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Three-dimensional digital evaluation of thickness accuracy of mock-ups fabricated by silicone matrices: An *in vitro* study

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Abstract

Purpose: Although mock-ups have been widely used in dental esthetic rehabilitation, their accuracy has not been quantitatively evaluated, and the methods of fabricating mock-ups are various. This *in vitro* study investigated the thickness accuracy of mock-ups fabricated with different silicone matrices.

Methods: Mock-ups of maxillary anterior teeth were respectively fabricated by 72 silicone matrices that were equally divided into four groups (n=18 for each group) according to two variables of the silicone matrices: labial margin position (equigingival or cover labial gingiva for 1–2 mm) and palatal notches (with or without notches on the palatal side of silicone matrices). The thickness accuracy of the mock-ups was analyzed using 3D scanning and 3D deviation analysis techniques compared with diagnostic waxing. The thickness change ratios of the mock-ups were compared using a two-way analysis of variance (ANOVA). One-way ANOVA and Kruskal-Wallis tests were used to compare differences in thickness change ratios between different teeth in each group.

Results: The thickness accuracy of the mock-ups was significantly affected by the labial margin position and the palatal notches of the silicone matrices, respectively, in the labial area and the incisal area. The most accurate mock-ups were made using silicone matrices with equigingival labial margins and palatal notches. The thickness accuracy of the mock-ups was also inconsistent on different teeth.

Conclusion: The mock-ups fabricated by silicone matrices were thicker than the diagnostic waxing. The application of silicone matrices to equigingival labial margins and palatal notches was beneficial to the thickness accuracy of mock-ups.

Keywords: Accuracy, Dental veneers, Esthetics, Mock-up

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1. Introduction

Veneer restoration of anterior teeth is a minimally invasive esthetic rehabilitation treatment, which has a higher demand for precise tooth preparation than other restorations[1]. The clinical outcomes and prognoses of veneers[2], including esthetics[3,4], bonding strength[5], and fracture resistance[6], are largely determined by the accuracy of tooth preparation, which is affected by the thicknesses of mock-ups to a certain extent[7–9].

In traditional tooth preparation techniques, tooth tissue is directly prepared and removed from adjacent tooth surfaces as a reference[10]. The preparation depth is estimated and controlled by the visual acuity and clinical experience of the operators, which can be easily disturbed by malocclusion and abnormal tooth morphology. Magne and Belser[11] and Gürel[12] suggested that final restorations should be predesigned through mock-ups of which the surface can

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be considered the baseline of tooth preparation to achieve minimal invasion. The combination of mock-ups and precise tooth preparation can create a sufficient and appropriate restoration space according to the preoperative design, which is verified by many relevant studies[11–17]. Based on this principle, the tooth preparation depth is influenced by the thickness of mock-ups. Insufficient tooth reduction that will eventually lead to inappropriate tooth contours and compromised esthetic outcomes can result from excessively thick mock-ups. Importantly, the bonding strength and fracture strength of porcelain bonded to enamel are higher than those of dentin[5,6]. Unnecessary loss of enamel and dentin exposure that seriously influences the prognosis of veneers can result from excessive tooth reduction caused by mock-ups with inadequate thicknesses. When using no-preparation and ultra-thin veneers for minimally invasive restorations, the accuracy of mock-ups has a more obvious impact on preoperative esthetic expression and dentist-technician communication.

The main approach for the fabrication of mock-ups is to transfer the contours of diagnostic waxings onto untreated teeth using resin materials and silicone impressions, which are called silicone matrices that were first introduced by Magne and Belser[11] and Gürel[18]. A recommended design of silicone matrices was proposed by Magne and Belser[11], but no evidence-based guidelines or quantitative evaluations were provided. In clinical practice, as well as in the reported literature, a layer of redundant resin material covers adjacent teeth and gingiva after the fabrication of mock-ups[11,13,14,16,17]. The redundant resin layers suggest the possibility that mock-ups fabricated by silicone matrices could have inaccurate thicknesses compared to predesigned diagnostic waxings.

With the development of digital technologies, computer-aided designed and computer-aided manufactured (CAD-CAM) mock-ups have been used to simplify the workflow and provide more aesthetic choices for patients in a single appointment. Mock-ups can be made not only intraorally using three-dimensional (3D) printed matrices[19] but can also be directly milled or 3D printed[20,21]. Cattoni et al.[21] suggested that milled mock-ups are more reliable than those made by traditional methods. Although CAD-CAM mock-ups have shown many advantages, the traditional approach is still widely used because of its convenience and low cost. However, studies evaluating the thickness accuracy of traditional mock-ups are rare[21].

The purposes of this study were to perform a 3D quantitative evaluation of the thickness accuracy of mock-ups fabricated by silicone matrices and investigate the influence of the labial margin position and the palatal notches of silicone matrices. The null hypotheses were that mock-ups would not have significant differences in thicknesses compared to diagnostic waxing, and neither the labial margin position nor the palatal notches of silicone matrices would have effects on the thickness accuracy of mock-ups.

2. Materials and Methods

A maxillary typodont model (D16FE, Nissin Dental Products Inc.) was selected, and a plaster replica cast was fabricated by a two-step putty-wash impression technique using vinylpolysiloxane impression material (Variotime Dynamix Heavy Tray and Variotime Light Flow, Heraeus Kulzer GmbH) and was cast with type IV gypsum (Herastone CN, Heraeus Kulzer GmbH). After over 120 h of setting[22], the replica cast and the typodont model were separately scanned using a lab scanner (Activity 880, Smartoptics), and the 3D images were exported as standard tessellation language (STL) files. Diagnostic waxing of the maxillary anterior teeth was made on the plaster replica cast, which evenly increased the thicknesses in the labial area and the length in the incisal areas. The plaster replica cast with diagnostic waxing was scanned by the same lab scanner. All models scanned in this study were sprayed with scanning powder (UD-ST, Marktec Corporation).

The 3D image of the plaster replica cast with diagnostic waxing was imported into Geomagic Studio software (Geomagic Studio 2014, 3D Systems). The mold used to fabricate the silicone matrices was designed (**Fig. 1**) and 3D printed (**Fig. 2**) in polylactic acid material (PLA, Beijing Sinotech) using a fused deposition modeling (FDM) 3D printer (Lingtong II, Beijing Sinotech) to keep the thickness and shape of the silicone matrices consistent.

The plaster replica cast with diagnostic waxing was fixed on the lower part of the PLA mold (**Fig. 2**). Seventy-two silicone matrices were fabricated using the two-step putty-wash impression technique (SwissTec A-Silicone Putty Soft and SwissTec A-Silicone Light Body, Coltène/Whaledent Inc.), assisted by the PLA mold. The silicone matrices were randomly divided into four equal groups (n=18) according to factorial design to analyze the interaction effects and the main effects of two variables: the labial margin position and the palatal notches of silicone matrices. For the silicone matrices in Group A, the labial margins of the working section (anterior teeth) were trimmed to conform to the margins of the labial gingiva (equigingival), and the palatal notches were not made. For the silicone matrices in Group B (**Fig. 3A**), the labial margins were trimmed to equigingival as in Group A, and V-shaped notches were made from each cingulum of the working teeth to the palatal edge of the matrices. In Group C (**Fig. 3B**), the labial margins of silicone matrices were trimmed to uniformly cover 1–2 mm of the labial gingiva, and no palatal notches were made. In Group D, the labial margins of the silicone matrices covered 1–2 mm of labial gingiva as in Group C, and the palatal notches were made. The sample size adopted was referenced from a previously reported study[21] and was verified by power analysis using a statistical program software (Power Analysis and Sample Size 11, NCSS).

Bis-acrylic resin (Protemp4 A2, 3M ESPE) was injected into the working section of the silicone matrix uniformly for 10–15 s from the left canine to the right canine, filling 2/3 of the space of each working tooth. The silicone matrix was promptly and completely seated on the typodont model with two 500 g weights placed on the bilateral premolar area providing constant and coincident pressures during the curing of the resin material. The mock-ups were 3D scanned with the same lab scanner (Activity 880, Smartoptics) after the silicone matrix and excess resin materials were removed, and the 3D images were exported as STL files.

3D images of the typodont model, with and without mock-ups, were imported into the Geomagic Studio software program and registered through the “Best fit alignment” command using posterior teeth as the common area. The thicknesses of mock-ups in the labial area and the incisal area, for the complete anterior teeth and each tooth separately, were calculated by 3D deviation analyses (**Fig. 4**) and represented in root mean square errors (measured in mm). Similarly, the thicknesses of diagnostic waxing were calculated based on the 3D images of the plaster replica cast with and without diagnostic waxings. The ratios of thickness change between mock-ups and diagnostic waxings were calculated. The main workflow of this experi-

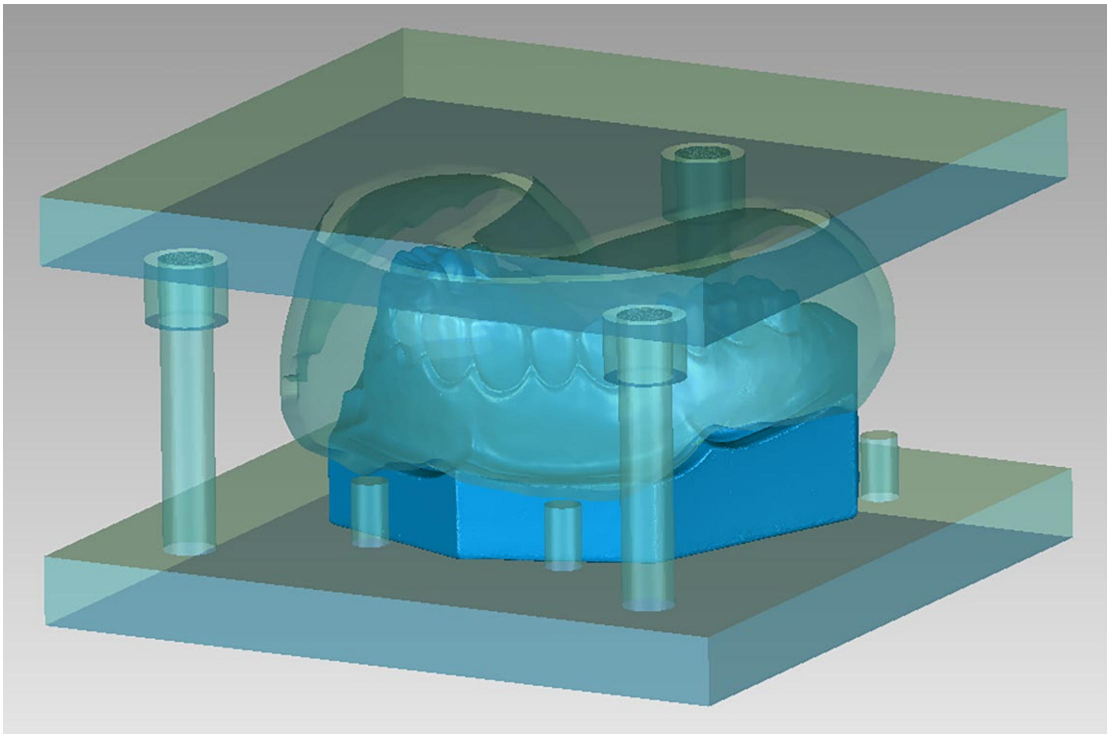

Fig. 1. Design of PLA mould
The computer-aided design of PLA (polylactic acid) mould.

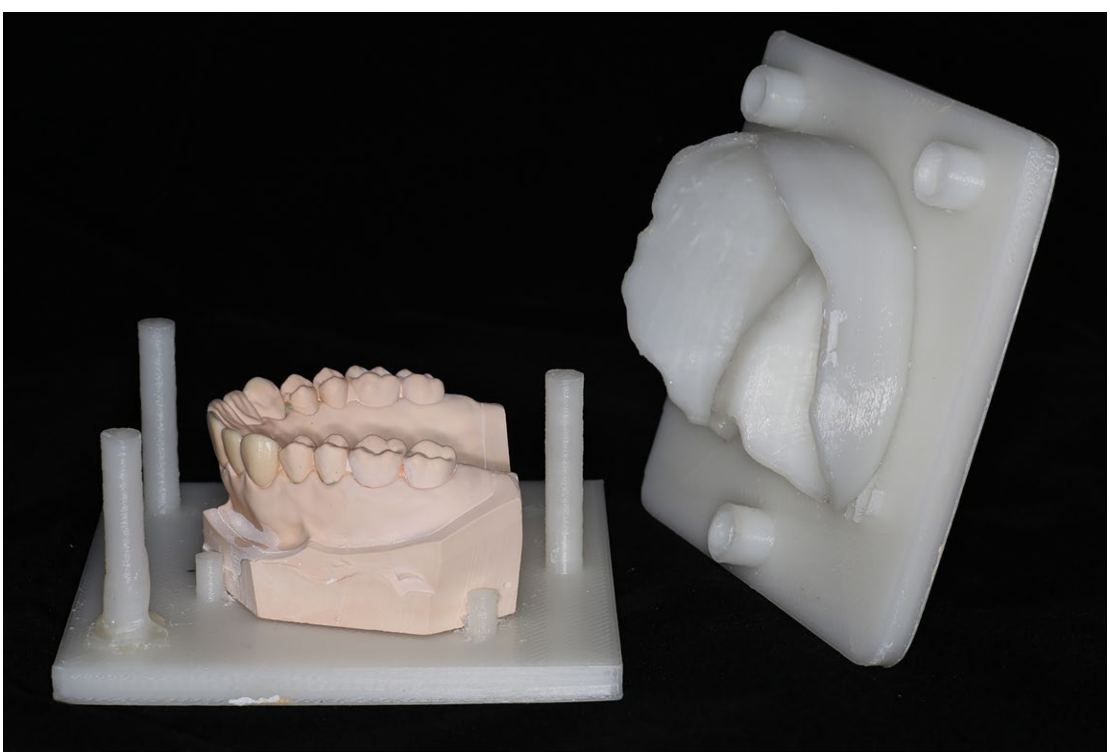

Fig. 2. Fabrication of PLA mould
The PLA mould that 3D printed by FDM (fused deposition modeling) printer.

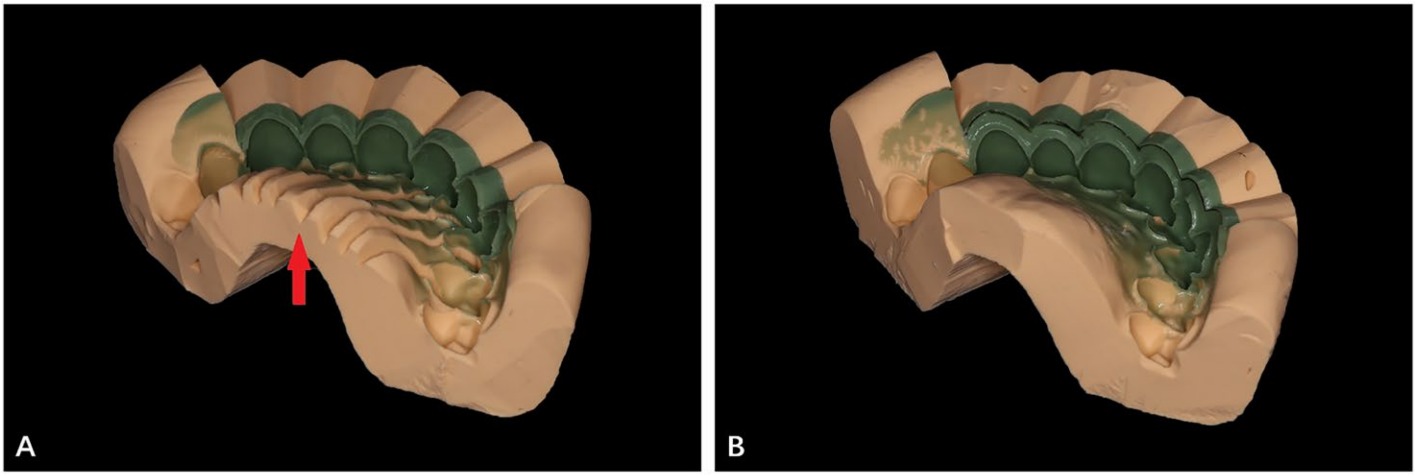

Fig. 3. Different designs of labial margin and palatal notches of silicone matrices.
A. Silicone matrix (Group B) with equigingival labial margin and V-shaped palatal notches (indicated by red arrow) B. Silicone matrix (Group C) with 1-2mm coverage of labial gingiva and without palatal notches.

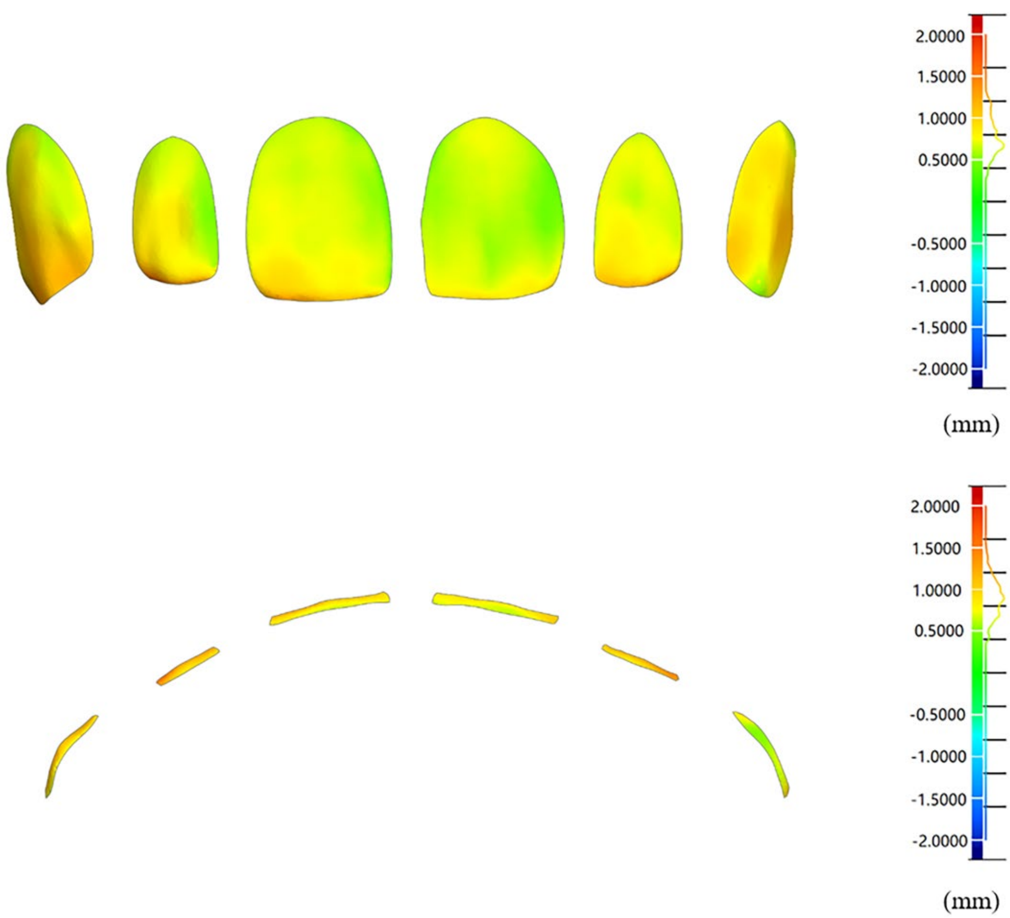

Fig. 4. Calculation of the thicknesses of mock-ups
Use 3D deviation analysis to calculate the thicknesses of mock-ups (labial area and incisal area were analyzed separately)

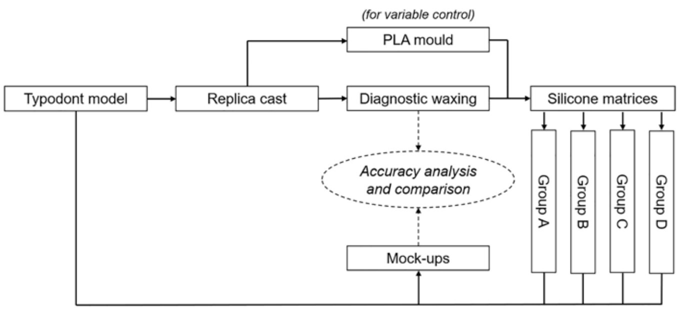

Fig. 5. Basic workflow for analyzing the thickness accuracy of mock-ups
Group A: Silicone matrices with equigingival labial margin and without palatal notches.
Group B: Silicone matrices with equigingival labial margin and palatal notches.
Group C: Silicone matrices with 1-2mm coverage of labial gingiva and without palatal notches.
Group D: Silicone matrices with 1-2mm coverage of labial gingiva and palatal notches.

ment is shown in **Figure 5**.

A statistical software program (Statistical Product and Service Solutions 20.0, IBM) was used for all statistical analyses, and the significance level was set at 0.05. The Shapiro-Wilk test and Levene test were used to examine the normality and homogeneity of variance of the thickness change ratios of mock-ups. To determine the best design of silicone matrices in this study, a two-way analysis of variance (ANOVA) was used to test the interaction effects and main effects of the two variables (labial margin position and palatal notch of silicone matrices). One-way ANOVA and Kruskal-Wallis tests were used to compare the thickness change ratios of mock-ups between different teeth in each group.

3. Results

The average thicknesses (95% confidence interval) of diagnostic waxings were 0.65 (0.61–0.69) mm in the labial area and 0.62 (0.56–0.67) mm in the incisal area, less than that in the mock-ups. The thickness change ratios of the mock-ups in different areas satisfied the normality and homogeneity of variance and are shown in **Table 1**.

No interactions were found between the labial margin position and palatal notches in the labial area (P=0.650) or in the incisal area (P=0.209). Meanwhile, different labial margin positions of silicone matrices had a significant effect on the accuracy of mock-ups in the labial area (F=10.374, P<0.01), and the presence of palatal notches had a significant effect on the accuracy of the mock-ups in the incisal area (F=103.528, P<0.01).

In the incisal area, the thickness change ratio of the mock-ups in Group B, of which the silicone matrices had equigingival labial margin and palatal notches, was minimum among all experimental groups. In the labial area, the thickness change ratio of the mock-ups in Group B was greater than that of Group A and less than that of Group C and Group D, but no statistically significant differences were found between Group B and Group A (P>0.05).

The thickness change ratios of mock-ups on different teeth are shown in **Table 2**. One-way ANOVA and Kruskal-Wallis tests performed in Groups B and D showed that the thickness change ratios of mock-ups in both labial and incisal areas significantly differed between different teeth (P<0.001). Tukey's HSD post hoc test and further pairwise comparison showed that the thickness change ratio of the mock-ups in the labial area of the canines was significantly lower than that of the central incisors or lateral incisors (P<0.05), but no significant differences were found between the central incisors and the lateral incisors (P>0.05). In the incisal area of Group B and Group D, the thickness change ratio of the mock-ups in the central incisors was significantly higher than in the lateral incisors or canines (P<0.05), but no significant differences were found between the lateral incisors and the canines (P>0.05). In the incisal area of Group A and Group C, significant differences were found between different teeth (P<0.001). Pairwise comparison showed that the thickness change ratios of the mock-ups of canines were significantly lower than that of incisors (P<0.05). Meanwhile, the thickness change ratios of the mock-ups of the lateral incisors were significantly lower than those of the central incisors (P<0.05). In the labial area of Group A and Group C, no significant differences were found between different teeth (P>0.05). However, the mean thickness change ratios in the canines were still lower than those in the incisors.

4. Discussion

According to the results, the null hypotheses of mock-ups that would not have significant differences in thicknesses compared to diagnostic waxing, and neither the labial margin position nor the palatal notches of silicone matrices would have effects on the thickness accuracy of mock-ups, were rejected. Two-way ANOVA showed that silicone matrices with an equigingival labial margin and palatal notches could improve the thickness accuracy of mock-ups, but no interactions were found between the two variables. Despite using the optimal design of silicone matrices, there remained a 15.7% to 22.7% thickness change in mock-ups on average, compared with the diagnostic waxing.

Due to the requirement of optimal esthetic outcomes and the thinness of enamel on anterior teeth[7,8], tooth preparation of veneers should create enough restoration space for prostheses and be limited within the enamel layer to prevent dentin exposure, which can decrease the long-term success rate of veneers[2,9]. The tooth preparation depth of veneer restorations, which may be directly affected by the thicknesses of mock-ups, should be precisely controlled. The results of this study showed that the thicknesses of the mock-ups were greater than that of the diagnostic waxings, which explained the existence of the aforementioned phenomenon in relevant research[11,13,14,17]. Therefore, tooth preparation based on mock-ups may lead to insufficient tooth reduction compared with preoperative designs. In some cases, mock-ups should be tested for several days and adjusted chairside according to the requirements of patients, which means that the inaccuracy of mock-ups may cost more chairside time for adjustment.

The mock-up technique, which uses the internal space between the teeth and silicone matrices to shape temporary resin materials into the specific contour of diagnostic waxing, is widely used in clinical practice due to its effectiveness and convenience[11–17]. Since the skills of dentists and materials used vary, the process of fabricating mock-ups can be affected by many factors that are difficult to control, such as the mechanical strength and positioning accuracy of silicone matrices, the flowability of resin materials, and the external pressures applied on matrices. Different designs of silicone matrices

Table 1. Means (95% confidence interval [CI]) of thickness change ratios of mock-ups (%) in different areas*

	Designs of silicone matrices		Thickness change ratios of mock-ups	
	Labial margin position	Palatal notches	Labial area	Incisal area
Group A	equigingiva	-	13.7 (11.2-16.3) [a]	47.0 (40.3-53.8) [c]
Group B	equigingiva	+	15.7 (13.5-18.0) [a]	22.7 (18.2-27.2) [d]
Group C	1-2mm coverage of gingiva	-	17.6 (14.9-20.3) [b]	54.5 (47.7-61.3) [c]
Group D	1-2mm coverage of gingiva	+	20.8 (16.9-24.8) [b]	23.2 (18.6-27.8) [d]
	P value of interaction		0.65	0.209

* Analyzed by two-way ANOVA
a,b,c,d: For each area, groups identified by different letters had statistically significant differences (P<0.05)

Table 2. Means (95% confidence interval [CI]) of thickness change ratios of mock-ups (%) among different teeth.

Areas		Central incisors	Lateral incisors	Canines	*P*
Group A	Labial *	15.7(13.0-18.3)	15.8(13.0-18.5)	12.7(10.5-15.0)	0.165
	Incisal **	74.7(67.4-82.0) [a]	45.8(40.3-51.2) [b]	32.1(26.8-37.4) [c]	< 0.001
Group B	Labial *	21.4(18.5-24.4) [d]	19.2(15.8-22.6) [d]	12.1(9.3-15.0) [e]	< 0.001
	Incisal **	38.7(33.9-43.5) [f]	21.6(17.5-25.8) [g]	15.9(10.0-21.8) [g]	< 0.001
Group C	Labial **	19.7(16.8-22.6)	19.9(17.2-22.7)	16.0(13.9-18.1)	0.051
	Incisal **	86.2(78.7-93.7) [h]	50.7(44.3-57.0) [i]	39.3(33.1-45.5) [j]	< 0.001
Group D	Labial **	27.9(24.4-31.5) [k]	25.0(20.0-30.1) [k]	16.4(12.3-20.6) [l]	< 0.001
	Incisal **	38.1(33.4-42.8) [m]	22.3(17.0-27.7) [n]	20.2(15.5-25.0) [n]	< 0.001

* One-way ANOVA and Tukey HSD post hoc test
** Kruskal-Wallis test and Bonferroni adjusted pairwise comparison
a-n: Each tooth position that identified by different letters had statistically significant differences (P<0.05)

were analyzed in this study because they can be easily adjusted by dentists in clinical operations and because no consensus has been reached. To minimize errors caused by other factors, "variable-control" was strictly performed in this study. An exclusive 3D printed PLA mold for fabricating silicone matrices was used to ensure that the thicknesses and shape of the silicone matrices were identical so that the mechanical strength of the silicone matrices was kept consistent. Two 500 g weights were placed in the same position in the premolar area to simulate sustained external pressures. When analyzing the 3D images in the Geomagic Studio software program, the selected areas for best fit alignment and 3D deviation analyses were consistent among different samples using the "projection" command of the same curves. These approaches mentioned above kept the non-research factors as consistent as possible. As for the target variables, the design of the equigingival labial margins could ensure the integrity of the mock-ups and reduce the resistance of the resin material flowing to the labial side; the V-shaped notches starting from the cingulum of the anterior teeth could reduce the resistance of the resin material flowing to the palatal side. Two-way ANOVA showed that there were no interactions between these two variables and only had significant effects in the labial area and the incisal area, respectively, which means that silicone matrices should be partially trimmed according to specific requirements.

Introduced by Magne and Belser[11], sustained external pressures should be applied in bilateral premolar areas, which were simulated by two 500 g weights in this experiment. According to the results in **Table 2**, the thickness deviations of the mock-ups had a trend of becoming greater with distance from the premolar areas, which may result from increasing distance between mock-ups and the supporting area. It was not conducive to the accuracy of long-span mock-ups if no external pressures were applied to the working section of silicone matrices, which was inconsistent with Magne and Belser's introduction[11]. However, the thicknesses of the mock-ups could have been excessively reduced if external pressures were applied inappropriately. Although the external pressures were controlled for in this study, further research is still required to investigate how to apply the optimal external pressures. In addition, the thicknesses of the diagnostic waxing remained the same as a non-research factor in this study. The relationship between the thickness changes of mock-ups and the thicknesses of diagnostic waxings must be investigated in future research.

Cattoni et al.[21] suggested that the mock-ups that were milled or 3D printed were more accurate than those fabricated using silicone matrices, which corresponds to the results of this study. However, even when using computer-aided manufacturing techniques, errors exist in the process of fabricating mock-ups. In the future, combining preoperative virtual design techniques[23] and advanced tooth preparation techniques, such as tooth preparation guide plates[24] and automatic robots[25,26], mock-ups can be used only as a tool for doctor-patient communication but no longer as the baseline of tooth preparation, to avoid their unexpected effects on tooth preparation.

5. Conclusion

Within the limitations of this study, the following conclusions may be drawn:

1. Mock-ups fabricated by silicone matrices on the maxillary anterior teeth are thicker than corresponding diagnostic waxings.
2. Application of silicone matrices with equigingival labial margin and palatal notches can improve the thickness accuracy of mock-ups.
3. Considering mock-ups fabricated with silicone matrices as the baseline of tooth preparation may lead to insufficient tooth reduction.

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Conflicts of interest

The authors declare that there are no conflicts of interest.

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