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Three-dimensional Quantification of Enamel Preservation in Tooth Preparation for Porcelain Laminate Veneers: A Fully Digital Workflow *In Vitro* Study

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Clinical Relevance

We proposed a fully digital workflow to evaluate the preservation of enamel after tooth preparation at different depths, with the final objective of providing scientific guidelines for the digital analysis of the preparation depths for porcelain laminate veneers.

SUMMARY

Objective: This *in vitro* study aimed to evaluate the preservation of enamel after tooth preparation for porcelain laminate veneers (PLVs) at different preparation depths based on a fully digital workflow.

Methods and Materials: Sixty extracted human maxillary anterior teeth, including 20 maxillary central incisors (MCIs), 20 maxillary lateral incisors (MLIs), and 20 maxillary canines (MCs) underwent microcomputed tomography (CT) scanning, and were reconstructed as three-dimensional (3D) enamel and dentin models. Subsequently, the three-dimensional (3D) enamel models were imported into Materialise, where each enamel model underwent seven types of virtual preparation for PLVs at preparation depths

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at 0.1-mm increments from 0.1-0.3-0.5 mm (D1) to 0.7-0.9-1.1 mm (D7). The enamel surface was depicted by merging the virtual preparation and, respective, dentin models. The enamel area and prepared surface were measured to calculate the percentage of enamel (*R*%). The data were statistically analyzed using one-way analysis of variance (ANOVA) (α=0.05).

Results: The group-wise mean (standard deviation) *R* values for the MCIs were as follows: D1-D3: 100.00 (0) each, and D4-D7: 74.70 (2.45), 51.40 (5.12), 24.40 (3.06), and 0.00 (0), respectively. The group-wise mean *R* values for the MLIs were 100.00 (0), 73.70 (3.40), 53.50 (3.44), 25.20 (3.79), and 0.90 (0.99) for the D1-D5 groups, respectively; and 0.00 (0) each for the D6-D7 groups. The group-wise mean (standard deviations) *R* values for the MCs were as follows: D1-D3: 100.00 (0) each, and D4-D7: 99.00 (1.34), 77.10 (3.28), 74.20 (3.61), and 52.20 (4.09), respectively. The one-way ANOVA revealed significant differences between the seven groups in the MCIs, MLIs, and MCs (p<0.05).

Conclusions: Our results recommended preparation depths of up to 0.3-0.5-0.7 mm (MCIs), 0.1-0.3-0.5 mm (MLIs), and 0.4-0.6-0.8 mm (MCs) to facilitate complete intraenamel preparation. Moreover, 50% enamel was preserved at preparation depths of 0.5-0.7-0.9 mm (MCIs), 0.3-0.5-0.7 mm (MLIs), and 0.7-0.9-1.1 mm (MCs).

INTRODUCTION

The esthetic indications of porcelain laminate veneers (PLVs) have increased, because they provide clinicians with a more minimally invasive treatment method by allowing for greater preservation of tooth structure.[1] Since their retention relies solely on adhesion, a reliable bond strength between the veneer and tooth structures is critical for the clinical success of PLVs.[2] This bond strength is influenced by several factors, including the depths of tooth preparation and enamel preservation of the original tooth substrate.[3]

The preparation depth for PLVs is approximately 0.3-0.7 mm and varies from the incisal edge to the cervical margin.[4,5] Recently, minimally invasive preparations limited to within 0.3 mm or even nonreduction for ultrathin veneers has garnered considerable attention for the intraenamel preparation for PLVs.[6,7] Cherukara and others[8] found that tooth preparation at a depth of 0.5 mm was mainly intraenamel, except in the cervical region. Wang and others[9] established digital tooth models to indicate dentin exposure in standard tooth preparations for PLVs on maxillary central incisors (MCIs). LeSage[10] devised a classification to divide preparation depths, volume of remaining enamel, and percentage of dentin exposed. However, the preparation depths that facilitate complete intraenamel preparation for PLVs on maxillary anterior teeth have not been quantified.

Although intraenamel preparation is desired for PLVs, discolored or misaligned teeth may require a deeper reduction to improve the esthetic result, causing inevitable dentin exposure.[11] Enamel preservation is critical for the bond strength of PLVs. Öztürk and others[12] indicated that the bond strength of porcelain to dentin was 75% lower than that of porcelain and enamel. Gresnigt and others[13] have confirmed that 50% remaining enamel substrate demonstrated a significantly higher bond strength compared to a 25% residual enamel substrate, but there is a lack of quantitative analyses on the preparation depths that facilitate 50% enamel preparation for PLVs.

The purpose of this study was to quantitatively assess enamel preservation after tooth preparation at different preparation depths for PLVs for maxillary anterior teeth. The null hypothesis was that there would be no association between the preparation depths and enamel preservation in maxillary anterior teeth.

METHODS AND MATERIALS

Sample Collection

The protocol of this study was approved by the Ethics Committee of our institution (Approval Number: WCHSIRB-D-2019-122) (Figure 1). Sixty noncarious maxillary anterior teeth were extracted from patients (21-50 years old) within the last 6 months, including 20 MCIs, 20 maxillary lateral incisors (MLIs), and 20 maxillary canines (MCs). The inclusion criteria were as follows: normal crown shape, absence of dentin exposure or significant wear, and no history of root canal treatment or tooth fractures.

Digital Reconstruction of Teeth

All samples were thoroughly cleaned under the microscope, followed by scanning with microcomputed tomography (micro-CT) (scanning parameters: 80 Kv, 500 μA, 19.64 μm, and 800 ms), and the data were converted into the Digital Imaging and Communications in Medicine (DICOM) format. The DICOM files of the teeth were imported into a reverse engineering software (Mimics 17.0; Mimics), and the three-dimensional (3D) enamel and dentin models were reconstructed using the "adjust threshold," "region

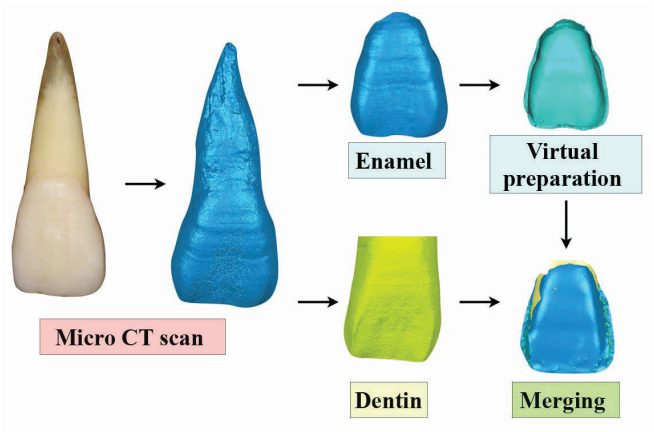

Figure 1. *Workflow diagram of this study.*

growth," and "calculate 3D" tools. These data were saved in the standard template library (STL) format.

Virtual Preparation

The enamel models of all 60 teeth were imported into the Materialise software (Magics 23; Materialise). The labial surface of each enamel model was selected and shifted inward by using the "Offset" tool to perform virtual preparation, as described by Gao and others.[14] The design of the virtual preparation was based on the standard clinical criteria of window preparation for PLVs, namely 0.3 mm, 0.5 mm, and 0.7 mm in cervical, middle, and incisal, respectively (0.3-0.5-0.7 mm); virtual preparations at seven different depths were performed on each enamel model, at 0.1-mm increments from 0.1-0.3-0.5 mm (D1) to 0.7-0.9-1.1 mm (D7) (Table 1). The virtually prepared surfaces, especially the transitional areas of different depths, were selected and smoothed using the "Smooth" tool.

Measurement of Enamel Substrate Area

All seven virtual preparation models and the respective dentin model of each tooth were imported into the Geomagic software (Studio12.0; Geomagic). The distributions of enamel and dentin substrates on the preparation surface were illustrated by merging the virtual preparation and dentin models. The enamel area was also measured (mm^2) using Geomagic. The surface was smoothed, the boundaries of the enamel surface and whole preparation surface were created using the "polygon" tool. The areas of the enamel surface (A_e) and whole preparation surface (A_w) were calculated with the "calculation" tool.

The percentage of enamel surface (R%) was calculated with the following equation: $R\% = A_e/A_w \times 100\%$.

The numerical (quantitative) data were presented as the mean and standard deviation. One-way analysis of variance (ANOVA) was used to statistically compare the percentage of enamel between multiple groups. The test standard was a two-tailed p-value of 0.05. The significance level was set at $\alpha = 0.05$. Statistical analyses were performed using the SPSS software (SPSS 25.0, SPSS).

Table 1: *Reduction Depths of Virtual Preparation in Seven Groups (mm)*

Groups	Cervical	Middle	Incisal
D1	0.1	0.3	0.5
D2	0.2	0.4	0.6
D3	0.3	0.5	0.7
D4	0.4	0.6	0.8
D5	0.5	0.7	0.9
D6	0.6	0.8	1.0
D7	0.7	0.9	1.1

RESULTS

The three-dimensional (3D) models of enamel and dentin for each sample tooth were reconstructed using micro-CT and the Mimics software (Figure 2).

The digital models for virtual preparation were created using the Materialise software. Seven types of virtual preparation were performed on the enamel model of each tooth. The distributions of the enamel and dentin surfaces were presented by superimposing the virtual preparation and dentin models (Figure 3). Figure 4 presents the distributions of the enamel surfaces with different preparation depths after tooth preparation for PLVs on the maxillary anterior teeth.

The percentages of the enamel substrate after virtual preparation of the maxillary anterior teeth are presented in Table 2. The preparation surface included only enamel in groups D1-3 in the MCIs. The percentage of the enamel surface was decreased significantly from group D4 to D7. In group D5, 50% enamel was preserved on the preparation surface. No enamel was preserved on the preparation surface in group D7. The entire preparation surface of the MLIs was composed of enamel substrate in group D1. Dentin exposure was 50% in group D3, and no enamel was preserved on the preparation surface in groups D5-D7. The preparation surface was composed entirely of enamel in groups D1-D4 in the MCs, while 50% of the surface enamel substrate was preserved in group D7. The one-way ANOVA revealed significant differences between the groups for each type of maxillary anterior tooth ($p<0.05$).

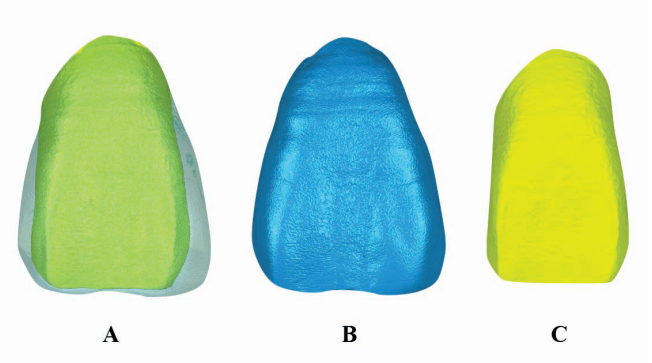

Figure 2. *Three-dimensional models of enamel and dentin: (A) enamel and dentin models, (B) enamel model, and (C) dentin model.*

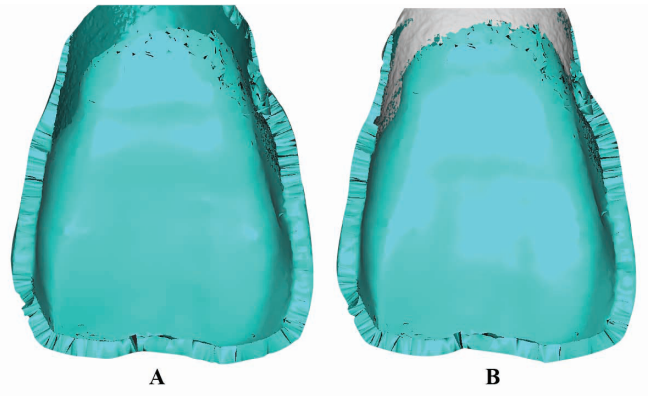

Figure 3. *Virtual preparation: (A) virtual preparation model and (B) superimposition of the virtual preparation and dentin models.*

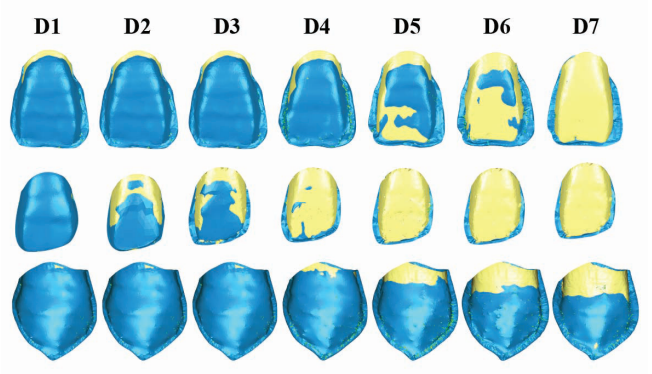

Figure 4. *Enamel distribution after preparation of the maxillary anterior teeth. Blue: Region of enamel, Yellow: Region of dentin.*

DISCUSSION

This study was the first to examine the preservation of enamel after tooth preparation for PLVs at different preparation depths using a fully digital workflow. The results of this study rejected the null hypothesis that there was no association between the preparation depths and enamel preservation in the maxillary anterior teeth.

In this study, 3D enamel and dentin models were reconstructed from the micro-CT scans of the teeth. Micro-CT has been proven to provide accurate 3D reconstructions of the scanned teeth.[9] Virtual preparations were performed on the 3D enamel models, which has been reported to control the preparation depths precisely.[15] The enamel and dentin surface were depicted by the superimposition of the virtual preparation and dentin models.[9] The fully digital workflow reduces the operative errors caused by manual preparation and limits the scanning error of the prepared tooth, and can thus be used to improve the accuracy of quantitative evaluation.[16,17]

We evaluated the preparation depths of the complete intraenamel preparation for PLVs. Complete intraenamel preparation for PLVs has garnered considerable attention owing to the concept of minimally invasive dentistry,[18] the analysis of targeted restorative space,[19] and the recommendations of tooth preparation guides.[20] Our results show that complete intraenamel preparation can be realized with preparation depths up to 0.3-0.5-0.7 mm in the MCIs, 0.1-0.3-0.5 mm in the MLIs, and 0.4-0.6-0.8 mm in the MCs. The enamel distribution of maxillary anterior teeth is uneven, with a mean thickness of 0.4 mm at the gingival-third, 0.9 mm at the middle- third, and 1.0 mm at the incisal-third[21]; thus, the preparation depths vary over the length of the tooth.

The preparation depths are also associated with the space required for the restoration, since its thickness should be sufficient to ensure mechanical durability. However, the preparation depths are critically limited by the thickness of the cervical enamel. Hence, special attention should be focused on the preparation depths in the cervical region, which should be within 0.3 mm for MCIs, 0.1 mm for MLIs, and 0.4 for MCs for the complete intraenamel preparation for PLVs. These findings are consistent with the results that maintaining cervical reduction within 0.3 mm provides complete intraenamel preparation for extrathin PLVs.[22,23] Considering all of these data and our results, it is reasonable to suggest that the preparation depths should be limited within 0.3-0.5-0.7 mm for MCIs, 0.1-0.3-0.5 mm for MLIs, and 0.4-0.6-0.8 mm for MCs, in order to facilitate complete intraenamel preparation.

This study also evaluated the preparation depths that facilitated the maintenance of 50% enamel substrate after tooth preparation for PLVs: 50% enamel reduction has been identified as the preparation criterion for PLVs,[21] as PLV debonding appears to occur if the remaining enamel substrate was less than 50%.[24-26] This study was the first to demonstrate that 50% of enamel

Table 2: *Percentages of Enamel Surfaces After Virtual Preparation on Maxillary Anterior Teeth: Mean, Standard Deviation (SD), and Respective Confidence Intervals (CI=95%)*[a]

Groups	Maxillary Central Incisors (MCIs)				Maxillary Lateral Incisors (MLIs)				Maxillary Canines (MCs)			
	N	Mean (SD)	95% CI for Mean		N	Mean (SD)	95% CI for Mean		N	Mean (SD)	95% CI for Mean	
			Lower	Upper			Lower	Upper			Lower	Upper
D1	20	100.00 (0) a	100.00	100.00	20	100.00 (0) A	100.00	100.00	20	100.00 (0)*	100.00	100.00
D2	20	100.00 (0) a	100.00	100.00	20	73.70 (3.40) B	72.11	75.29	20	100.00 (0)*	100.00	100.00
D3	20	100.00 (0) a	100.00	100.00	20	53.50 (3.44) C	51.89	55.11	20	100.00 (0)*	100.00	100.00
D4	20	74.70 (2.45) b	73.55	75.85	20	25.20 (3.79) D	23.43	26.97	20	99.00 (1.34)*	98.37	99.63
D5	20	51.40 (5.12) c	49.00	53.8	20	0.90 (0.97) E	0.447	1.353	20	77.10 (3.28)#	75.57	78.63
D6	20	24.40 (3.07) d	22.96	25.84	20	0.00 (0) E	0.00	0.00	20	74.20 (3.61)^	72.51	75.89
D7	20	0.00 (0) e	0.00	0.00	20	0.00 (0) E	0.00	0.00	20	52.20 (4.09)†	50.29	54.11

[a]*Different letters and symbols indicate statistically significant differences (p<0.05) among groups for each type of teeth.*

was preserved with preparation depths of 0.5-0.7-0.9 mm for MCIs, 0.3-0.5-0.7 mm for MLIs, and 0.7-0.9-1.1 mm for MCs. Previously, the degree of enamel preservation was evaluated visually after preparation with 34% phosphoric acid for 10 seconds; however, the preparation depths that allowed for 50% enamel preservation were unclear.[27] Recently, Farias-Neto and others[6] reported that tooth preparation at depths of 0.5-1.0 mm preserved approximately 50% to 80% of the enamel substrate. In this study, the distributions of the enamel surfaces indicated that dentin exposure occurs at the cervical area of the tooth, while the incisal preparation remains completely within the enamel at preparation depths of 0.5-1.0 mm. Thus, the preparation depths at the middle-third region are the most meaningful for 50% enamel reduction and should be maintained under 0.7 mm for MCIs, 0.5 mm for MLIs, and 0.9 mm for MCs.

These results provide new clinical methods for the analysis of PLVs using virtual preparation of the digital wax-up before the tooth preparation procedure.[14] The preparation depths can be measured by merging the virtual preparation and original tooth models. The preparation depths were further evaluated for the maintenance of 50% enamel surface or the preferred complete intraenamel preparation.

CONCLUSIONS

We arrived at the following conclusions within the limitations of this study.

1. Preparation depths can be measured by merging the virtual preparation and original tooth models to evaluate the maintenance of enamel surface after tooth preparation for PLVs.
2. Complete intraenamel preparation requires that the preparation depths should be limited within 0.3-0.5-0.7 mm for MCIs, 0.1-0.3-0.5 mm for MLIs, and 0.4-0.6-0.8 mm for MCs.
3. The maintenance of 50% enamel surface requires preparation depths of up to 0.5-0.7-0.9 mm for MCIs, 0.3-0.5-0.7 mm for MLIs, and 0.7-0.9-1.1 mm for MCs.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the human subjects' oversight committee

guidelines and policies of the Ethics Committee of Sichuan University (Approval Number: WCHSIRB-D-2019-122).

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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