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3D Evaluation of Accuracy of Tooth Preparation for Laminate Veneers Assisted by Rigid Constraint Guides Printed by Selective Laser Melting

Zhong Yi LI[1], He Fei BAI[1], Yi Jiao ZHAO[1], Yong WANG[1], Hong Qiang YE[2], Yu Chun SUN[1]

Objective: *To design and fabricate 3D-printed rigid constraint guides for the tooth preparation for laminate veneers and to evaluate the accuracy of guide-assisted preparation.*
Methods: *Twenty maxillary right central incisor resin artificial teeth were randomly divided into two equal groups and prepared for laminate veneers. Tooth preparations were performed, assisted by guides in the test group and by depth gauge burs in the control group, and both were finished by freehand operation. The typodonts were 3D scanned before preparation, after initial preparation and after final preparation. The tooth preparation depths at each step, including initial preparation depth, final preparation depth and loss of tooth tissue during polishing, were measured by 3D deviation analysis. Statistical analyses were conducted to investigate differences.*
Results: *The initial preparation depth was 0.488 mm (median, quartile 0.013 mm) in the test group and 0.521 mm (median, quartile 0.013 mm) in the control group. A statistically significant difference was found between them ($P < 0.05$). The final preparation depth in the test group (0.547 ± 0.029 mm) was significantly less than that in the control group (0.599 ± 0.051 mm) ($P < 0.05$), and closer to the predesigned value (0.5 mm). There was no statistically significant difference in the loss of tooth tissue during polishing between the test group (0.072 ± 0.023 mm) and the control group (0.089 ± 0.038 mm) ($P > 0.05$).*
Conclusion: *In maxillary central incisors, the tooth preparation for laminate veneers could be conducted using 3D-printed rigid constraint guides, the accuracy of which is better than that of depth gauge burs.*
Key words: *3D printing, computer-aided design (CAD), dental veneers, guide, tooth preparation*
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A proper and precise tooth preparation is key to successful aesthetic rehabilitation. As a minimally invasive treatment, laminate veneer restoration demands a more precise tooth preparation[1]. Excessive or insufficient tooth preparation for veneers may affect outcomes in many aspects, such as bonding, aesthetics and fracture resistance of the prostheses[2,3].

Brunton et al[4] and Aminian and Brunton[5] found that tooth preparations performed freehand without any depth-indicating equipment or techniques can easily lead to insufficient tooth reduction and the use of depth gauge burs can cause overreduction. Errors greater than 0.1 mm still occur when using loupes or microscopes[6]. Otani et al[7] used an automated robotic system to complete the tooth preparation for laminate veneers. Compared to the conventional method of depth gauge burs, the robotic system showed higher accuracy on margin preparation, but the accuracy of

1 Centre of Digital Dentistry, Department of Prosthodontics, Peking University School and Hospital of Stomatology, National Clinical Research Centre for Oral Diseases, National Engineering Laboratory for Digital and Material Technology of Stomatology, Beijing Key Laboratory of Digital Stomatology, Beijing, P.R. China.
2 Department of Prosthodontics, Peking University School and Hospital of Stomatology. Beijing, P.R. China.

Corresponding authors: Dr Yu Chun SUN, Centre of Digital Dentistry, Department of Prosthodontics, 22# Zhongguancun South Avenue, HaiDian district, Beijing, 100081, P.R. China. Tel: 86-10-82195553; Fax: 86-10-62142111. Email: polarshining@163.com

Dr Hong Qiang YE, Department of Prosthodontics, 22# Zhongguancun South Avenue, HaiDian district, Beijing, 100081, P.R. China. Tel: 86-10-82195370; Fax: 86-10-62142111. Email: yehongqiang@hsc.pku.edu.cn

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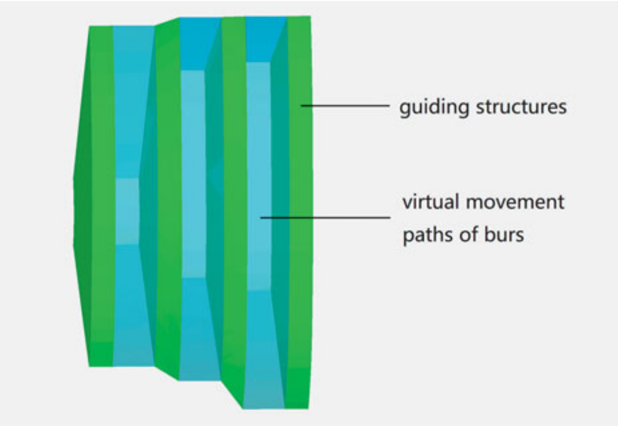

Fig 1 3D images of guiding structures and virtual movement paths of burs.

incisal preparation and the overall stability were not satisfactory.

Passive constraint guidance is one of the tooth preparation guide techniques[8], which can passively control the movement paths and cutting depths of burs. Compared to visual guidance, which only provides operators with visual references, passive constraint guidance can reduce reliance on ability and operator experience by providing physical guidance for cutting instruments. Compared to automated techniques such as robot systems and laser systems[9] which still pose unresolved technical problems, tooth preparation guides are much safer to use intraorally and more acceptable to patients. In addition, the tooth preparation guide technique is relatively low cost and can be individually designed and manufactured chairside. Yu et al[10] introduced the target restoration space (TRS) guide for the accurate preparation of depth-guiding holes to ensure that the depth of the tooth preparation was consistent with the preoperative designed depth. However, the main function of TRS guides is to indicate depth, which means that they cannot constrain the tooth reduction process directly and rigidly. Furthermore, there have been no quantitative evaluations of TRS guides thus far.

The purpose of this study was to design and fabricate a rigid constraint tooth preparation guide which would allow the operators to complete the tooth preparation on the labial side of laminate veneers, and to perform a 3D quantitative evaluation of the accuracy of tooth preparation assisted by the guides. The null hypothesis was that no significant differences would be found in the accuracy of tooth preparation between the group using 3D-printed rigid constraint guides and the group using conventional depth gauge burs.

Materials and methods

Computer-aided design (CAD)/3D printing of rigid constraint tooth preparation guides

A typodont of standard maxillary dentition (D16FE, Nissin Dental Products, Kyoto, Japan) was prepared and scanned by a 3D lab scanner (Activity 880, Smart Optics, Bochum, Germany). The 3D image was exported as a standard tessellation language (STL) file. A cylindroid flat-ended diamond bur (Diatech G835-016, Coltène/Whaledent, Altstätten, Switzerland) was inserted in a high-speed turbine handpiece (Boralina, Bien-Air Dental, Bienne, Switzerland). The length of the exposed part of the bur was measured using a digital caliper (111N-101V-10E, Guilin Guanglu Measuring Instrument, Guilin, China) and recorded as L.

The 3D image of the typodont was imported into Geomagic Studio 2014 (3D Systems, Rock Hill, SC, USA) software. The labial surface of the maxillary right central incisor was selected and offset to the lingual side for 0.5 mm to obtain the virtual prepared teeth for a 0.5-mm thick laminate veneer. The labial surface of the virtual prepared teeth was offset to the labial side for the length L to generate the original guide surface. The 3D images of the virtual prepared teeth and the original guide surface were exported as STL files and then imported into Imageware software (Imageware 13, Siemens PLM Software, Plano, TX, USA). Virtual movement paths of burs and corresponding guide structures were designed, resulting in several paralleled fan-shaped objects (Fig 1). Meanwhile, the retainers for the tooth preparation guides were designed in Geomagic Studio. The 3D images of the tooth preparation guides were created through Boolean operations of the virtual movement paths, guide structures and retainers. In the Boolean operations, a space between the target teeth and the tissue surface of the guide was reserved for cooling water.

The cylinder diamond bur which was sandwiched between the paralleled guide structures could move perpendicularly to the tooth surface and the depths of its movements were rigidly constrained, which meant that grooves with a certain width and depth could be prepared on the labial surface. Each guide had three movement paths so that three corresponding grooves could be prepared. Two guides were designed and used together (Fig 2), ensuring that the grooves made by them were overlapped, to achieve the initial preparation on the labial side. The guides were 3D printed by selective laser melting (SLM) using titanium alloy powder

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(Ti-6Al-4V, FalconTech, Wuxi, China) in a 3D metal printer (Titanium 150, Profeta, Nanjing, China) (Fig 3).

Tooth preparation for laminate veneers

Twenty maxillary right central incisor resin artificial teeth were randomly divided into 2 equal groups and tooth preparations were conducted in a phantom head simulator by the same operator. The aforementioned tooth preparation guides were used in the test group for the tooth preparation for 0.5-mm thick laminate veneers. Initial preparation was conducted using the cylindroid flat-ended diamond bur with the assistance of the rigid constraint guides and the typodonts were 3D scanned. The 3D images were exported as STL files. A taper round end bur with extra fine diamond grit (Dia-Burs TR-13EF, Mani, Utsunomiya, Japan) was used to polish the tooth surface subsequent to finishing the tooth preparation (Fig 4). The typodonts were 3D scanned after final preparation and the 3D images were exported as STL files.

A conventional tooth preparation method (wheel-shaped depth gauge bur) was used in the control group. Three depth-guiding grooves were prepared, with one groove in each of the cervical, middle and incisal areas of the labial surface by a 0.5-mm wheel-shaped depth gauge bur (Diatech G834-021, Coltène/Whaledent) and the 3D images were then obtained and exported. A standard-grit taper round-end diamond bur (Dia-Burs TR-13, Mani) was used to remove the tooth tissue between the depth-guiding grooves and an extra fine bur was used to polish the tooth surface. The typodonts were scanned and the 3D images were exported as STL files.

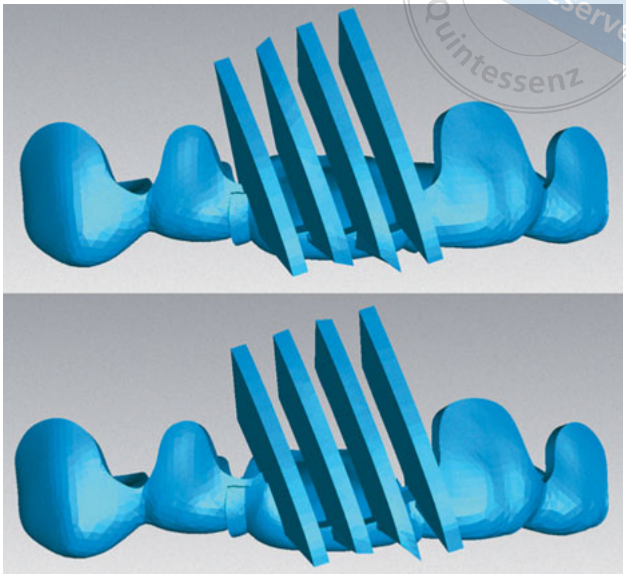

Fig 2 3D images of a pair of tooth preparation guides with complementary guiding structures.

Accuracy analysis of tooth preparation

For each resin tooth sample in the test group, one image was obtained at each of the three stages before tooth preparation, after initial preparation and after final preparation. For each resin tooth sample in the control group, 3D images of the typodont were also obtained before tooth preparation, after the depth-guiding grooves were prepared and after final preparation. When analysing the tooth preparation depths, the 3D images were imported into Geomagic Studio and aligned using the “Best fit alignment” function, according to the bilateral posterior teeth.

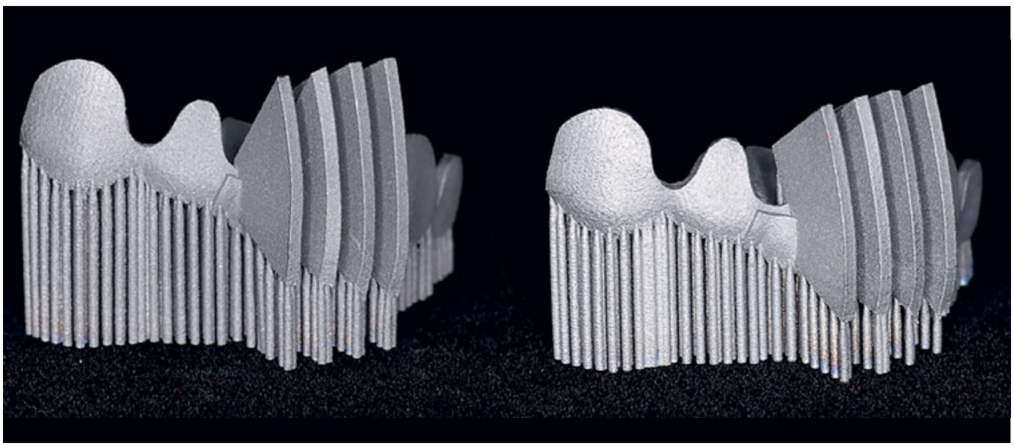

Fig 3 A pair of tooth preparation guides 3D printed with titanium alloy (with supporting structures).

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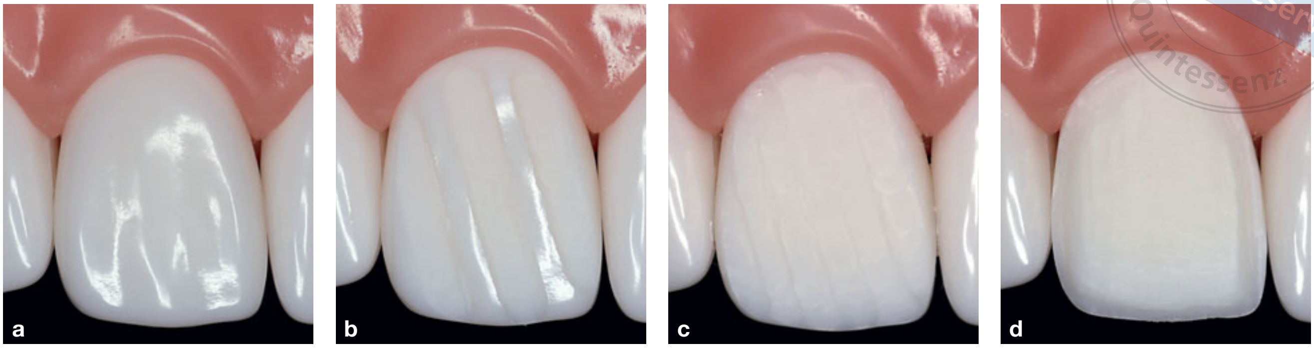

Fig 4 Tooth preparation processes assisted by rigid constraint tooth preparation guides. **(a)** Unprepared tooth. **(b)** Tooth reduction using the first guide. **(c)** Initial tooth preparation using the guides. **(d)** Final tooth preparation.

After alignment, the tooth preparation depths at each step were measured using the "3D deviation analysis" function. In the test group, the deviation between the initial prepared tooth surface and unprepared tooth surface was defined as the initial preparation depth; the deviation between the prepared tooth surface and unprepared tooth surface was defined as the final preparation depth; and the deviation between the initial prepared tooth surface and prepared tooth surface was defined as the loss of tooth tissue during polishing. In the control group, the deviation between the bottom of the depth-guiding grooves and the unprepared tooth surface was defined as the initial preparation depth. Similarly, the deviation between the bottom of the depth-guiding grooves and the prepared tooth surface was defined as the loss of tooth tissue during polishing in the control group. The final preparation depth in the control group was defined in the same way as in the test group. All the results of the 3D deviation analysis were expressed by root mean square errors (RMSEs).

Statistical analysis

A Shapiro-Wilk test was used to examine the normality of data in all groups. A Mann-Whitney U test was used to test statistical differences between the groups in which the data were not normally distributed. A Levene's test was used to test the homogeneity of variance for the groups in which the data were normally distributed. An independent-samples *t* test was performed to test statistical differences between the two groups in which the homogeneity of variance was satisfied; otherwise, a Welch *t* test was used. A statistical software program (SPSS 18.0, IBM, Armonk, NY, USA) was used for all statistical analysis and the significance level was set at 0.05. The sample size of each group (n = 10) was calculated based on the results recorded prior to the experiment.

Results

The initial preparation depth in the test group was described by median and quartile because the Shapiro-Wilk test showed that it did not meet the normal distribution. Other data were described by mean and standard deviation (SD). The initial preparation depth, final preparation depth and loss of tooth tissue during polishing for both groups are shown in Table 1. The initial preparation depth was 0.488 mm (median, quartile 0.013 mm) in the test group and 0.521 mm (median, quartile 0.013 mm) in the control group (Fig 5a), and a Mann-Whitney U test showed a statistically significant difference between the two groups ($P < 0.05$). The final preparation depth was 0.547 ± 0.029 mm in the test group and 0.599 ± 0.051 mm in the control group (Fig 5b). Because homogeneity of variance was not satisfied, a Welch *t* test was used and a statistically significant difference was found ($P < 0.05$). In the test group, subsequent polishing was necessary for the rough tooth surface. Similarly, in the control group, the residual tooth tissue between the depth-guiding grooves needed to be removed and the tooth surface needed to be polished. These procedures led to further loss of tooth tissue on the tooth surfaces which had been prepared to a certain depth. In this study, the depth of tissue loss caused by the aforementioned operations was referred to as the loss of tooth tissue during polishing, which was 0.072 ± 0.023 mm in the test group and 0.089 ± 0.038 mm in the control group. An independent-samples *t* test showed that no statistically significant difference was found between the two groups ($P > 0.05$).

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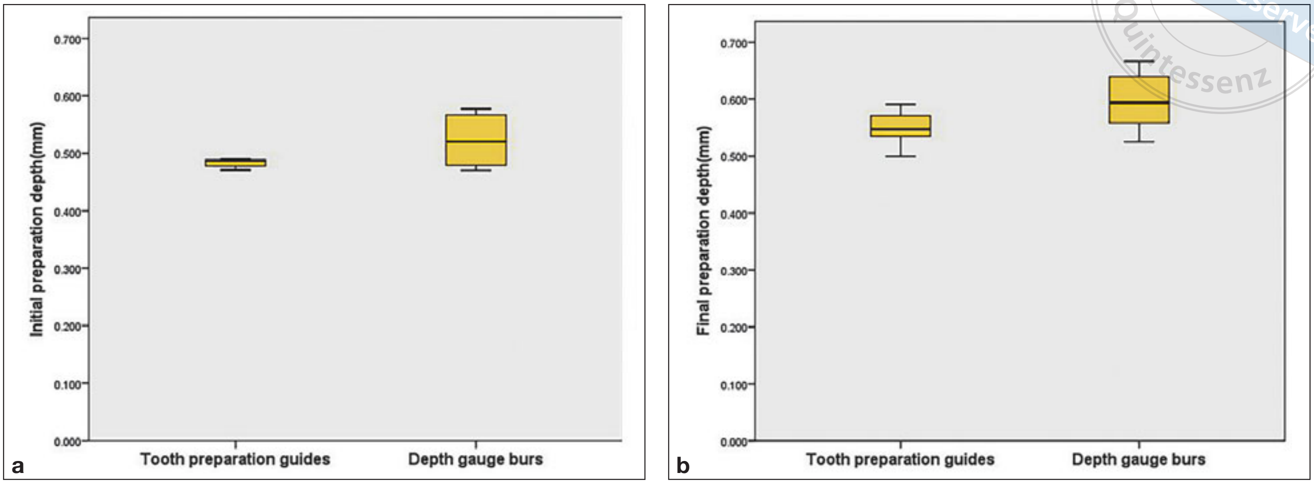

Fig 5 Tooth preparation depths at different steps. **(a)** Initial preparation depths. **(b)** Final preparation depths.

Discussion

This study assessed how accurately a tooth preparation guide technique can perform tooth preparation for laminate veneers, compared with conventional depth gauge burs. The null hypothesis of this study was rejected because of the statistically significant differences found in the initial and final preparation depths between the two groups.

Minimal invasion is one of the most important advantages of laminate veneer restorations[11]. Laminate veneers usually lack mechanical retention forces as a result of only involving a single tooth surface. The key to ensuring good retention is to keep an adequate area bonded to the enamel, which can improve the mechanical properties of porcelain laminate veneers at the same time[2,3,12]. Preservation of enamel is a key factor in laminate veneer restorations and directly influences the success of veneer treatments[1]. However, the thickness of enamel is limited. For maxillary central incisors, the thickness of cervical enamel is just 0.3 to 0.5 mm[13,14], even 0.17 mm reported in a study[15]. Therefore, precise tooth preparation is important for laminate veneer restorations.

To achieve precise tooth preparation, relevant techniques and methods have been developed and studied. At present, depth gauge techniques are the most commonly used methods to improve the accuracy of tooth preparation. Some studies have shown that tooth preparation guided by depth-guiding grooves or dimples was not satisfactory and that dentine exposure could reach one-quarter of the labial surface[16,17]. The wheel-shaped depth gauge bur used in this study is frequently used for the preparation of depth-guiding grooves for laminate veneer restorations. Brunton et al[4] found that this bur could lead to overreduction, which was coincident with the results of this study. The final preparation depth for the control group was 0.599 ± 0.051 mm, overreducing by 0.1 mm compared to the preoperative design of 0.5 mm depth, which may cause more dentine exposure and affect the outcomes of restoration. In comparison, the final preparation depth for the test group was 0.547 ± 0.029 mm, differing significantly from that of the control group, which meant that the tooth preparation assisted by rigid constraint guides had greater accuracy. Furthermore, the median of the initial preparation depth for the test group was 0.488 mm and the quartile was 0.013 mm, which meant that the depth limitation in

Table 1 Tooth preparation depths at different steps using tooth preparation guides and depth gauge burs (mm).

	Tooth preparation guides (mean ± SD)	Depth gauge burs (mean ± SD)	P value
Initial preparation depth[a]	0.488 (0.013)*	0.521 (0.088)*	< 0.05
Final preparation depth[b]	0.547 ± 0.029	0.599 ± 0.051	< 0.05
Loss of tooth tissue during polishing[c]	0.072 ± 0.023	0.089 ± 0.038	0.23

[a], Mann-Whitney U test; [b], Welch's t test; [c], Independent-sample t test; *, median (quartile).

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the test group was more accurate and stable than that in the control group. This advantage may result from the titanium alloy material and the SLM technique which make the contact between the guiding structures and the handpiece totally rigid and could constrain the bur movements more strictly. According to the results for the final preparation depths, the accuracy of tooth preparation assisted by guides improved to 50 µm with less deviation, which means more tooth tissue could be preserved in the tooth preparation processes.

Tooth preparation guides can also be designed individually. Although the resin artificial teeth were prepared to a uniform depth in this study, tooth preparation depths in different areas are usually inconsistent in clinical practice due to malocclusion, discolouration or unsatisfactory contours. Gürel[18] and Magne and Belser[19] suggested that tooth preparation should be conducted using depth gauge burs based on mock-ups which rehabilitated the ideal contours of teeth, to reduce invasion and simplify preparation processes. This method is convenient and effective, but deviations can occur in the fabrication of mock-ups and tooth preparation processes[4,5,20]. Tooth preparation guides made using CAD/CAM techniques can be combined with the preoperative design of digital wax-ups in dental CAD software. Tooth preparation based on virtual mock-ups can be conducted directly using tooth preparation guides to avoid deviations from mock-ups. When designing the tooth preparation guides, the relevant parameters can be adjusted according to experimental results and the accuracy of CAM equipment. The evidence-based adjustment of the guides by an experienced operator can make the tooth preparation depth closer to the preoperative design, but further research is needed to verify this method. Although Brunton et al[4] proposed to reduce the size of depth gauge burs to compensate for the overreduction, tooth preparation guides showed more advantages regarding depth compensation because of their stability. Furthermore, adjusting the size of depth gauge burs cannot eliminate the deviations caused by mock-ups.

One of the limitations of using tooth preparation guides was that the tooth surface after initial preparation was not completely smooth and needed further freehand polishing. As a result, further loss of tooth tissue was observed and was the main error in the test group. More advanced designs for tooth preparation guides need to be developed in the future. Tooth preparation guides also increase treatment costs, but these costs can be reduced along with the development of CAD software and 3D printing techniques.

In this study, the "3D deviation analysis" function of Geomagic Studio software was used to measure and calculate tooth preparation depths holistically. The preparation depths were expressed by RMSEs, which was the root mean square value of distances of numerous paired points with a one-to-one mapping relationship between two corresponding surfaces. This method was used in previous studies to evaluate the deviations between two curved surfaces[21-24]. Compared to the conventional evaluation method in which isolated sites were selected to measure the distance between two surfaces[4-7], the 3D deviation analysis contained a large amount of information about the distance between the two surfaces and could provide a more comprehensive and objective evaluation of the tooth preparation depths. In order to conform the exact predesigned preparation depth at each point, the preparation depth was designed as a uniform value so that it could be correctly evaluated by RMSEs, and was different from the uneven preparation depths in real clinical applications. However, as mentioned above, tooth preparation guides can be designed with uneven tooth preparation depths. In addition, tooth preparation was performed on the same tooth and by the same operator in this study in order to avoid unexpected interferences caused by different tooth positions and operators. This experiment design was consistent with relevant research[4-7], but the influence of different tooth positions and operators needs to be evaluated in the future.

Conclusion

In summary, the rigid constraint tooth preparation guides 3D-printed using titanium alloy improved the accuracy of tooth preparation on the labial side of laminate veneers on maxillary anterior teeth, and the deviation was controlled within 50 µm. The tooth preparation depth achieved by using the tooth preparation guides was more stable than that achieved by using depth gauge burs. The deviations in this tooth preparation guide technique mainly resulted from freehand operations. Therefore, further improvements of tooth preparation guides or further research into automated tooth preparation techniques[8] are needed to reduce or avoid inaccurate freehand operations in guided tooth preparation processes.

Conflicts of interest

The authors declare no conflicts of interest related to this study.

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Author contribution

Dr Zhong Yi LI conducted the experiment and prepared the manuscript; Dr He Fei BAI contributed to the data collection and analysis; Ms Yi Jiao ZHAO and Prof Yong WANG played an important role in the technical support for digital technology; Drs Yu Chun SUN and Hong Qiang YE proposed and designed the research and were responsible for revising the manuscript. All the authors reviewed the manuscript.

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References

1. Gurel G, Sesma N, Calamita MA, Coachman C, Morimoto S. Influence of enamel preservation on failure rates of porcelain laminate veneers. Int J Periodontics Restorative Dent 2013;33:31–39.
2. Piemjai M, Arksornnukit M. Compressive fracture resistance of porcelain laminates bonded to enamel or dentin with four adhesive systems. J Prosthodont 2007;16:457–464.
3. Öztürk E, Bolay Ş, Hickel R, Ilie N. Shear bond strength of porcelain laminate veneers to enamel, dentine and enamel-dentine complex bonded with different adhesive luting systems. J Dent 2013;41:97–105.
4. Brunton PA, Aminian A, Wilson NH. Tooth preparation techniques for porcelain laminate veneers. Br Dent J 2000;189:260–262.
5. Aminian A, Brunton PA. A comparison of the depths produced using three different tooth preparation techniques. J Prosthet Dent 2003;89:19–22.
6. Ge YJ, Liu XQ. Effects of loupes and microscope on laminate veneer preparation [in Chinese]. Beijing Da Xue Xue Bao Yi Xue Ban 2019;51:100–104.
7. Otani T, Raigrodski AJ, Mancl L, Kanuma I, Rosen J. In vitro evaluation of accuracy and precision of automated robotic tooth preparation system for porcelain laminate veneers. J Prosthet Dent 2015;114:229–235.
8. Li ZY, Bai HF, Wang Y, Sun YC. Research status of tooth preparation quantitative guide technique [in Chinese]. Zhonghua Kou Qiang Yi Xue Za Zhi 2018;53:137–140.
9. Yuan F, Wang Y, Zhang Y, Sun Y, Wang D, Lyu P. An automatic tooth preparation technique: a preliminary study. Sci Rep 2016;6:25281.
10. Yu HY, Zhao YW, Li JY, et al. Minimal invasive microscopic tooth preparation based on endodontic, periodontal and functional health [in Chinese]. Hua Xi Kou Qiang Yi Xue Za Zhi 2019;37:229–235.
11. Edelhoff D, Sorensen JA. Tooth structure removal associated with various preparation designs for anterior teeth. J Prosthet Dent 2002;87:503–509.
12. Ge C, Green CC, Sederstrom D, McLaren EA, White SN. Effect of porcelain and enamel thickness on porcelain veneer failure loads in vitro. J Prosthet Dent 2014;111:380–387.
13. Ferrari M, Patroni S, Balleri P. Measurement of enamel thickness in relation to reduction for etched laminate veneers. Int J Periodontics Restorative Dent 1992;12:407–413.
14. Pahlevan A, Mirzaee M, Yassine E, et al. Enamel thickness after preparation of tooth for porcelain laminate. J Dent (Tehran) 2014;11:428–432.
15. Atsu SS, Aka PS, Kucukesmen HC, Kilicarslan MA, Atakan C. Age-related changes in tooth enamel as measured by electron microscopy: implications for porcelain laminate veneers. J Prosthet Dent 2005;94:336–341.
16. Cherukara GP, Seymour KG, Zou L, Samarawickrama DY. Geographic distribution of porcelain veneer preparation depth with various clinical techniques. J Prosthet Dent 2003;89:544–550.
17. Cherukara GP, Davis GR, Seymour KG, Zou L, Samarawickrama DY. Dentin exposure in tooth preparations for porcelain veneers: a pilot study. J Prosthet Dent 2005;94:414–420.
18. Gürel G. The Science and Art of Porcelain Laminate Veneers. London: Quintessence Publishing Co Ltd, 2003.
19. Magne P, Belser UC. Novel porcelain laminate preparation approach driven by a diagnostic mock-up. J Esthet Restor Dent 2004;16:7–16.
20. Cattoni F, Teté G, Calloni AM, Manazza F, Gastaldi G, Capparè P. Milled versus moulded mock-ups based on the superimposition of 3D meshes from digital oral impressions: a comparative in vitro study in the aesthetic area. BMC Oral Health 2019;19:230.
21. Yoon HI, Hwang HJ, Ohkubo C, Han JS, Park EJ. Evaluation of the trueness and tissue surface adaptation of CAD-CAM mandibular denture bases manufactured using digital light processing. J Prosthet Dent 2018;120:919–926.
22. Jin MC, Yoon HI, Yeo IS, Kim SH, Han JS. The effect of build angle on the tissue surface adaptation of maxillary and mandibular complete denture bases manufactured by digital light processing. J Prosthet Dent 2020;123:473–482.
23. Hwang HJ, Lee SJ, Park EJ, Yoon HI. Assessment of the trueness and tissue surface adaptation of CAD-CAM maxillary denture bases manufactured using digital light processing. J Prosthet Dent 2019;121:110–117.
24. Liu Y, Ye H, Wang Y, Zhao Y, Sun Y, Zhou Y. Three-dimensional analysis of internal adaptations of crowns cast from resin patterns fabricated using computer-aided design/computer-assisted manufacturing technologies. Int J Prosthodont 2018;31:386–393.