verona, Italy) was then used to acquire the two-dimensional (2D) digital imaging and communication (DICOM) scan data from the maxillae and mandibles of the 20 volunteers. Triangulated mesh model reconstruction of the mandibular scan data was then performed using medical image processing software (Mimics 17.0; Leuven, Belgium). The 3D data of the mandibular first molar were segmented and stored as STL files (Fig 1).

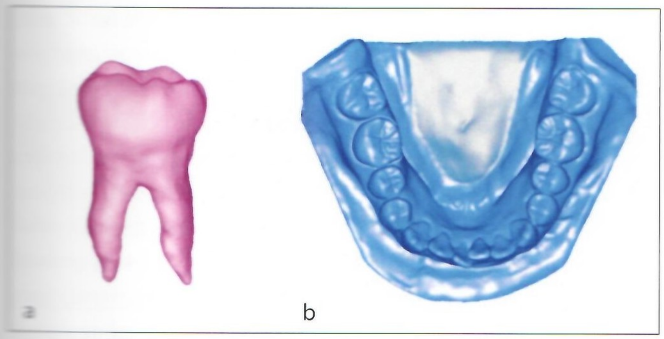

Fig 1 Triangle mesh reconstruction results. (a) Three-dimensional (3D) model of computed tomography (CT) reconstruction for the mandibular first molar. (b) 3D model of the complete dentition acquired via a dental model scan.

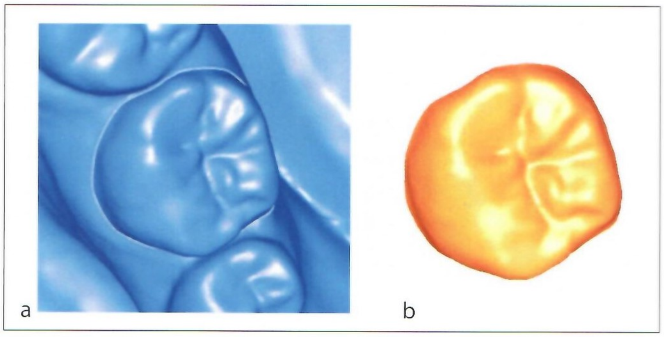

Fig 2 Extraction of crown data from mandibular first molar. (a) Extraction of gingival margin. (b) Extracted crown.

Computed tomography data based on iterative deformation and fusion with dental model scan data

The dental model scan data were imported into self-developed full crown preparation CAD software. A gingival margin extraction algorithm based on a heuristic search strategy – see equation (1) below – was applied to crop and extract the crown surface data of the mandibular first molar from the dental model scan data (Fig 2):

$$f(n) = w_a f_{dir1} + w_b f_D + w_c f_{dir2} + w_d f_C \quad (1)$$

where $f(n)$ is the evaluation function, w_d, w_a are the weight functions, f_C is the curvature function, f_D is the distance function, and f_{dir} is the direction function.

The 3D computed tomography (CT) reconstruction mandibular first molar data was imported into the full crown preparation CAD software. As the CT and dental model scan data were not in the same coordinate system during data acquisition, interactive picking was first applied to select four corresponding non-collinear points from the 3D data of the mandibular first molar and the crown data of the mandibular first molar extracted from the dental model scan data. Initial registration of the two datasets was then achieved through alignment of feature points (Fig 3), followed by the implementation of the iterative closest point (ICP) on the registered data to achieve precise matching of the multisource data (Fig 4).

The deformable surface model of CT-acquired mandibular first molar reconstruction data was transformed from Cartesian to Laplacian coordinates. The correspondence between

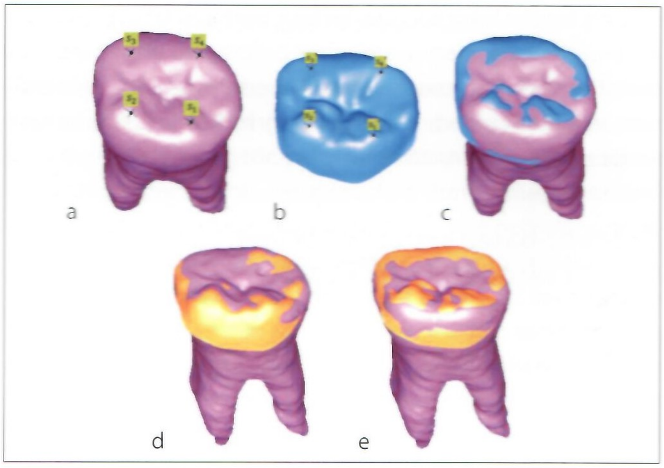

Fig 3 Initial registration and precision matching of CT reconstruction 3D data of mandibular first molar and extracted crown data of mandibular first molar. (a) Selection of CT model feature points. (b) Selection of scan model feature points. (c) Results of initial registration. (d) Iteration process. (e) Iteration results.

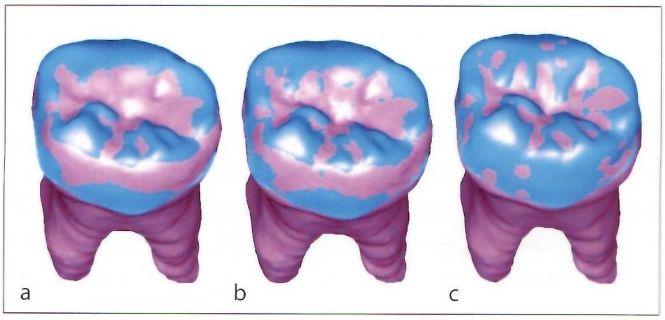

Fig 4 Fusion of iterative deformation.

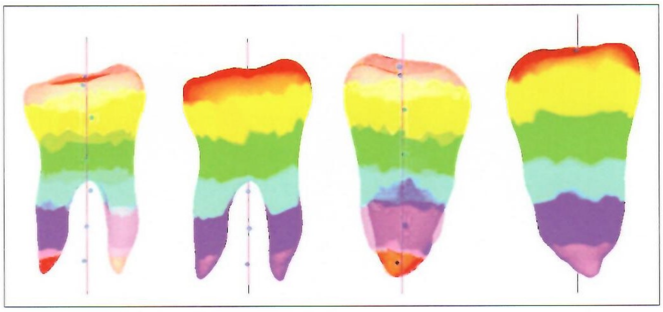

Fig 5 Stratified center fitting of the long axis.

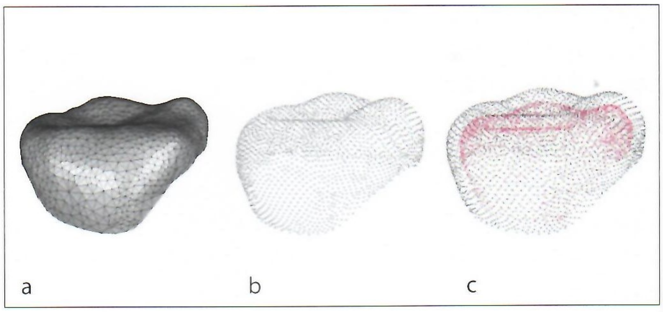

Fig 6 Offsetting process of the crown model. (a) Tooth mesh model. (b) Model point cloud representation. (c) Effect after offsetting.

the deformable and fixed surfaces was then used to establish the constraints required for deformation. Lastly, through the solving for the least squares system, and based on the invariance of the Laplacian coordinates before and after deformation, the Cartesian coordinates of the surface after deformation were obtained, thus yielding high-precision crown surface CT reconstruction data.

Geodesic-based extraction of long axis of tooth from CT reconstruction model

A single point on the crown was selected as the geodesic origin. The geodesic distances of all points on the model from the geodesic origin were then calculated, and all were labeled with these values. The values were then normalized, and the range of geodesic length was divided into several intervals. The points within each interval were grouped together to achieve model stratification. Lastly, the center of each layer in the model was obtained, and spatial linear fitting was applied to fit the center of each layer to a spatial line passing through the midpoint of the model, thus extracting the long axis (Fig 5).

Parametric design of full crown preparation

Acquisition of clinical crown 3D data

Using the gingival margin extraction algorithm based on a heuristic search strategy, the gingival feature points selected through manual interactive picking were connected into a line, followed by the separation of the mandibular first molar model reconstructed using fused CT data. This process yielded the clinical crown and root 3D data. When cropping, the intersecting line between the gingival margin and the mesh model was first calculated, then the intersecting line was transformed into an edge in the triangle mesh and added to the mesh. Lastly, the model was segmented along the cropping line, and the mesh on both sides of the intersecting line was triangulated to complete the cropping of the crown model.

Generation of shoulder of preparation

The CAD software uses a model offset algorithm based on the classification of feature point sets to perform parametric model offsetting in order to generate the geometric features of the shoulder. This process involves four steps: (1) Data preprocessing: the clinical crown 3D data to be offset are preprocessed in accordance with their mesh conditions to obtain a uniform manifold mesh model. (2) Feature classification is performed on the mesh point sets, where the model points are classified according to the corresponding geometric entity features into surface, edge, and point feature point sets. (3) Point offsetting is performed for different classes of feature point sets, using different offset algorithms to generate the offset point set. (4) Voxel-based model representation is used for interior point filtering, and the interior points are labelled by determining the class of the topological boundary point. Points labeled as the interior are removed, and mesh triangulation is performed to generate the offset crown mesh model.

This process is shown in Fig 6. The offset distance was set as the shoulder width distance to complete the parametric offset, then the gap between the offset clinical crown 3D data and the clinical root 3D data was stitched together to generate the shoulder plane.

A hole-filling technique for mesh models was used when stitching the gap in the model. This study employed a hole-filling method based on the variational implicit surface approach to generate the shoulder. Specifically, by picking points on the boundary and the directions of their normal vectors, a surface was constructed based on variational implicit functions, on which triangulation was performed. The original boundary points were then projected onto the curved mesh and cropped. Lastly, the cropped mesh and original mesh were stitched together to complete the hole-filling process. The stitching procedure included the following three steps: (1) Obtaining the interpolation and normal constraints. (2) Establishing variational implicit surface function for mesh processing of the surface. (3) Cropping and stitching of the surface. At this point, the stitching of annular holes was complete, and a 3D model of the preparation shoulder was generated.

Generation of occlusal surface of preparation

A model offset algorithm was applied to offset the occlusal surface of the clinical crown model by a specified distance to generate the occlusal surface of the preparation that satisfied the constraints. As the occlusal surface of the preparation did not require prominent grooves, fossa, ridges, pits or other surface features of the original occlusal surface, the offset surface was smoothed. When cropping the offset crown surface to generate the occlusal surface after preparation, an algorithm for cropping and projecting the margin was applied to confirm the occlusal boundary of the prepared tooth. Fig 7 shows a schematic diagram of the process.

First, a point on the inner margin of the shoulder model, A, was selected and offset by distance Δl along the direction perpendicular to the long axis. This offset point was projected along the direction parallel to the long axis to intersect with the crown surface at point A'. Angle α' between straight line A to A' and the long axis was measured and compared with 1/2 the standard convergence angle α. If angle α' was smaller than the standard convergence angle, then the offset distance Δl was increased and a line was projected again to solve for the angle. If angle α' was larger than the standard convergence angle, then the offset distance Δl was decreased, and this iteration was used as the projection line to solve for the angle. The increase in the occlusal convergence angle with the offset distance Δl is linear, and its minimum value is smaller than the convergence angle at the initial position. Hence, there must be a corresponding point for a given convergence angle. All points on the crown corresponding to the boundary points of the shoulder were solved in succession. The corresponding points were joined together, and the crown was cropped to generate the occlusal surface of the tooth preparation.

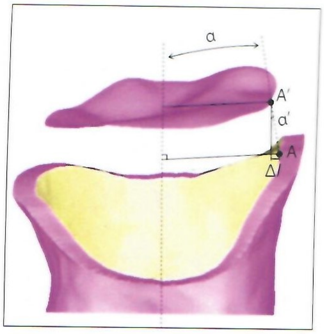

Fig 7 Schematic diagram of the generation of the occlusal surface of the preparation.

Fig 8 Generation of the tooth preparation.

Generation of axial surface of preparation

The axial surface of the preparation was the oblique lateral wall of the preparation model, and the degree of occlusion was the main geometric constraint. As the requirements for the convergence angle were satisfied during the generation of the occlusal surface, the boundary of the occlusal surface could be stitched to the inner margin of the shoulder to generate the axial surface of the preparation that satisfied the requirements of the convergence angle. The stitching procedure of the axial surface is similar to that for shoulder hole-filling. By interpolating along the direction of convergence and constructing bands of triangular patches, the gaps between the occlusal surface and shoulder were stitched together in succession until a smooth transition was achieved for the surfaces of the two models. At this point, the 3D model of the axial surface of the preparation was complete (Fig 8).

Parameter evaluation of full crown preparation

Parameter evaluation of the tooth preparation was mainly based on three indicators: thickness of the occlusal surface, shoulder width, and occlusal convergence angle. This process involved the following four steps: (1) 3D models of the crown before and after preparation and of the tooth preparation were imported. (2) The inner margin of the shoulder of the preparation model was extracted in order to extract the long axis of the tooth. (3) A line was projected along the long axis toward the occlusal surface, and the preparation thickness passing through the occlusal surface of the model before and after preparation was evaluated. (4) The long axis of the tooth

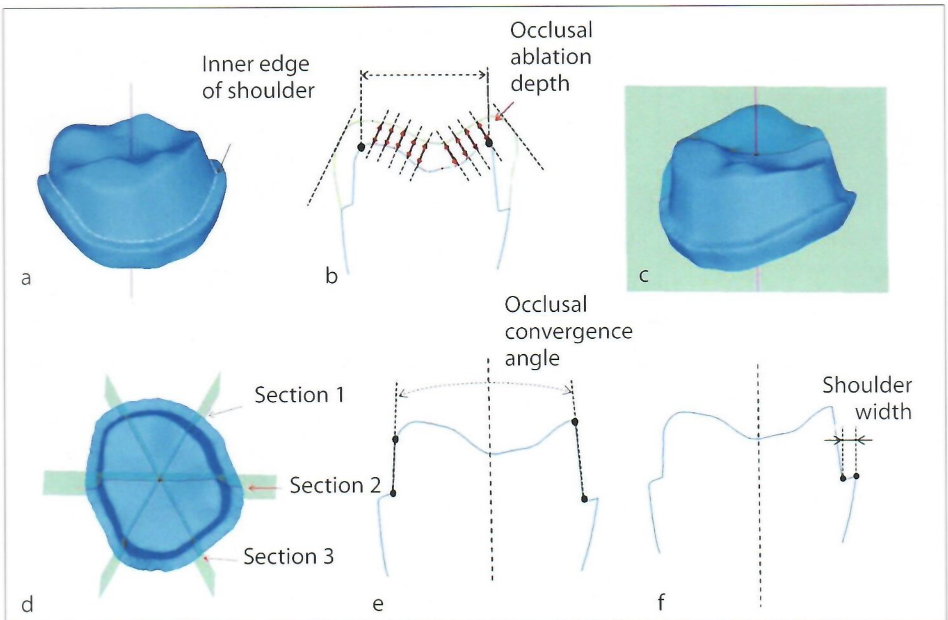

Fig 9 Parametric evaluation of the full crown preparation. (a) Extraction of the long axis of the tooth from the preparation model. (b) Measurement of occlusal ablation depth. (c) Schematic diagram of a single cross-section of the preparation. (d) Schematic diagram of cross-sectional distribution in the preparation. (e) Measurement of the occlusal convergence angle. (f) Measurement of shoulder width.

was considered as the model cross-section, and the shoulder width and occlusal convergence angle were measured in the cross-sectional view.

Extraction of long axis of tooth from preparation model

First, the inner margin of the shoulder of the preparation model was extracted manually. The normal vectors of all lines connecting the curve points with the center were then integrated. Figure 9a shows the extraction of the long axis of the tooth from the preparation model.

Parameter measurement of occlusal ablation depth

The distance between the two occlusal surfaces along the long axis of the tooth was obtained. Through uniform sampling on the occlusal surface, the projection line was used to derive the sampling points along the long axis of the tooth. Thus, the distance between the projection line and the intersection of the two models was the size of the occlusal ablation depth. Figure 9b is a schematic diagram illustrating the measurement of occlusal ablation depth.

Parameter measurement of shoulder width

Three cross-sections were taken at intervals of 60 degrees around the long axis of the tooth preparation model (Fig 9d). The points at which the cross-sectional planes and mesh model intersected were joined to form the cross-sectional line. The feature points of shoulder width were identified on the cross-sectional line, and the distance between the feature points perpendicular to the long axis was measured as the shoulder width. Figure 9f shows the schematic diagram and width measurement of the model cross-section. Two shoulder-width values were measured for each cross-section, and the calculation of the values of the three cross-sections gave a set of shoulder-width data for one model.

Parameter measurement of occlusal convergence angle

Parameter measurement of the occlusal convergence angle was similar to that for shoulder width. In the cross-sectional view of the preparation model, the inner turning points and occlusal boundary feature points of the two shoulders in the model were obtained and connected to form an oblique straight line. The angle between these two lines was then measured as the occlusal convergence angle. The convergence angles obtained from different cross-sections in the same model formed one set of occlusal convergence angles for a particular preparation. Figure 9e is a schematic diagram illustrating the measurement of the occlusal convergence angle.

Via the steps above, measurement data for the occlusal ablation depth, shoulder width, and occlusal convergence angle were obtained from the preparation model. By com-

Table 1 ANOVA of occlusal ablation depth errors with different tooth morphology

	Sum of squares	df	Mean square	F	Sig.
Between groups	0.001	19	0.000	0.644	0.829
Within groups	0.001	20	0.000		
Total	0.001	39			

Table 2 Independent samples *t* test of occlusal ablation depth errors with different design standards

F	Levene's test for equality of variances		*t* test for equality of means				
	Sig.	*t*	df	Sig. (2-tailed)	Mean difference	Std. error difference	
Equal variances assumed	8.115	0.007	-1.471	38	0.150	-0.0027450	0.0018664
Equal variances not assumed			-1.471	28.076	0.152	-0.0027450	0.0018664

Table 3 ANOVA of convergence angle errors with different tooth morphology

	Sum of squares	df	Mean square	F	Sig.
Between groups	0.209	19	0.011	0.913	0.577
Within groups	0.240	20	0.012		
Total	0.449	39			

paring these measurement data with the standard parametric range, the quality of the surgical preparation model was then evaluated.

Results

Forty full crown preparations were designed using self-developed full crown tooth preparation CAD software. Among them, the preparation designs of 20 teeth involved an occlusal ablation depth of 2 mm, a shoulder width of 1 mm, and an axial convergence angle of 6 degrees, whereas the other 20 had an occlusal ablation depth of 1 mm, a shoulder width of 0.5 mm, and an axial convergence angle of 4 degrees. Parametric evaluation via the software indicated that the design precision for occlusal ablation depth was greater than that for shoulder width, which in turn was greater than that for axial convergence angle. The results of one-way ANOVA analysis showed that there were no statistically significant differences between the full crown preparations designed for teeth with different morphologies ($P > 0.05$) (Tables 1, 3, and 5). Moreover, the independent samples *t* test results did not show any statistically significant differences in the design precision of full crown preparations with different design standards ($P > 0.05$) (Tables 2, 4, and 6). Among the 40 full crown preparations, the maximum error values were 0.0890 mm for occlusal ablation depth, approximately 0.0017 mm for shoulder width, and approximately 0.5124 degrees for axial convergence angle. The minimum error values were 0.0001 mm for occlusal ablation depth, approximately 0 mm for shoulder width, and approximately 0.0001 degrees for axial convergence angle. The mean error values were 0.0096 ± 0.0108 mm for occlusal ablation depth, approximately 0.0006 ± 0.0004 mm for shoulder width, and approximately 0.1201 ± 0.1288 degrees for axial convergence angle (Figs 10 to 12).

Table 4 Independent samples *t* test of convergence angle errors with different design standards

F	Levene's test for equality of variances		*t* test for equality of means				
	Sig.	*t*	df	Sig. (2-tailed)	Mean difference	Std. error difference	
Equal variances assumed	0.494	0.486	1.971	38	0.056	0.0645400	0.0327417
Equal variances not assumed			1.971	37.742	0.056	0.0645400	0.0327417

Table 5 ANOVA of shoulder width errors with different tooth morphology

	Sum of squares	df	Mean square	F	Sig.
Between groups	0.000	19	0.000	0.599	0.865
Within groups	0.000	20	0.000		
Total	0.000	39			

Table 6 Independent samples *t* test of shoulder width errors with different design standards

F	Levene's test for equality of variances		*t* test for equality of means				
	Sig.	*t*	df	Sig. (2-tailed)	Mean difference	Std. error difference	
Equal variances assumed	0.390	0.536	-0.792	38	0.433	-0.0000450	0.0000568
Equal variances not assumed			-0.792	37.986	0.433	-0.0000450	0.0000568

Discussion

Tooth preparation is a clinical procedure performed by dentists that involves the quantitative removal and shaping of hard tissue (including physiological and pathological enamel, dentin, and cementum) in a patient's diseased teeth. It is an important component of the process of treating dental hard tissue diseases.

Currently, clinical tooth preparation is often performed using traditional manual methods that have significant shortcomings and deficiencies. The human oral cavity is a challenging operational space that is small (the vertical height of the opening is usually 2.5 to 5.0 cm); semi-closed; presents resistance from labial, buccal, and lingual muscles and soft tissues; has a high demand for complete safety and protection; and is potentially prone to unpredictable movements at any time. Hence, it is inevitable that manually performing a large number of repetitive and laborious yet intricate operations in this space could lead to human visual deviations or errors in controlling hand positioning. This may lead to lower precision and efficiency of clinical tooth preparation, and difficulties in achieving good clinical practices and associated standards. Therefore, both excessive and insufficient tooth preparation are common occurrences that result in clinical tooth preparations with poor precision and low efficiency. This can lead to iatrogenic injuries of the gingival, labial, buccal, or lingual mucosa. In addition, traditional dental drills often produce shrill noise and vibrations that can cause discomfort to patients and dentists.[14-16]

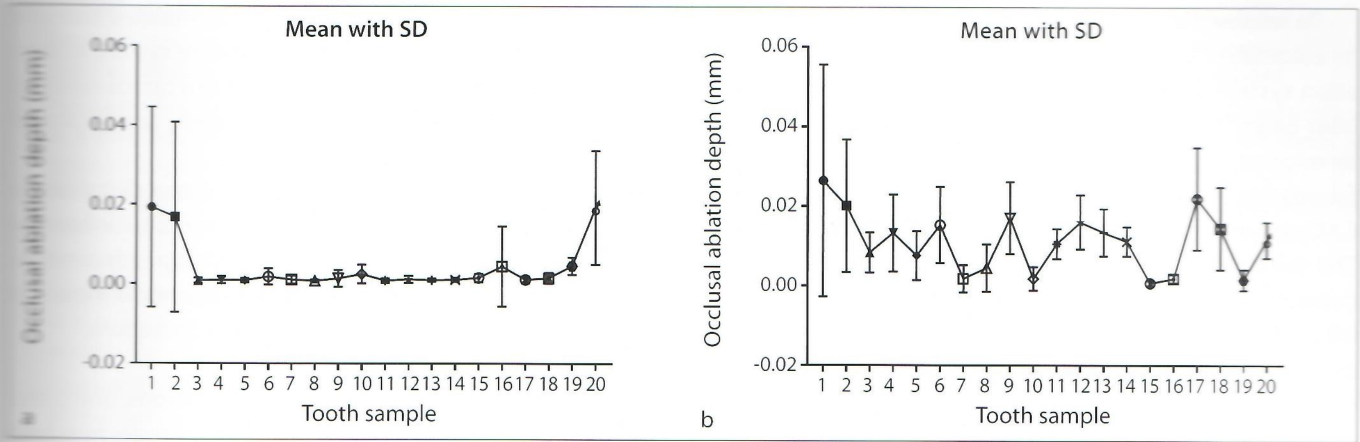

Fig 10 Statistical diagram of the occlusal ablation depth error of 40 tooth samples. (a) The design standard of the occlusal ablation depth was 1 mm. (b) The design standard of the occlusal ablation depth was 2 mm.

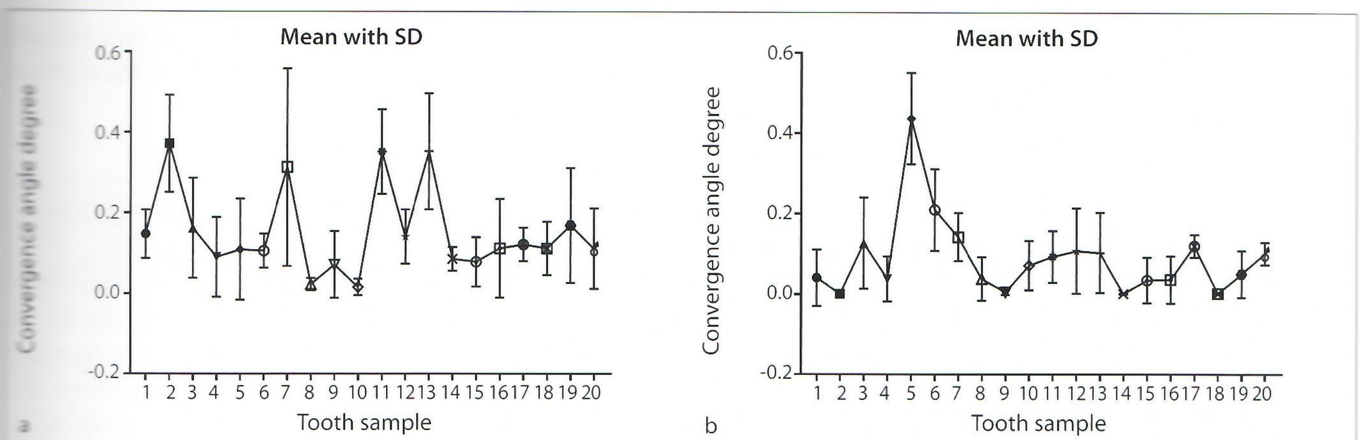

Fig 11 Statistical diagram of the convergence angle degree error of 40 tooth samples. (a) The design standard of the convergence angle degree was 4 degrees. (b) The design standard of the convergence angle degree was 6 degrees.

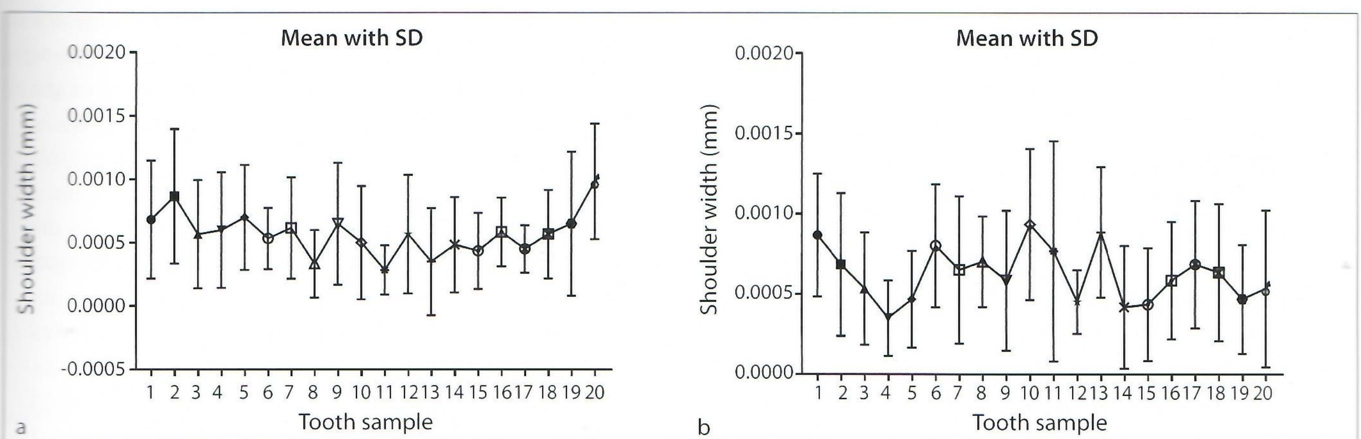

Fig 12 Statistical diagram of the shoulder width error of 40 tooth samples. (a) The design standard of the shoulder width was 0.5 mm. (b) The design standard of the shoulder width was 1 mm.

To resolve the shortcomings of manual tooth preparation, an automated 'oral cavity clinical micro-robotic tooth preparation system with numerically controlled ultra-short pulse laser beam' (a 'tooth preparation robot,' in short) has been developed.[5] Precise and accurate tooth preparation is the foundation of robotic tooth preparation. In the current study, CAD was used to create a precise tooth preparation model. The parametric design of tooth preparation models with complex morphology and multiple constraints was examined. After considering the pros and cons of some common parametric methods and their applicability in different situations, a parametric operational method was developed that is suitable for preparation model design.

Highly precise design work was successfully achieved using the weak constraints of discrete model data. To verify model precision after model design and processing, techniques for the quality evaluation of tooth preparation models were assessed, and specific parameter evaluation algorithms were examined for each constraint index of tooth preparation. Parametric evaluation not only allowed for the evaluation of the preparation precision of specific models, but also provided data facilitating the formulation of quantitative evaluation criteria for tooth preparations. An overall framework for a parametric tooth preparation design system was investigated, which involved analyzing the overall flow and technical routes. Using practical applications in clinical cases, a detailed digital design process of tooth preparation models was developed, and the design capability, precision, and stability of the newly devised software system was verified.

The software has the following features:

1. High degree of automation: The software achieves the parametric and automated design of tooth preparations by applying a tooth preparation-oriented digital design method and formulating individualized treatment plans based on disease types.
2. High precision of the model design: The proposed system incorporates new optical scanning measurements, CAD and computer-aided processing, and a series of other digital technologies to replace the traditional 'visual + manual' clinical mode of operation. The software substantially enhances precision during the tooth preparation stage, elevating preparation precision from the 'millimeter scale' to the 'micrometer scale.'
3. Strong application extensibility: The types of tooth preparations amenable to the system are complex and diverse. In addition to tooth preparations for full crown restorations, the software could also be applied for inlays, veneers, and other forms of tooth preparations. Different modes of preparation design can be formulated based on different dental types. As the software system is completely self-developed, the model design can be modified at any point according to clinical needs, and improved functions can be added.
4. Strong design flexibility: As the system uses a digital design process and supports dynamic modification, further processing is possible after completing design adjustments. The software has strong design flexibility and is more suitable for practical applications in clinical operations.

Currently, the software still has some limitations; one is that multisource fusion technology requires a relatively high level of precision with regard to the initially collected data, ie, high-quality CT and optical scan reconstruction data are needed to achieve results with good precision. Another limitation is that current tooth parametric design modules are still unable to achieve good parametric designs for teeth with severe damage. There is a need for further developments in this area.

Conclusion

The experimental results demonstrated that the design route of the full crown preparation CAD software was feasible. The occlusal ablation depth error could be controlled to within 0.0890 mm, that of shoulder width to within 0.0017 mm, and that of axial convergence angle to within 0.5124 degrees.

Acknowledgments

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Disclaimer

The authors declare no conflicts of interest.

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Hochpräzises digitales Modelldesign für die dentale Vollkronenpräparation

Schlüsselwörter: *Digitalmodell, CAD, Genauigkeitsprüfung, restaurative Behandlung, Zahnmorphologien, Zahnpräparation*

Zusammenfassung

Ziel: Die Voraussetzung für eine erfolgreiche dentale Restauration ist eine präzise Zahnpräparation. In der engen Mundhöhle wird eine derartige Präzision bei der traditionellen händischen Operation durch Sichtbehinderungen, Blindzonen des menschlichen Auges und Fehler bei der händischen Orientierung erschwert. Um diese Einschränkungen zu überwinden, wurde ein Minirobotersystem zur Zahnpräparation entwickelt, das einen Ultrakurzpulslaser bis zum Abschluss der automatisierten Präparation eines Zielzahns steuert. Die automatisierte Zahnpräparation basiert auf dreidimensionalen Daten. In dieser Studie wurden die Grundlagen digitaler Abläufe bei der Vollkronenpräparationen untersucht, außerdem wurde die erzielte Designpräzision quantitativ evaluiert.
Materialien und Methoden: Bei 20 Freiwilligen wurde eine digitale Volumentomografie durchgeführt und die Scandaten eines dentalen Modells erhoben. Anhand dieser Daten wurde ein kompletter systematischer Prozess für ein digitales Design von Vollkronenpräparationen entwickelt. Die Studie wurde mit zwei Designtypen an 40 Fällen durchgeführt. Die von der Software für die präparierte okklusale Dicke, Schulterbreite und den axialen Konvergenzwinkel errechneten Werte wurden mit den Präparationsdaten der Designs verglichen.
Ergebnisse: Das Design der Schulterbreite war präziser als das Design der okklusalen Ablationstiefe und dieses wiederum präziser als dasjenige des axialen Konvergenzwinkels. Die einseitigen ANOVA-Ergebnisse ermittelten bei verschiedenen Zahnmorphologien keine signifikanten Unterschiede in der Designpräzision der Vollkronenpräparationen. Der t-Test für unabhängige Stichproben ergab keine signifikanten Unterschiede zwischen den Designstandards. Der mittlere Fehler betrug für die okklusale Ablationstiefe 0,0096 ± 0,0108 mm, für die Schulterbreite 0,0006 ± 0,0004 mm und für den axialen Konvergenzwinkel 0,1201 ± 0,1288.
Schlussfolgerung: Die Designroute unserer CAD-Software zur Vollkronenpräparation ist sehr praktikabel und präzise.