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Comparison of four CAD-CAM guides for preparing guiding planes of removable partial dentures

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ABSTRACT

Background and objective: To evaluate the effect of guiding structure and 3D-printing material of CAD-CAM guides on the accuracy of guiding planes preparation.

Methods: Four types of computer-aided design and computer-aided manufacturing (CAD-CAM) guides for preparing guiding planes of removable partial denture (RPD) were designed in two types of guiding structures (triple-constraint and single-plane constraint) and were 3D printed using resin and cobalt-chromium (Co–Cr) alloy. Guiding plane preparation of identical resin casts was performed using CAD-CAM guides (resin template, metal template, resin guided device, and metal guide device) in four test groups and by freehand in the control group ($n = 22$ per group). All prepared casts were then scanned (Test) and aligned to the reference cast with designed guiding planes. 3D compare analysis was performed and root-mean-square (RMS) values were calculated for assessing the 3D trueness and 3D precision of guiding plane preparation. The angle between the prepared guiding plane (Test) and the designed path of placement of RPD (Reference) was measured for evaluating the direction trueness.

Results: RMS values of the metal template group for 3D trueness (39.7 ± 14.6 μm) and 3D precision (28.6 ± 6.8 μm) were significantly lower than that of other groups ($p < .05$). For direction trueness, the metal template group showed the least angle deviation (1.09 ± 0.56°), and the freehand group demonstrated the largest angle deviation (7.03 ± 2.83°).

Conclusions: The Co–Cr alloy guides with triple-constraint guiding structure can assist to prepare accurate guiding planes of RPD.

1. Introduction

Guiding planes are two or more vertically parallel surfaces on abutment teeth and/or fixed dental prostheses oriented so as to contribute to the direction of the path of placement of removable partial dentures (RPDs) [1]. Correctly constructed guiding planes can improve the retention and stability of RPDs, reduce plaque accumulation, and avoid food impaction [2,3]. According to Mothopi-Peri et al., the retention of RPDs could be increased by 1.6–10.2-fold when guiding planes were precisely in contact with the proximal plates [4]. Furthermore, guiding planes prepared as close to the gingival margin as possible might decrease plaque accumulation, improving RPD prognosis and long-term survival [5]. Guiding planes are usually prepared by freehand in the clinic, which tends to be imprecise because of limited mouth opening, rough naked eye inspection, and insufficient clinician experience [6,7]. To wonder if the guiding planes are parallel, some dentists took several impressions, or a series of scanning images. These extra steps are time-consuming and labor-intensive [8]. Especially, the most experienced practitioners found it challenging to prepare parallel guiding planes on bilateral teeth, let alone novice dental students [6].

Some computer-aided design and computer-aided manufacturing (CAD-CAM) guides had been proposed for assisting the preparation of the guiding planes more accurately [2,3,9–12]. These CAD-CAM guides could be classified into 2 types by their guiding structures, single-plane

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constraint guide and triple-constraint guide. One type of CAD-CAM guide had single-plane guiding structure and indicated the cutting position of the guiding plane and the direction of the path of placement [2,9,11]. However, it cannot entirely restrict the movement of the diamond rotary instrument. Another type of CAD-CAM guide had triple-constraint guiding structures which strictly guide the movement of the diamond rotary instrument using restrictions applied in 3 directions during tooth preparation [12,13]. However, there is no published direct evidence determining the more effective guiding structure.

The CAD-CAM guides are commonly fabricated using computer numerical control (CNC) milling and addictive manufacturing (AM) technologies [14,15]. Compared with the CNC, AM (3D printing) become popular as it is suitable for fabricating objects with complex structures and is efficient at reducing materials waste [16]. Currently, the most common type of material used to fabricate CAD-CAM guides is resin [17,18]. However, the CAD-CAM guides fabricated using resin material are prone to wearing out or fracturing due to their weak hardness and poor strength [15,19]. Recent advances in AM technologies and compatible metal alloys allow for the highly accurate manufacture of selective laser melting (SLM) cobalt-chromium (Co–Cr) and titanium prostheses and frameworks of RPDs [20–23]. The CAD-based SLM technology is efficient for fabricating objects with complex topography [24]. Furthermore, these developments show that compared with the resin guides, the additively manufactured metal guides can provide a more desirable guiding structure, thinner design, higher strength, and superior cooling efficiency [20,21]. However, it is still unclear whether the guiding structure and the 3D-printing materials of CAD-CAM guides affect the tooth preparation accuracy of guiding planes.

Freehand parallel guiding plane preparation is also difficult and often inaccurate. Despite several presented CAD-CAM guides in the literature, their accuracy has not been quantitatively analyzed yet. The purpose of this study was to evaluate the effect of the guiding structure and 3D-printing material of CAD-CAM guides on the accuracy of guiding plane preparation. The null hypothesis was that the guiding structure and 3D-printing material of CAD-CAM guide have no effect on tooth preparation accuracy of guiding plane.

2. Materials and methods

2.1. Reference cast

A mandibular Kennedy class III cast (mandibular right first molar missing) was printed 110 times using an industrial stereolithography (SLA) printer (iSLA800; ZRapid) (nominal accuracy 50 μm, repositioning precision 10 μm) and compatible photopolymerizing resin (ZR710; ZRapid). After digital cast surveying, the path of placement of RPD was designed perpendicular to the occlusal plane, and then the distal guiding plane of the right second premolar (FDI #45) and mesial guiding plane of the right second molar (FDI #47) were virtually prepared in a reverse engineering software (Geomagic Wrap 2015; 3D Systems). The digital cast with virtually prepared guiding planes was set as the reference cast (Fig. 1).

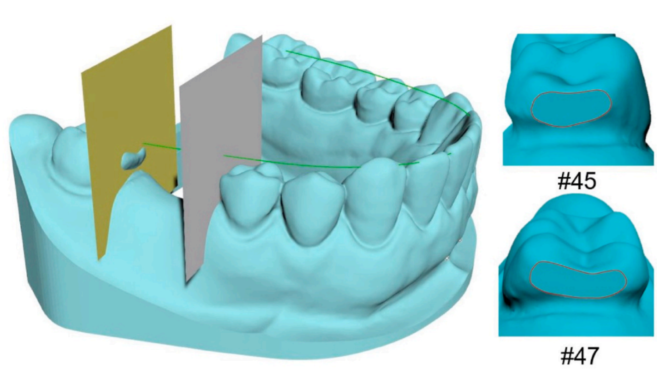

Fig. 1. Virtually designed guiding planes of abutment teeth (FDI #45 and #47).

2.2. Design and 3D printing of CAD-CAM guides

Four types of CAD-CAM guides for preparing guiding planes were designed in two types of guiding structures. Each design was 3D printed using photopolymerizing resin (VeroClear; Stratasys) and cobalt-chromium alloy (MetcoAdd 78A; Oerlikon) (n = 22). These CAD-CAM guides were designed following the techniques described by Lee et al. (guide device: single-plane constraint guiding structure) (Fig. 2A) and Ye et al. (template: triple-constraint guiding structure) (Fig. 2B) [11,12]. The 3D printers were calibrated according to the manufacturer's instructions before commencing the printing process. Supportive structures of CAD-CAM guides were visibly removed, and the Co–Cr alloy guides fabricated by SLM were additionally sandblasted with 50 μm aluminum oxide powder for removing the oxidation layer. The technical descriptions of the 3D printers and printing materials are shown in Table 1. The design settings of CAD-CAM guides are shown in Table 2. According to manufacturing guidelines, the 4 types of CAD-CAM guides were designed with different thicknesses for satisfying the strength requirements of CAD-CAM guides.

The CAD-CAM guide with triple-constraint guiding structure mainly consists of guide rails and retainer. The upper surface of guide rails restricts the occlusal-gingival preparation depth of diamond rotary instrument, while the inner surfaces of guide rails guide the movement of the bottom part of the diamond rotary instrument. The track grooves of the retainer prevent the top part of the diamond rotary instrument from rotating in the distal or mesial direction. The CAD-CAM guide of single-plane guiding structure consists of retainer and a cross-section for indicating the preparation position and the path of placement of RPD.

2.3. Classification of the groups

Four types of CAD-CAM guides were equally divided into 4 test groups (n = 22): resign template (RT) group, metal template (MT) group, resin guide device (RGD) group, and metal guide device (MGD) group. Guiding plane preparation were performed by freehand in the control group (n = 22).

2.4. Internal adaptation assessment

The internal adaptation of CAD-CAM guides was assessed using the digital silicone replica (dual-scan) technique [25,26]. Firstly, a visual inspection was performed to confirm that no CAD-CAM guide had gross misfit. Secondly, the CAD-CAM guide was coated with a thin layer of vinyl polyether silicone material (Type 3 Light Body; HUGE) at its intaglio surface and then seated over the resin cast with finger pressure for 4 min.

The CAD-CAM guide was removed from the resin cast carrying the complete silicone replica along with it. The intaglio surface of the CAD-CAM guide was lightly coated with an antiglare spray (average particle size of 3 μm) (Easy scan; Alphadent) and scanned twice at before and after removing the silicone replica using a laboratory scanner (D2000, 3Shape A/S). The precision of the D2000 scanner was 5 μm (ISO 12836). The occlusal internal gap between the CAD-CAM guide and the cast was assessed using 3D compare analysis in the Geomagic Wrap 2015 software after best-fit alignment of two scanning data (Fig. 3A, B and 3C).

2.5. Tooth preparation of guiding planes

Resin cast was mounted in a phantom head simulator (NISSIM Type I, NISSIN). The distal guiding plane of the right second premolar (FDI #45) and the mesial guiding plane of the right second molar (FDI #47) were prepared using an identical high-speed handpiece (Boralina

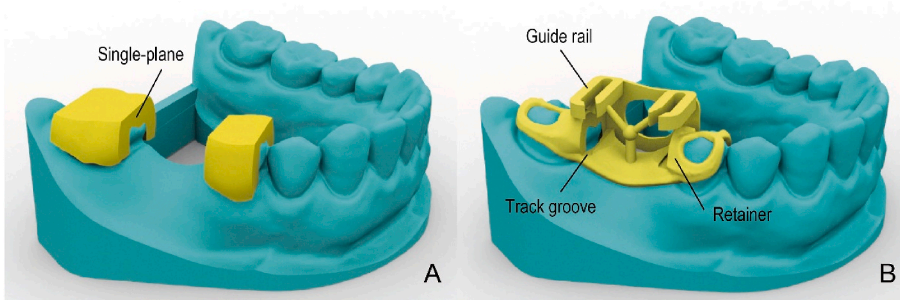

Fig. 2. Two types of guiding structures of CAD-CAM guides. A, Single-plane guiding structure. B, Triple-constraint guiding structure.

Table 1
Technical descriptions of 3D printers and printing materials.

3D printer	Manufacturing technology	Printing materials	Build volume (X-, Y-, and Z-axis)	Resolution (X-, Y-, and Z-axis)	Layer thickness	Spot diameter	Powder size	Software
Objet30 Pro (Stratasys, Eden Prairie, USA)	PolyJet	VeroClear (Stratasys, Eden Prairie, USA)	300*200*150 mm	600*600*1600 dpi	16 μm	–	–	Objet Studio
Tr150 (Profeta, Nanjing, China)	Selective Laser Melting	MetcoAdd 78A (Oerlikon, Zurich, witzerland)	150*150*80 mm	X*Y-50 μm Z-30 μm	30 μm	30 μm	10–30 μm	Profeta

Table 2
Design settings of CAD-CAM guides (n = 22).

CAD-CAM guide	Thickness (mm)	Offset from teeth (μm)	Offset from the diamond rotary instrument (μm)
RGD	3.0	50	–
MGD	2.0	50	–
RT	2.5	50	50
MT	1.2	50	50

RGD, Resin guide device; MGD, Metal guide device; RT, Resin template; MT, Metal template.

1600373-001, Bien Air Dental) by the same dental postgraduate student (H.B.). The tooth preparation was performed by freehand in the control group and assisting by the 4 types of CAD-CAM guides in the test groups (RT, MT, RGD and MGD) (Fig. 4A, B, 4C and 4D). To limit the influence of operator fatigue for tooth preparation, all casts was prepared within 11 days and 2 casts were prepared per day for each group. A new flat-ended diamond rotary instrument (SF-31; MANI) was changed daily for reducing the influence of abrasion between the CAD-CAM guide and diamond rotary instrument. All casts that had been prepared were scanned using a D2000 laboratory scanner. The scanning data was set as Test cast.

2.6. Registration of the test cast and reference cast

The “N-Point Registration” and “Best-Fit Alignment” were performed using identical 5 pairs of corresponding characteristic points and neighboring tooth surface of guiding planes to align the test cast to the reference cast using the Geomagic Wrap 2015 software. All scanning data of prepared casts (test) was aligned to the reference cast within an identical coordinate system after best-fit registration. The z-aixs of this coordinate system was parallel to the designed path of placement of RPD.

2.7. Direction trueness assessment

In the Geomagic Wrap 2015 software, the angle between the prepared guiding plane (test) and the direction of the designed path of placement of RPD was calculated for assessing direction trueness of tooth preparation of guiding plane. Six mesio-distal cross-sections were constructed parallel to the designed path of placement (0, 0, 1) for each prepared guiding plane. The direction vector (x, y, z) of intersecting line of the prepared guiding plane and each cross-section was used to calculate the angle (α) between the prepared guiding plane and the designed path of placement using the following formula (Fig. 5A). Six angles ($\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6$) of each prepared guiding plane were obtained to calculate the mean values.

$$\alpha = \arccos < \overrightarrow{Nv}, \overrightarrow{Pp} > | = |\arccos \frac{1}{\sqrt{x^2 + y^2 + z^2}}$$

where $\overrightarrow{Nv}$ (x, y, z) is the direction vector of intersecting line of the

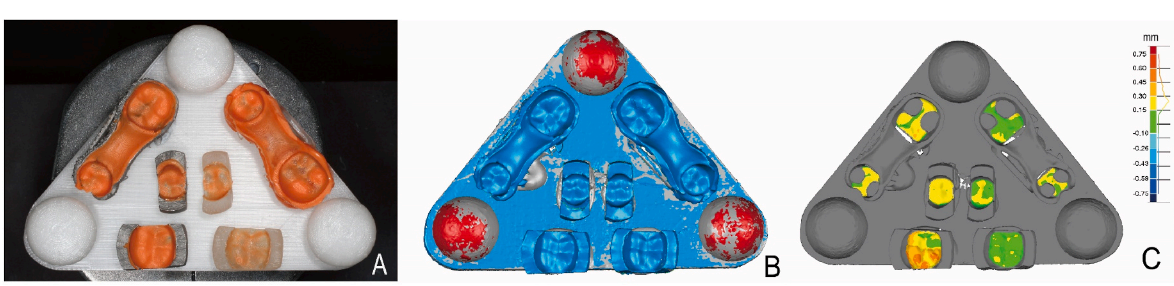

Fig. 3. Internal adaptation assessment of CAD-CAM guides. A, Internal gaps replicated by impression material. B, Three hemispheres were selected for aligning 2 scanning data. C, Internal gap thickness was assessed using 3D-compare analysis.

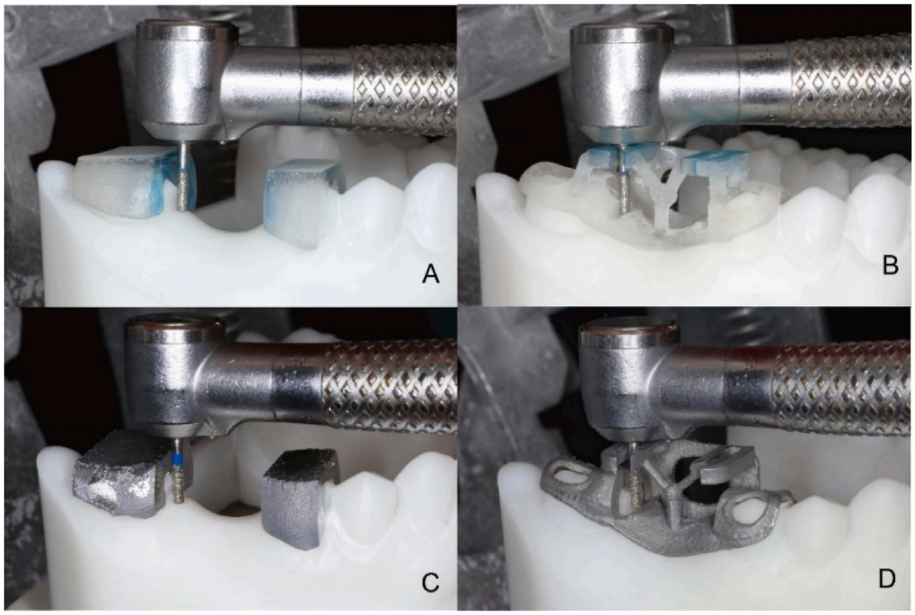

Fig. 4. Tooth preparation of guiding planes assisted by 4 types of CAD-CAM guides. A, Resin guiding device (RGD). B, Resin template (RT). C, Metal guiding device (MGD). D, Metal template (MT).

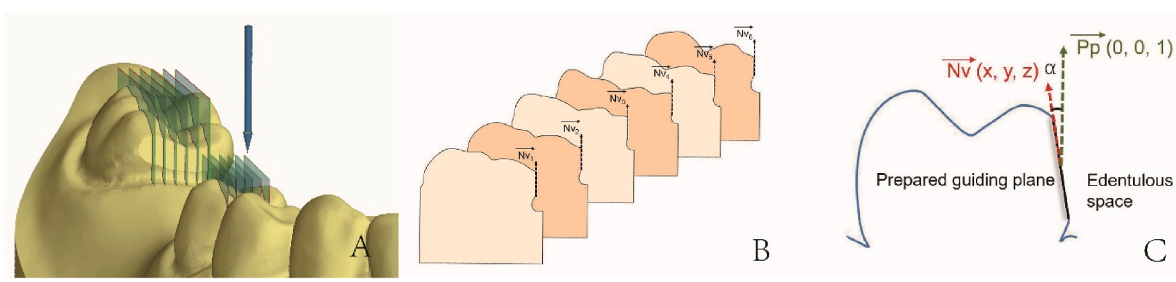

Fig. 5. Evaluation of angle between the prepared guiding plane (test) and the designed path of placement. A, Creation of six cross-sections parallel to the path of placement for each guiding plane. B, The direction vector ($\overrightarrow{Nv}$) of guiding plane preparation on each cross-section. C, Measurement of angle (α) between the direction vector of prepared guiding plane ($\overrightarrow{Nv}$) and the vector ($\overrightarrow{Pp}$) of the path of placement on each cross-section.

prepared guiding plane and each cross-section and $\overrightarrow{Pp}$ (0, 0, 1) is the 3D vector of the direction of the designed path of placement (Fig. 5B and C).

2.8. Three-dimensional trueness and precision assessment

The 3D trueness and 3D precision of guiding plane preparation were evaluated in the Geomagic Wrap 2015 software. The 3D compare analysis between the virtually designed guiding planes (reference) and prepared guiding planes (test) of two abutment teeth (FDI #45 and #47) was conducted and the root-mean-square (RMS) estimation values were calculated to evaluate the 3D trueness of guiding plane preparation. The representative color-coded maps of 3D deviation of 3D trueness of

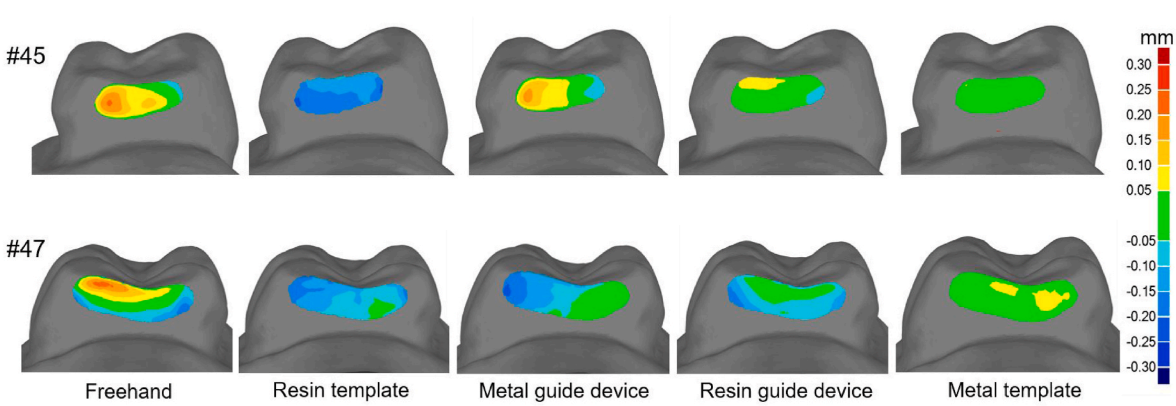

Fig. 6. Representative color-coded maps of 3D deviation of 3D trueness of guiding plane preparation. Green: deviation ≤50 μm. Yellow through red: inadequate preparation. Cerulean blue through dark blue: excessive preparation.

guiding plane preparation were generated (Fig. 6).

Five test casts were randomly selected from each group, after that, the pairwise comparisons of the 5 test casts were performed within the group (10 pairs for each group) and the RMS values were calculated for assessing the 3D precision of guiding plane preparation of two abutment teeth (FDI #45 and #47). The RMS values were calculated using the following formula [27]:

$$RMS = \frac{1}{\sqrt{n}} \times \sqrt{\sum_{i=1}^{n} \left(x_{1,i} - x_{2,i}\right)^2}$$

Where $x_{1,i}$ is the measuring point i in the test data, $x_{2,i}$ is the measuring point i in the Reference data, and n is the total number of measuring points.

2.9. Statistical analysis

A sample calculation was firstly performed basing on a pilot study (n = 5) using statistical software (G*Power 3, Heinrich Heine), which indicated that having at least 2 casts per group will reveal direction trueness difference of specimens with the power of 80% at a significance level of 0.05. In this in vitro study, 22 specimens per group (direction trueness and 3D trueness) and 5 specimens per group (3D precision) were selected for minimizing the possibility of type-I and type-II errors.

All statistical analysis was performed using statistical software (IBM SPSS Statistics 19, IBM Corp). The Shapiro–Wilk tests and the Levene's test data were performed for investigating the data normality and the equivalence for variance. One-way ANOVA was used to estimate the differences of the internal adaptation of CAD-CAM guides and the differences of 3D precision of guiding plane preparation among 5 groups. To evaluate direction trueness, 3D trueness and 3D precision of guiding plane preparation between the 2 abutment teeth (#45 and #47), the independent sample *t* tests and Mann–Whitney *U*-tests were calculated. To analyze the preparation direction trueness and 3D trueness among 5 groups, the Kruskal–Wallis *H* tests, post hoc Mann–Whitney *U*-tests, and Bonferroni correction ($\alpha = 0.005$) were calculated. The level of statistical significance was set to $\alpha = 0.05$.

3. Results

Statistically significant differences were found in internal adaptation among the 4 CAD-CAM guides ($p < .05$, one-way ANOVA) (Table 3). RT showed the best internal adaptation (133.3 ± 29.1 μm), followed by the RGD group (170.4 ± 38.6μm), MT group (200.4 ± 33.4 μm), and MGD group (234.3 ± 35.2 μm).

Statistically significant differences were also found in direction trueness, 3D trueness and 3D precision of guiding plane preparation among five groups ($p < .05$) (Fig. 7). The guiding plane preparation that was performed assisting by MT (triple-constraint guiding structure and Co–Cr alloy) showed the best accuracy (direction trueness, 3D trueness and 3D precision). In most of the analyses except for 3D precision of the right second molar, the guiding plane preparation that was performed by freehand had the lowest accuracy (direction trueness, 3D trueness and 3D precision). Furthermore, in most of the analyses except for 3D precision of the right second molar ($p > .05$), no statistically significant difference was found in accuracy of guiding plane preparation among the other test groups (RT, RGD and MGD).

Table 3
Internal adaptation of CAD-CAM guides(n = 22, μm).

CAD-CAM guide	Mean ± Standard Deviation	Maximum	Minimum
RGD	170.4 ± 38.6[a]	223.0	101.4
MGD	234.3 ± 35.2[b]	300.7	167.5
RT	133.3 ± 29.1[c]	190.5	89.1
MT	200.4 ± 33.4[d]	256.3	142.9

RGD, Resin guide device; MGD, Metal guide device; RT, Resin template; MT, Metal template. Significant by One-way ANOVA; $p < .05$. [abcd] Different letters indicate significant differences by Bonferroni test; $p < .05$.

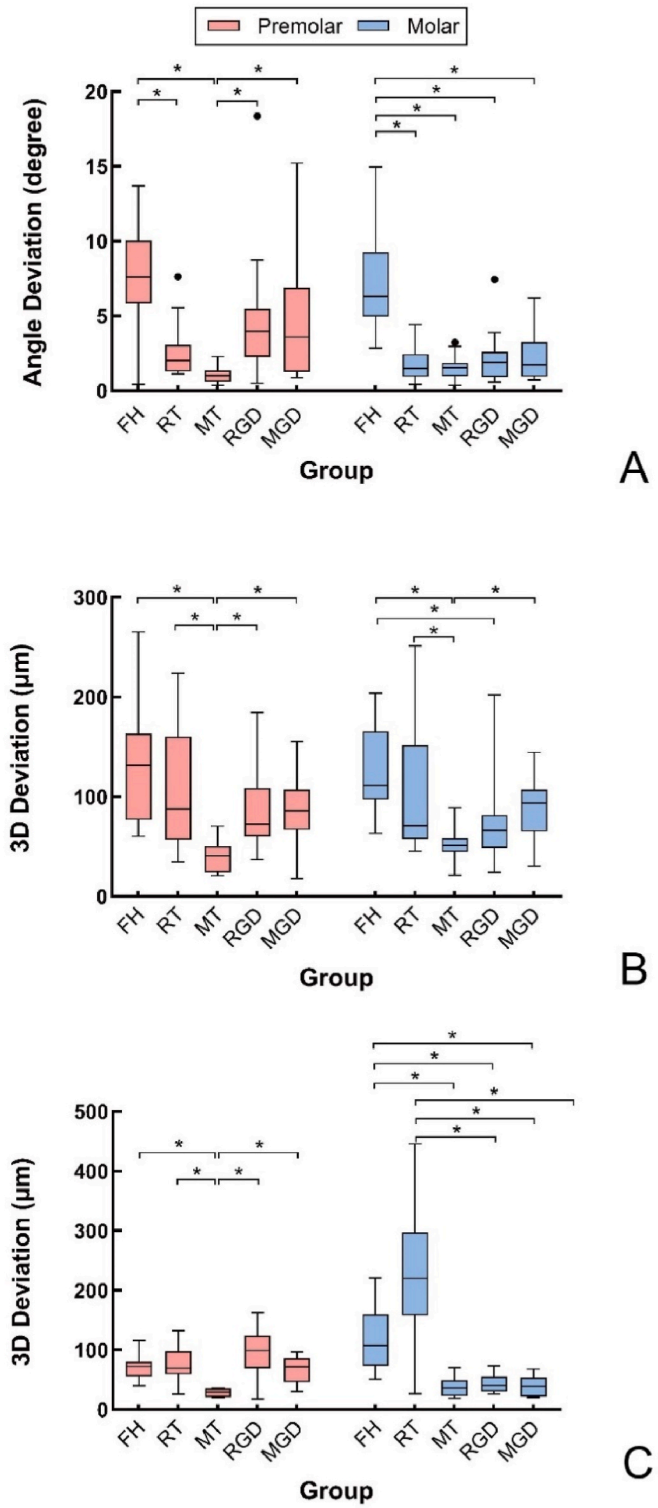

Fig. 7. Boxplots of accuracy of guiding plane preparation. A, Direction trueness. B, 3D trueness. C, 3D precision. *Asterisk indicates statistically significant difference ($p < .05$).

Table 4 shows the result of guiding plane preparation accuracy (direction trueness, 3D trueness and 3D precision) of both abutment teeth in the 5 groups. The MT group showed the best direction trueness [0.99 (0.76)°], 3D trueness (39.7 ± 14.6 μm), and 3D precision (28.6 ± 6.8

Table 4
Direction trueness, 3D trueness and 3D precision of guiding plane preparation of two abutment teeth (FDI #45 and #47).

	Group	N	Premolar				Molar				p
			Mean	SD	Median	IQR	Mean	SD	Median	IQR	
Direction trueness (°)	FH	22	7.78	3.18	7.61	4.21	7.03	2.83	6.33	4.29	0.313*
	RT	22	2.51	1.64	2.01	1.78	1.64	0.98	1.49	1.52	0.027**
	MT	22	1.09	0.56	0.99	0.76	1.52	0.74	1.56	0.9	0.038**
	RGD	22	4.48	3.71	3.98	3.22	2.1	1.55	1.88	1.69	0.001**
	MGD	22	4.69	4.03	3.57	5.66	2.29	1.7	1.72	2.34	0.035**
3D trueness (μm)	FH	22	133.3	63.5	131.5	86.6	125.2	41.7	111.1	68.7	0.628*
	RT	22	106.3	59.8	87.9	103.6	108.9	64.4	70.8	94.3	0.833**
	MT	22	39.7	14.6	41.0	26.2	52.2	15.0	51.1	13.9	0.008*
	RGD	22	85.7	35.5	72.5	48.4	68.5	35.5	66.0	33.2	0.080**
	MGD	22	87.5	33.6	85.7	40.2	90.6	28.5	93.8	41.8	0.740*
3D precision (μm)	FH	5	71.7	21.1	72.6	75.9	118.2	53.5	107.6	170.1	0.020*
	RT	5	75.7	29.2	69.5	106.2	227.5	134.6	220.2	419.3	0.030*
	MT	5	28.6	6.8	29.2	16.5	37.5	16.6	36.0	51.3	0.133*
	RGD	5	96.7	46.8	98.8	144.9	43.8	15.2	40.6	47.0	0.003*
	MGD	5	67.3	22.3	71.8	66.7	39.5	16.5	39.5	47.9	0.005*

FH, Freehand; RGD, Resin guide device; MGD, Metal guide device; RT, Resin template; MT, Metal template. IQR, interquartile range. *Significance determined by Independent sample *t*-test, $p < .05$; **Significance determined by Mann–Whitney *U* test, $p < .05$.

μm) of guiding plane preparation among 5 groups. Statistically significant differences were found in direction trueness and 3D trueness of the MT group between 2 abutment teeth ($p < .05$). The FH group showed the lowest direction trueness (7.78 ± 3.18°) and 3D trueness (133.3 ± 63.5 μm), whereas the group RT had the lowest 3D precision (227.5 ± 134.6 μm) of the right second molar.

4. Discussion

The results showed that the null hypothesis that the guiding structure and 3D-printing material of CAD-CAM guide have no effect on tooth preparation accuracy of guiding plane was rejected.

All the resin casts were printed using a high-precision SLA printer (nominal accuracy 50 μm, repositioning precision 10 μm) and were prepared within two weeks for avoiding the aging influence of the photopolymerizing resin [28]. The PolyJet printer (16 μm) and SLM printer (30 μm) had high resolution and their printing accuracy had been systematically assessed (ISO 178 and ASTM F2792-12a) in previous studies [29–31].

The precision of 3D measurements was controlled in this study. All scanning processes were conducted according to manufacturing guidelines by a fully trained operator (H.B.) using a high-precision laboratory scanner (ISO 12836). Peter et al. reported that the RMS values of less than 50 μm was considered to be a clinical acceptable fit of data alignment [32]. In the present study, the RMS values of the "Best-fit registration" were within the range of 10–30 μm indicating a good internal fit.

The internal adaptation of the CAD-CAM guides was firstly assessed because it was a prerequisite for utilizing the CAD-CAM guides. The internal occlusal gap of Co–Cr crowns printed using the SLM technology was reported between 250 μm and 350 μm in previous studies [33]. In this study, the internal adaptation of the 4 types of CAD-CAM guides within the clinically acceptable range [34].

The PolyJet manufactured resin CAD-CAM guides showed better internal adaptation than the SLM manufactured metal CAD-CAM guides having the identical guiding structure. That could be explained by a higher printing accuracy of the PolyJet printer [20]. Furthermore, the resin CAD-CAM guides were more likely to tightly fit on abutment teeth with finger pressure. And remaining protruding metal pearls of intaglio surface obstructed the insertion of metal CAD-CAM guides [21]. In this study, MT and RT of long spans (3 units) showed superior internal adaptation than RGD and MGD of one unit. The smaller internal gaps of RT and MT than that of RGD and MGD may be explained by excess impression materials overflowed from occlusal windows. It is still unclear whether using other methods to assess internal adaptation will obtain similar results.

Accuracy consists of trueness and precision (ISO 5725-1). Trueness represents how the measurements deviate from the actual objects measured, and precision means how close a series of measurements of the same object are to each other. Direction trueness was indicated by the angle between the prepared guiding plane (test) and the designed path of placement of RPD in this study. Because the angle was measured on cross-sections, hence the direction precision was not evaluated in this study.

In the present study, the direction trueness of guiding plane preparation of FH group was similar with the result (7.15 ± 5.10°) reported by Uemura E et al. [22]. In another study, the direction trueness of guiding plane prepared using MT was close to that using the rigidly constrained equipment ParalAB (1.02 ± 0.85°), indicating that the MT can strictly constraint the cutting tools during tooth preparation [22]. Furthermore, MT was easier to intraorally utilize than ParalAB as its smaller size, particularly to utilize at the posterior teeth.

Previous studies generally analyzed the parallelism of guiding plane preparation but not took the preparation depth into account [22,35]. In this study, the 3D trueness and 3D precision of guiding plane preparation were also assessed for obtaining a more comprehensive result. In terms of 3D trueness and 3D precision of guiding plane preparation, the RMS values of MT group were significantly smaller than that of RGD and MGD groups, especially for preparing the distal guiding plane of the right second premolar (FDI #45). Surprisingly, both of the FH and RT showed poorer 3D trueness and 3D precision than other groups and no statistically significant difference was found between the 2 groups, indicating that the RT assisted procedure lacked of adequate guidance for guiding plane preparation. The complicated structure of RT hampered direct vision of the target tooth surface, resulting more wear of RT than that of RGD. The similar wear was not found on the MT, that may be explained by the high-hardness of Co–Cr alloy. The discrepancies of accuracy values of guiding plane preparation among five groups were small in this study may due to a small designed preparation depth of guiding planes (268 μm). Furthermore, the 3D precision of guiding plane preparation has been improved as the number of preparation times increased.

The results indicated that the CAD-CAM guides was good for improving guiding plane preparation, respect to the freehand procedure.

The parallel guiding planes will increase stability and retention of RPD and satisfaction of patients [9]. Applying CAD-CAM guides not only help novices to accurately prepare guiding planes but it could also help experienced and inexperienced dentists to prepare parallel guiding planes in a simple and predictable way. Additionally, fast and reliable tooth preparation could be conducted for frail elder patients using CAD-CAM guides [36]. Compared with MT and RT, RGD and MGD with single-plane guiding structure can simplify the design process, save 3D-printing material and reserve the direct vision of target tooth surface, although their constraint ability for the movement of diamond rotary instrument were poorer.

Although the CAD-CAM guides assisted procedure can improve tooth preparation, the design and fabrication process required additional time and cost. Some of the advantages of the digital workflow may be diminished by the increased cost or technique sensitivity. Hence dentists should receive systematic training before engaging in comparable types of digital treatments. The potential benefits for patients and dentists contain reduced chairside time, reduction of the follow-up visits, and long-term success of RPDs. Along with development of the special design software and AM technology, the designing process will become more cost-effective in the future, which just like the implant surgical template. With the development of the predictable tooth preparation technology, the accurate preparation of rest seats and groove for embrasure clasps should be also considered. It is expected that RPD will be pre-fabricated according to the virtually prepared cast and be immediately delivered to the patient after the tooth preparation performed using CAD-CAM guides at the second visits [18,37]. Such digital workflow of RPD therapy will simplify the present clinical procedure with the development of CAD-CAM technology [38].

Limitations of this in vitro study was that it did not consider tooth hardness, tooth mobility, saliva, soft tissue, mouth opening of patient, and movement of patient. Additionally, RT and RGD were printed using translucent resin material, which made it is difficult for the operator to distinguish the position of the designed guiding plane. Hence, the guiding surfaces of RGD and RT were marked in blue, and all preparations were performed in the brilliant light. In this study, tooth preparation was performed on the same mandibular casts by the same dental postgraduate student for avoiding unexpected interferences caused by different dental arches and operators. The effect of dentist experience and abutment tooth position have not yet been evaluated. Clinical trials are further needed to be conducted on natural teeth.

5. Conclusion

Within the limitations of this in vitro study, the following conclusions were drawn:

1. The CAD-CAM guides assisted procedure can improve tooth preparation of guiding planes, respect to freehand procedure.
2. The Co–Cr alloy guides (metal template) with triple-constraint guiding structure can assist to prepare accurate guiding planes of RPD without need of direct vision.
3. The resin guide with complex guiding structure (triple-constraint) could lead to more imprecise guiding plane preparation than that with single-plane guiding structure.

CRediT authorship contribution statement

Hefei Bai: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Hongqiang Ye:** Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Project administration. **Hu Chen:** Resources, Writing – review & editing, Supervision. **Yong Wang:** Writing – review & editing, Supervision. **Yongsheng Zhou:** Writing – review & editing, Supervision. **Yuchun Sun:** Software, Resources, Visualization, Project administration, Funding acquisition.

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