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The accuracy of a novel 3D digital evaluation method of intraoral fitness for removable partial dentures

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ABSTRACT

With the development of three-dimensional (3D) scanning and measurement technologies, the internal adaptation of restorations was measured by the 3D analysis method. The purpose of this study was to explore a novel 3D digital evaluation method to assess the intraoral fitness of removable partial dentures (RPDs) and evaluate the accuracy of this novel digital method in vitro. A 3D digital method to evaluate the clinical fitness of RPD was introduced. A standard stone cast of a partially edentulous mandible simulating the oral tissues and a corresponding RPD were used to evaluate the accuracy of this novel digital method (3D analysis on duplicated polyether cast) and another reported 3D digital evaluation method (3D analysis on RPD directly) for intraoral fitness of RPD in vitro. 12 polyvinyl siloxane (PVS) replica specimens were fabricated in each method in vitro, and the thicknesses of these PVS replicas were measured by 3D analysis on duplicated polyether cast (named Polyether group), 3D analysis on RPD directly (named Denture group), and 3D analysis on the stone cast (named Stone group), respectively. The thicknesses of PVS replicas were compared with analyses of variance (ANOVA) to evaluate the accuracy of these methods ($\alpha = 0.05$). The accuracy based on the mean thickness of the PVS replicas of Polyether group were better than that of Denture group ($P < 0.05$) and had no statistical difference with that of Stone group ($P > 0.05$). 3D analysis on duplicated polyether cast has comparable trueness and precision to 3D analysis on the stone cast and is feasible for evaluating clinical fitness of RPD.

1. Introduction

Despite the increasing popularity of implant-supported prostheses in recent years, removable partial dentures (RPDs) are still considered as important prostheses for partially edentulous arches. Good internal fit is one of the features to ensure good quality of RPDs, which can reduce plaque accumulation and torque forces on abutment teeth [1]. Some methods have been reported in the current literature to evaluate the fit of RPDs [2–4]. A previous study proposed a method that sectioned the prostheses seated on casts to assess their internal fitness, but this was not suitable for clinical cases [2,5]. Previous studies proposed visual inspection [6] and a pressing test [7] to evaluate the clinical fit of RPDs, these methods were useful for the qualitative evaluation alone. For quantitative evaluation, certain researchers have used polyvinyl siloxane (PVS) to reproduce the space between rest and major connector of RPDs and intraoral tissues [3,8]. Thickness of the PVS replicas could be measured in various methods, using a caliper [9], profile projector [4,10,11], stereomicroscope [8,12–16], and microcomputed tomography [17] which would indirectly represent the space between RPD and intraoral tissues. However, the number and location of measuring points could affect the accuracy of measurement [18].

With the development of three-dimensional (3D) scanning and measurement technologies, a 3D measurement method of crown fit, which was a non-destructive optical technique, was introduced by Kelly et al. [19] Some studies also evaluated the internal adaptation of restorations by measuring the thicknesses of PVS replicas between the restorations and casts by using 3D analysis method [20–22]. Surface reconstruction is the key to 3D-based reverse engineering, and the corresponding deviation should be calculated to evaluate the accuracy of surface reconstruction. The reverse engineering software program was

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used to construct an accurate surface for surface division and take the point cloud as the reference object to test the deviation of the model and point cloud. This method can reflect the fitness of the restoration more comprehensively and effectively because it measures a large number of distances between the restoration and the corresponding cast in the software program [23–26]. However, there is no acknowledged or standardized digital method to evaluate the clinical fitness of RPDs in vivo. This article explores a novel 3D digital evaluation technique, which uses a dental laboratory scanner and a 3D analysis software program to measure the thickness of PVS replicas to assess the fitness of RPDs in vivo.

The purpose of this study was to explore a novel 3D digital evaluation method to assess the intraoral fitness of RPDs and evaluate the trueness and precision of this novel digital method (3D analysis on duplicated polyether cast) and another reported 3D digital evaluation method (3D analysis on RPD directly) for intraoral fitness of RPD in vitro. The null hypotheses were that no significant differences in terms of trueness and precision would be found among the 3 kinds of methods (3D analysis on duplicated polyether cast, 3D analysis on RPD directly, and 3D analysis on the stone cast).

2. Materials and methods

1. A novel digital method (3D analysis on duplicated polyether cast)

A novel digital method that can evaluate the intraoral fitness of RPD named 3D analysis on duplicated polyether cast is introduced. Ethical approval was granted by the School and Hospital of Stomatology, Peking University (PKUSSIRB-201734042), and the participant provided informed consent.

1.1 Fabricate PVS replica

A patient with dentition defects was selected and treated using an RPD. The RPD was adjusted in the oral cavity to ensure that it was well seated by visual inspection and pressing test and the occlusal relationship was suitable. The RPD, with injected light-body PVS impression material (Variotime Light Flow, Heraeus Kulzer GmbH) on the intaglio surface, was seated well in the mouth keeping the patient maintaining the maximal intercuspal position until PVS completely polymerizes. The thickness of the PVS replica represents the space between RPD and corresponding intraoral tissues.

1.2 Fabricate polyether cast

An impression of the defective dentition, including RPD and the PVS replica, was made by using a stock metal tray with alginate impression material (ALGINoplast, Heraeus Kulzer GmbH). After the alginate impression material was completely set, the impression containing RPD and the PVS replica was removed from the patient's mouth (Fig. 1A). The auto-mixed polyether impression material (3 M ESPE Impregum, 3 M) was injected into the alginate impression containing RPD and the PVS replica to duplicate the shapes of the dentition and residual alveolar ridge with polyether. Subsequently, the base of the polyether cast was fabricated using silicone putty (Rapid, COLTENE) before the polyether impression material was polymerized. After the silicone putty and polyether impression material were completely polymerized, the alginate impression was removed, leaving RPD and the PVS replica on the polyether cast. Excessed PVS and polyether impression material that may hinder RPD dislocation were removed by using a sharp scalpel (Fig. 1B). Then the RPD was removed gently, leaving the PVS replica attached to the surface of the polyether cast (Fig. 1C).

1.3 3D analysis of PVS replica

The polyether cast attached with the PVS replica was scanned using a dental laboratory scanner (D2000, 3shape A/S) with a scanning accuracy of 5 μm (ISO 12836). Subsequently, the PVS replica was removed gently and the polyether cast was scanned alone. Finally, these two 3D images were exported into the standard tessellation language (STL) format, which was named "Test model" and "Ref model" sequentially. These two 3D images were imported to a reverse engineering software program (Geomagic Studio 2013, Raindrop Geomagic Inc.) for 3D measurement and analysis. According to the non-measurement areas that were the same in both 3D images, the Test model was registered to the Ref model that was fixed and acted as the reference object by using the "Best fit alignment" command [27]. The root mean square (RMS) value of the selected area used in best fit alignment was obtained by the "3D compare" command. The measuring areas in the Test model and the Ref model, such as occlusal rests, major connector, and denture base, were selected accurately by the "Creating a boundary from spline" command in the Geomagic studio software program. The mean discrepancy that represents the thickness of the PVS replica in each area was measured by the "3D compare" command and a color-coded difference map was produced (Fig. 1D, E, F). The gap between RPD and corresponding intraoral tissue was represented by the thickness of the PVS replica, which indicates the fit of RPD.

2. 3D analysis directly on RPD

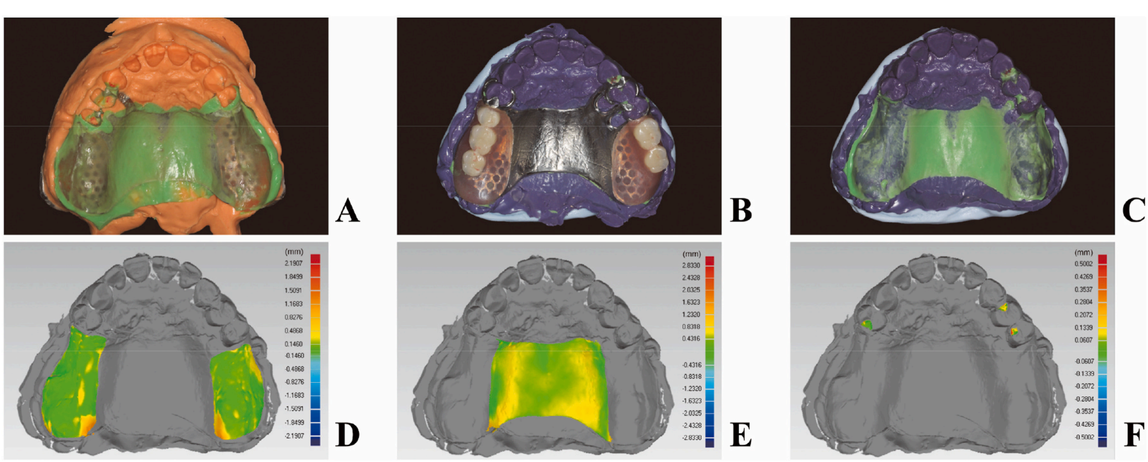

Fig. 1. 3D analysis on duplicated polyether cast. (A) Alginate impression with RPD and PVS replica. (B) Duplicating shape of intraoral tissues with polyether. (C) PVS replica on polyether cast after removing RPD. 3D color-coded map of the thickness of PVS replica on (D) Denture base, (E) Major connector, and (F) Occlusal rests. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Same with this novel digital method, 3D analysis directly on RPD also can evaluate the clinical fitness for RPD by duplicating the space between RPD and corresponding intraoral tissues using the PVS replicas [28]. With the same processes in 3D analysis on duplicated polyether cast method, the RPD with the PVS was seated well in the mouth keeping the patient maintaining the maximal intercuspal position until PVS completely polymerized. RPD with the PVS replica was removed from the patient's mouth gently. However, there aren't non-measurement areas in this method, the registration framework was fabricated for best-fit alignment and scanned using a dental laboratory scanner directly (Fig. 2A and B). Subsequently, the PVS replica was removed and the intaglio surface of RPD was scanned alone. The 3D measurement and analysis process was the same as that of the 3D analysis on duplicated polyether cast (Fig. 2C, D, E, F).

3. 3D analysis on the stone cast method

To evaluate the accuracy of these two evaluation methods in vitro, a standard stone cast of a partially edentulous mandible was used for simulating the oral tissues and fabricating an RPD. The RPD with cobalt-chromium (Co-Cr) alloy framework was manufactured using traditional methods. 3D analysis on the stone cast method is an accurate method for detecting the suitability of the intaglio surface of the restorations [21, 29] that only can be used in vitro. The PVS replica was fabricated to analyze the fitness of RPD. The RPD with light-body PVS impression material was seated well on the stone cast and was forced 2 kg until PVS was completely polymerized (Fig. 3A). Excessed PVS that obstructed RPD dislocation were removed by using a sharp scalpel (Fig. 3B). Then RPD was removed gently, leaving the PVS replica attached to the stone cast (Fig. 3C). The thickness of the PVS replica represents the gap between RPD and the stone cast. 3D measurement and analysis were the same as that of 3D analysis on duplicated polyether cast method (Fig. 3D, E, F).

4. Accuracy of two evaluation methods

12 PVS replica specimens were fabricated using the same stone cast and RPD in each group and the thicknesses of PVS replicas of these 3 groups were measured by 3D analysis on duplicated polyether cast (named Polyether group), 3D analysis on RPD directly (named Denture group), and 3D analysis on the stone cast (named Stone group), respectively. To keep the PVS replicas adhering to the intaglio surface of RPD while the RPD dislodging from the stone cast in the Polyether group and the Denture group, which were the same as in the mouth, a thin layer of separating agent (Dental separating agent, RUIER) was coated on the stone cast. 3D analyses were performed to measure the thickness of the 36 PVS replica specimens. The trueness of PVS replica thickness was evaluated by the deviation of the Polyether group and the Denture group from the Stone group. The precision of PVS replica thickness was evaluated by deviation within each group. All these processes were performed by the same person (J. Y.).

5. Statistical analysis

The power analysis (PASS 11; NCSS, Utah, USA) was used to calculate the sample size (power = 90%; $\alpha = 0.05$). The required sample size was lesser than or equal to the sample size collected. Statistical analyses were performed using SPSS (IBM SPSS Statistics 20.0, IBM SPSS Inc.). The Shapiro-Wilk test and Levene test ($\alpha = 0.05$) were used for determining normality and homogeneity of variances between each group, respectively. If the normality assumption was met, a one-way analysis of variance (ANOVA) was used to evaluate differences among 3 groups ($\alpha = 0.05$), and post hoc comparisons were used with the LSD test. When normality and homogeneity assumptions were not met, Kruskal-Wallis non-parametric ANOVA was performed followed by pairwise comparisons, the *P*-value was corrected by the Bonferroni method. The statistical significance level was set at 0.05.

3. Results

3D analysis on duplicated polyether cast can be used to evaluate the clinical fitness of RPD in vivo, the polyether can duplicate the shapes of the dentition and residual alveolar ridge (Fig. 1B). And the PVS replica can adhere to and be completely separated from polyether cast (Fig. 1C). The RMS value of the alignment area of each measurement was 9.51 ± 3.06 μm, in the range of 5.3–19 μm, suggesting good alignment [30].

3.1. Trueness

According to the Shapiro-Wilk test and Levene test, the mean average thickness of the PVS replica in each component of RPD measured by each method satisfies the normality and equality of variance ($P > 0.05$). One-way ANOVA found statistically significant differences among these 3 methods in denture base and occlusal rests of RPD ($P < 0.001$). No significant differences were found among the data of these 3 groups in major connectors of RPD ($P = 0.107$). The mean thicknesses of the PVS replicas measured by 3 methods were shown in Table 1. The data obtained from the Polyether group (178.75 ± 13.87 μm in denture base, 104.83 ± 16.98 μm in occlusal rests) represented significantly smaller than that of the Denture group (222.58 ± 13.18 μm in denture base,

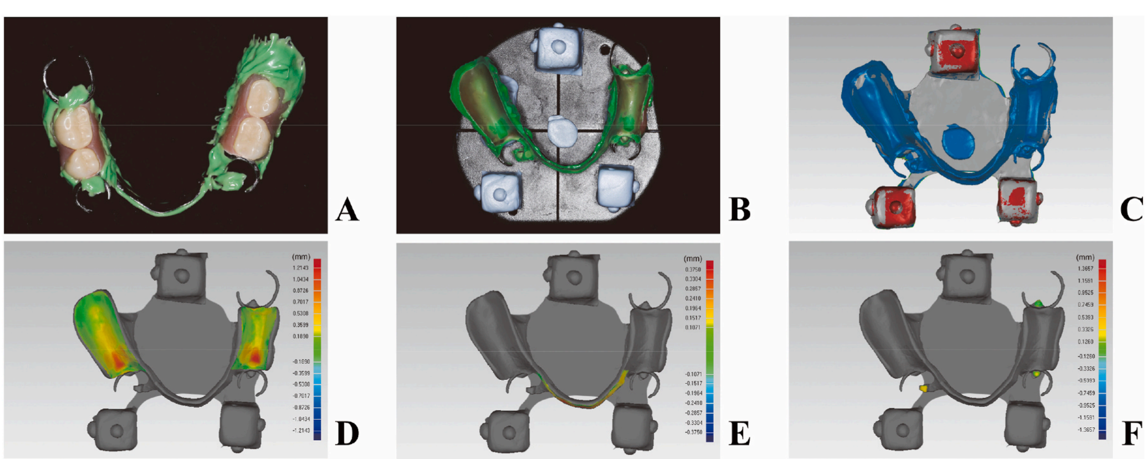

Fig. 2. 3D analysis on RPD directly. (A) The polished surface and (B) Intaglio surface of RPD with PVS replica. Denture with PVS replica after fixed on a registration frame. (C) Registration two 3D image through registration frame. 3D color-coded map of the thickness of PVS replica on (D) Denture base, (E) Major connector, and (F) Occlusal rests. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

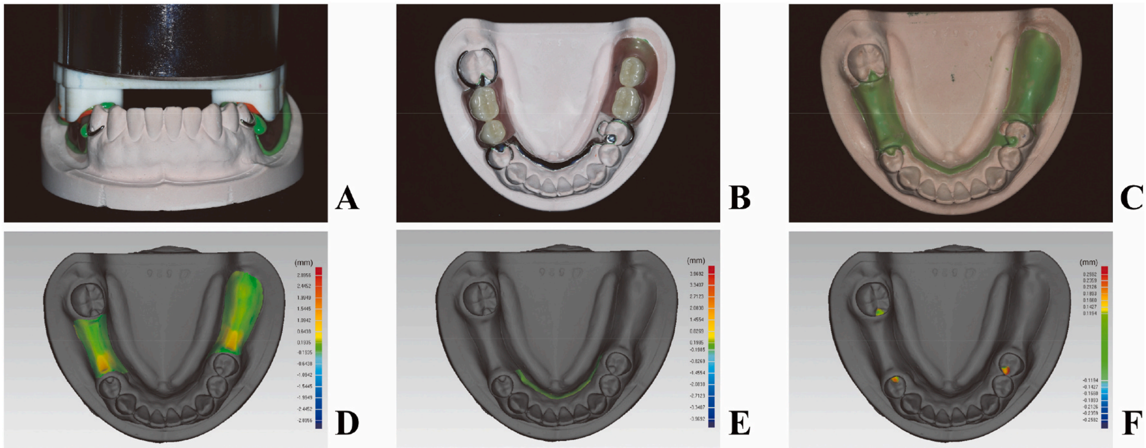

Fig. 3. 3D analysis on the stone cast. (A) Force 2 kg to place RPD well on the stone cast. (B) Remove excess PVS adhered to the polished surface of RPD. (C) Stone cast with PVS replica. 3D color-coded map of the thickness of PVS replica on (D) Denture base, (E) Major connector, and (F) Occlusal rests. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Trueness based on the mean thickness of the PVS replicas for three methods in each component of RPD (Mean ± SD, μm).

	Stone group	Polyether group	Denture group	P
Denture bases	184.17 ± 10.78†	178.75 ± 13.87‡	222.58 ± 13.18†, ‡	<.001*
Major connectors	172.17 ± 13.84	167.17 ± 8.16	158.17 ± 17.45	.107
Occlusal rests	116.08 ± 15.51†	104.83 ± 16.98‡	207.75 ± 39.49†, ‡	<.001*
Total	181.50 ± 10.37†	176.42 ± 13.02‡	215.42 ± 10.66†, ‡	<.001*

The same footnote†, ‡ show the significant differences. *Mean difference significant ($P < 0.05$).

207.75 ± 39.49 μm in occlusal rests). When we compared the data obtained from the Polyether group and the Stone group, the Polyether group showed a smaller value than the Stone group. But no significant difference was observed between them.

3.2. Precision

The averages of the two optional deviations of the thickness of the PVS replica in each component of RPD in each group were shown in Table 2. This data didn't meet with the Shapiro-Wilk test and Levene test. Kruskal-Wallis non-parametric ANOVA found statistically significant differences among these three methods in the major connector and occlusal rests ($P < 0.001$). For the major connector of RPD, pairwise comparison demonstrated the data in the Polyether group (9.30 ± 6.87 μm) was significantly smaller than that in the Stone group (15.67 ± 11.83 μm) and the Denture group (20.52 ± 13.82 μm, $P < 0.001$). For

Table 2
Precision based on the mean thickness of the PVS replicas for three methods in each component of RPD (Mean ± SD, μm).

	Stone group	Polyether group	Denture group	P
Denture bases	12.73 ± 8.45	15.92 ± 11.54	14.62 ± 11.65	.436
Major connectors	15.67 ± 11.83†	9.30 ± 6.87†, ‡	20.52 ± 13.82‡	<.001*
Occlusal rests	17.41 ± 13.45†	19.97 ± 13.43‡	46.53 ± 31.13†, ‡	<.001*

The same footnote†, ‡ show the significant differences. *Mean difference significant ($P < 0.05$).

occlusal rest of RPD, the data in the Denture group (46.53 ± 31.13 μm) was significantly larger than that in the Stone group (17.41 ± 13.45 μm) and the Polyether group (19.97 ± 13.43 μm, $P < 0.001$). For the denture base of RPD, no significant differences were found among the data of these 3 groups ($P > 0.05$).

4. Discussion

The null hypotheses that no differences in terms of trueness and precision would be found among the 3 kinds of methods were rejected.

Reproducing the gap by using a silicone material between the prosthesis and intraoral tissues to evaluate the fitness of the prosthesis has been applied for both fixed dentures and RPDs [8,12]. In previous studies, thicknesses of PVS replicas were presented by the average thickness of several selected points measured using stereomicroscopes [13,14]. For this method, the accuracy of the measurement depends on the number and location of the selected point which is time-consuming. Groten et al. [18] found that at least 50 measurement points were needed to evaluate the margin fitness for each crown. However, due to the complex structure of RPD, no commonly acceptable research about the number and location of measuring points for each component of RPD was reported. 3D analysis method can evaluate the fitness of RPD more accurately and systematically in clinical applications because it selects a large number of measurement points at each component of RPD for measurement [21,26,28]. The 3D analysis in this study showed that about 7200,1500 and 400 measurement points were selected on denture bases, major connector and occlusal rests respectively, which means 9–30 measurement points were selected per square millimeter. Compared with traditional methods, such as cross-sectional measurement of prostheses and PVS replicas, the 3D analysis method not only improve efficiency but also significantly simplify the measuring process and reduce errors resulting from the selection of measurement points [24,25]. In the Stone group measurement of PVS replica is accurate because PVS replica can closely adhere to the stone cast without deformation during displacement of RPD and a large number of measurement points were used to ensure the accuracy of measurement (Fig. 3).[21,29]

Alignment is a key step affecting the result of the 3D analysis. The alignment method used in this study is the same as that reported in previous studies [20,27]. The research by Peters et al. [30] found that the alignment accuracy was acceptable when the RMS value was less than 50 μm and excellent when the RMS value was less than 10 μm. To reduce the measurement deviation caused by alignment, only a non-measurement area was selected during aligning the Test model to the Ref model in this study.

Some researchers used the 3D analysis method to evaluate the fitness of RPD in vitro since PVS replica can adhere to stone cast closely [21, 28]. However, the PVS replica is difficult to adhere to the surface of the soft and hard tissue because of the influence of saliva in vivo. There wasn't any acceptable research about measuring the thickness of the PVS replica using 3D analysis in vivo. Therefore, the accuracy of the methods for the 3D analysis of RPD in vivo was evaluated in vitro using 3D analysis on stone cast as the control group. In this study, a thin layer of separating agent was coated on the stone cast to ensure the PVS replica adhering to the intaglio surface of RPD while the RPD dislodged from the stone cast, which was the same as what happened in the mouth. The thickness of coated separating agent was less than 1 μm based on measurement.

In the present technique, casts were poured with polyether after alginate impressions were made, which was similar to that of pouring stone casts. Polyether has adequate fluidity to allow duplication of the shape of intraoral tissues (Fig. 1B). Besides, because of suitable adhesion to polyether, PVS replicas can adhere to polyether casts when RPD are removed from the casts and can also be completely separated from polyether casts when these casts need to be scanned with and without PVS replicas (Fig. 1C). Two key points must be considered while performing this technique. First, the PVS replica must adhere to the polyether cast when the RPD is taken off from the polyether cast, which is derived from adhesion between the PVS replica and polyether, to ensure this, the excessed PVS material adhered to the polished surface of RPD should be removed with a sharp scalpel. Second, shapes of the dentition and residual alveolar ridge must be duplicated with polyether accurately without any bubbles which can make the measurement value biased. This novel method is suitable not only for evaluating the fitness of RPD but also for checking the internal fitness of other prostheses in vivo.

The results of this study showed that the thickness of PVS replicas in the Denture group represented significantly larger than that of the Stone group, which may result from the following two reasons. First, the PVS replica could not steadily adhere to the intaglio surface of the RPD when the RPD dislodeged from the stone cast forming invisible gaps between the PVS replica and intaglio surface of RPD, which may increase in the measured thickness of the PVS replica. Second, small and complex geometry in RPD, such as occlusal rests and clasps, could not be completely scanned by the optical scanner, which may cause the deviation of the measured thickness of the PVS replica.

The novel 3D digital evaluation method of intraoral fitness (3D analysis on duplicated polyether cast) could be used not only for RPD but also for prostheses containing small or complex geometries which may result in less steady adhesion between PVS and dentures, such as complete denture and maxillofacial prosthesis.

This study has some limitations. In this study, the trueness and precision of 3D analysis on duplicated polyether cast and 3D analysis on denture were measured compared with more accurate 3D analysis on stone cast in vitro because there was no accurate value of the fitness of RPD can be measured in vivo. In this study, both 3D analyses on duplicated polyether cast and 3D analysis on denture simulated intraoral condition in vitro to evaluate the fitness of RPD in vivo. The accuracy of 3D analysis on duplicated polyether cast in vivo needs further verification.

5. Conclusion

As polyether impression material has good fluidity and adhesion with PVS replica, polyether could duplicate the shape of intraoral tissues, and the thickness of PVS replica could be measured by 3D analysis using dental laboratory scanner and reverse engineering software program in vitro. This article demonstrates that the novel 3D digital evaluation method (3D analysis on duplicated polyether cast) we explored could be used to evaluate the clinical intraoral fitness of RPD in vivo which has similar trueness and precision compared with that of 3D analysis on the stone cast.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] A.B. Carr, D.T. Brown, McCracken's Removable Partial Prosthodontics, thirteenth ed., Mosby, 2015, pp. 6–7.

[2] C. Arnold, J. Hey, R. Schweyen, et al., Accuracy of CAD-CAM-fabricated removable partial dentures, J. Prosthet. Dent 119 (2018) 586–592, https://doi.org/10.1016/j.prosdent.2017.04.017.

[3] H. Ye, J. Ning, M. Li, et al., Preliminary clinical application of removable partial denture frameworks fabricated using computer-aided design and rapid prototyping techniques, Int. J. Prosthodont. (IJP) 30 (2017) 348–353, https://doi.org/10.11607/ijp.5270.

[4] K. Takahashi, M. Torii, T. Nakata, et al., Fitness accuracy and retentive forces of additive manufactured titanium clasp, J. Prosthodont. Res. 64 (2020) 468–477, https://doi.org/10.1016/j.jpor.2020.01.001.

[5] E. Dolev, Y. Bitterman, A. Meirowitz, Comparison of marginal fit between CAD-CAM and hot-press lithium disilicate crowns, J. Prosthet. Dent 121 (2019) 124–128, https://doi.org/10.1016/j.prosdent.2018.03.035.

[6] R.P. Frank, J.S. Brudvik, B. Leroux, et al., Relationship between the standards of removable partial denture construction, clinical acceptability, and patient satisfaction, J. Prosthet. Dent 83 (2000) 521–527, https://doi.org/10.1016/s0022-3913(00)70008-4.

[7] M.T. Wong, M.J. Calverley, W.W. Nagy, Removable partial denture framework try-in, J. Prosthet. Dent 69 (1993) 363–368, https://doi.org/10.1016/0022-3913(93)90181-m.

[8] J.W. Lee, J.M. Park, E.J. Park, et al., Accuracy of a digital removable partial denture fabricated by casting a rapid prototyped pattern: a clinical study, J. Prosthet. Dent 118 (2017) 468–474, https://doi.org/10.1016/j.prosdent.2016.12.007.

[9] D. Dunham, J.S. Brudvik, W.J. Morris, et al., A clinical investigation of the fit of removable partial dental prosthesis clasp assemblies, J. Prosthet. Dent 95 (2006) 323–326, https://doi.org/10.1016/j.prosdent.2006.02.001.

[10] V. Gowri, N.P. Patil, R.K. Nadiger, et al., Effect of anchorage on the accuracy of fit in removable partial denture framework, J. Prosthodont. 19 (2010) 387–390, https://doi.org/10.1111/j.1532-849X.2010.00594.x.

[11] Y. Kokubo, Y. Nagayama, M. Tsumita, et al., Clinical marginal and internal gaps of In-Ceram crowns fabricated using the GN-I system, J. Oral Rehabil. 32 (2005) 753–758, https://doi.org/10.1111/j.1365-2842.2005.01506.x.

[12] S. Suzuki, Y. Katsuta, K. Ueda, et al., Marginal and internal fit of three-unit zirconia fixed dental prostheses: effects of prosthesis design, cement space, and zirconia type, J. Prosthodont. Res. 64 (2020) 460–467, https://doi.org/10.1016/j.jpor.2019.12.005.

[13] M.J. Kim, Y.J. Choi, S.K. Kim, et al., Marginal accuracy and internal fit of 3-D printing laser-sintered Co-Cr alloy copings, Materials 10 (2017), https://doi.org/10.3390/ma10010093.

[14] B. Lee, K.C. Oh, D. Haam, et al., Evaluation of the fit of zirconia copings fabricated by direct and indirect digital scanning procedures, J. Prosthet. Dent 120 (2018) 225–231, https://doi.org/10.1016/j.prosdent.2017.08.003.

[15] H. Al-Imam, S. Michou, A.R. Benetti, et al., Evaluation of marginal and internal fit of acrylic bridges using optical coherence tomography, J. Oral Rehabil. 46 (2019) 274–281, https://doi.org/10.1111/joor.12746.

[16] P. Kohorst, H. Brinkmann, M.P. Dittmer, et al., Influence of the veneering process on the marginal fit of zirconia fixed dental prostheses, J. Oral Rehabil. 37 (2010) 283–291, https://doi.org/10.1111/j.1365-2842.2009.02053.x.

[17] C.C. Peng, K.H. Chung, H.T. Yau, et al., Assessment of the internal fit and marginal integrity of interim crowns made by different manufacturing methods, J. Prosthet. Dent 123 (2020) 514–522, https://doi.org/10.1016/j.prosdent.2019.02.024.

[18] M. Groten, D. Axmann, L. Pröbster, et al., Determination of the minimum number of marginal gap measurements required for practical in-vitro testing, J. Prosthet. Dent 83 (2000) 40–49, https://doi.org/10.1016/s0022-3913(00)70087-4.

[19] J.R. Kelly, S.H. Davis, S.D. Campbell, Nondestructive, three-dimensional internal fit mapping of fixed prostheses, J. Prosthet. Dent 61 (1989) 368–373, https://doi.org/10.1016/0022-3913(89)90147-9.

[20] Y. Liu, H. Ye, Y. Wang, et al., Three-dimensional analysis of internal adaptations of crowns cast from resin patterns fabricated using computer-aided design/computer-assisted manufacturing technologies, Int. J. Prosthodont. (IJP) 31 (2018) 386–393, https://doi.org/10.11607/ijp.5678.

[21] H. Ye, X. Li, G. Wang, et al., A novel computer-aided design/computer-assisted manufacture method for one-piece removable partial denture and evaluation of fit, Int. J. Prosthodont. (IJP) 31 (2018) 149–151, https://doi.org/10.11607/ijp.5508.
[22] B.E. Dahl, J.E. Dahl, H.J. Rønold, Digital evaluation of marginal and internal fit of single-crown fixed dental prostheses, Eur. J. Oral Sci. 126 (2018) 512–517, https://doi.org/10.1111/eos.12576.
[23] R.G. Luthardt, G. Bornemann, S. Lemelson, et al., An innovative method for evaluation of the 3-D internal fit of CAD/CAM crowns fabricated after direct optical versus indirect laser scan digitizing, Int. J. Prosthodont. (IJP) 17 (2004) 680–685, https://doi.org/10.1007/s00384-004-0613-5.
[24] K. Kuhn, S. Ostertag, M. Ostertag, et al., Comparison of an analog and digital quantitative and qualitative analysis for the fit of dental copings, Comput. Biol. Med. 57 (2015) 32–41, https://doi.org/10.1016/j.compbiomed.2014.11.017.
[25] H. Lee, H.S. Kim, K. Noh, et al., A simplified method for evaluating the 3-dimensional cement space of dental prostheses by using a digital scanner, J. Prosthet. Dent 118 (2017) 584–586, https://doi.org/10.1016/j.prosdent.2016.12.014.
[26] A. Tasaka, T. Shimizu, Y. Kato, et al., Accuracy of removable partial denture framework fabricated by casting with a 3D printed pattern and selective laser sintering, J. Prosthodont. Res. 64 (2020) 224–230, https://doi.org/10.1016/j.jpor.2019.07.009.
[27] S. O'Toole, C. Osnes, D. Bartlett, et al., Investigation into the accuracy and measurement methods of sequential 3D dental scan alignment, Dent. Mater. 35 (2019) 495–500, https://doi.org/10.1016/j.dental.2019.01.012.
[28] H. Chen, H. Li, Y. Zhao, et al., Adaptation of removable partial denture frameworks fabricated by selective laser melting, J. Prosthet. Dent 122 (2019) 316–324, https://doi.org/10.1016/j.prosdent.2018.11.010.
[29] K.B. Kim, J.H. Kim, W.C. Kim, et al., Three-dimensional evaluation of gaps associated with fixed dental prostheses fabricated with new technologies, J. Prosthet. Dent 112 (2014) 1432–1436, https://doi.org/10.1016/j.prosdent.2014.07.002.
[30] M.C. Peters, R. Delong, M.R. Pintado, et al., Comparison of two measurement techniques for clinical wear, J. Dent. 27 (1999) 479–485, https://doi.org/10.1016/s0300-5712(99)00027-5.