Original article

Quantitative evaluation of edentulous maxillomandibular relationship record using diagnostic complete dentures fabricated by CAD and 3D printing

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Abstract

Purpose: The present study aimed to quantitatively evaluate the accuracy of the edentulous maxillomandibular relationship record for diagnostic complete dentures fabricated using computer-aided design (CAD) and three-dimensional (3D) printing.
Methods: Six edentulous patients were enrolled. The maxillomandibular relationship obtained from diagnostic complete dentures (DiaCD test group), that obtained from complete dentures with artificial teeth in the intercuspal position (CD control group), and the centric relationship acquired by gothic arch tracing (CR standard group) were recorded, and 3D surface scanning was performed on these records. Using the CR standard group as a reference, the DiaCD test and CD control group displacements were measured in the horizontal antero-posterior, horizontal right-and-left, and vertical directions. The displacements for the DiaCD test group were compared with those for the CD control group using the Wilcoxon matched-pairs signed rank test.
Results: In terms of centric relationship, the 95% confidence interval of displacement in the horizontal antero-posterior direction was (0.54-1.89) mm in the DiaCD test group and (0.32-1.34) mm in the CD control group. The inter-group difference was significant ($P = 0.03$).
Conclusion: It is feasible to record the edentulous maxillomandibular relationship using diagnostic complete dentures fabricated by CAD/3D printing, but the protrusion of edentulous patients should not be neglected.

Keywords: complete denture, computer-aided design, edentulous, maxillomandibular relationship record, three-dimensional printing

Introduction

Establishment of the maxillomandibular relationship record for edentulous patients is a key stage in the production of complete dentures. Occlusal bases, which include record bases and wax rims, are traditionally used for recording maxillomandibular relationships in clinical procedures [1,2]. However, the preparation and use of occlusal bases were depended on clinicians' experience [3]. Clinicians may not be able to record maxillomandibular relationships reliably and consistently because the use of unevenly heated wax in an edentulous mouth may increase the likelihood of base displacement and mandibular deviation. Therefore, the clinical use of occlusal bases is still challenging and time-consuming for most young clinicians [4].

Different techniques have been proposed to reduce the difficulty in recording maxillomandibular relationships by modifying the production of wax rims. Kim et al. [5] proposed a method for reducing the likelihood of occlusal errors related to uneven contact of occlusal rims by adding four vertical wax stops on the manually produced occlusal rim. Sushma et al. [6] developed a new method for recording the centric relationship with the aid of three wax orientation balls, and found that this wax ball technique was faster than the conventional technique, but equally accurate. Additionally, Jayachandran et al. [7] presented a method for establishing the inclination of the occlusal rim by using the hamular notch-incisive papilla plane, making chairside trimming of the rims more straightforward. The above studies demonstrated that the use of wax material is effective for shaping and trimming occlusal rims, but requires some skill and experience in mastering the properties of wax. Digital dental techniques may facilitate the production of occlusal rims, with the advantages of higher accuracy, greater automation, and less reliance on experience.

Recently, computer-aided design/computer-aided manufacturing (CAD/CAM) technology has been integrated into the maxillomandibular relationship record stage for complete dentures. CAD and 3D printing have been used to produce custom trays and gothic arch tracers to acquire definitive impressions and centric relationship records [8-11]. By using intraoral scanning and 3D printing, existing complete dentures of patients can be duplicated, facilitating capture of definitive impressions and the maxillomandibular relationship record [12,13]. In addition, the maxillomandibular relationship can be easily acquired by intraoral scanning of CAD/CAM-produced immediate dentures [14]. Therefore, CAD/CAM technology can shorten the production cycle for complete dentures and simplify the procedure for obtaining the maxillomandibular relationship record. However, there has been no effective method for quantitatively evaluating the accuracy of the edentulous maxillomandibular relationship record obtained using CAD/CAM technology.

To bridge this gap, a quantitative method was proposed for evaluating the accuracy of edentulous maxillomandibular relation records obtained from diagnostic complete dentures prepared using CAD and 3D printing technologies. Based on the position of the centric relationship (CR), displacements of the maxillomandibular relationship recorded from diagnostic complete dentures (DiaCD) were measured and compared with those obtained from new complete dentures (CD) with artificial teeth in the intercuspal position. The null hypothesis was that there would be no differences between the maxillomandibular relationship records obtained using diagnostic complete dentures and those obtained using complete dentures.

Materials and Methods

This non-randomized, self-controlled clinical study was registered with the Chinese Clinical Trial Registry (ChiCTR1900022564) and approved by the Bioethics Committee of the Stomatological Hospital of Peking University, Beijing, P. R. China (PKUSSIRB-201838120). The procedures and risks involved with study participation were discussed with the volunteers, and written informed consent was obtained from all of them.

Six patients (four males and two females, aged 74.3 ± 8.8 years) were enrolled. Patients were eligible for inclusion if they were aged 55-85 years, were completely edentulous, had recovered for at least 3 months after extraction, and were able to understand and cooperate with the requirements of the study. Patients were excluded if they had temporomandibular
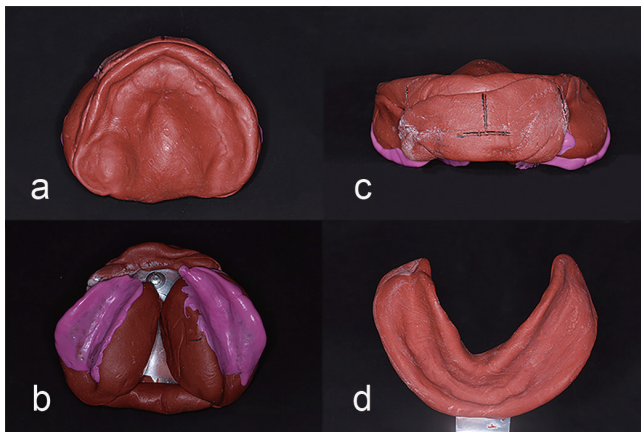
Fig. 1 Preliminary impressions and provisional maxillomandibular relationship for the DiaCD test group. (a) maxillary preliminary impression; (b) bottom view of the provisional maxillomandibular relationship; (c) frontal view of the provisional maxillomandibular relationship; (d) mandibular preliminary impression

Fig. 2 CAD and 3D printing of diagnostic complete dentures. (a) 3D construction of preliminary impressions for the maxillomandibular relationship; (b) CAD of the diagnostic complete dentures; (c) cameo surfaces of 3D printed diagnostic complete dentures; (d) intaglio surfaces of 3D printed diagnostic complete dentures
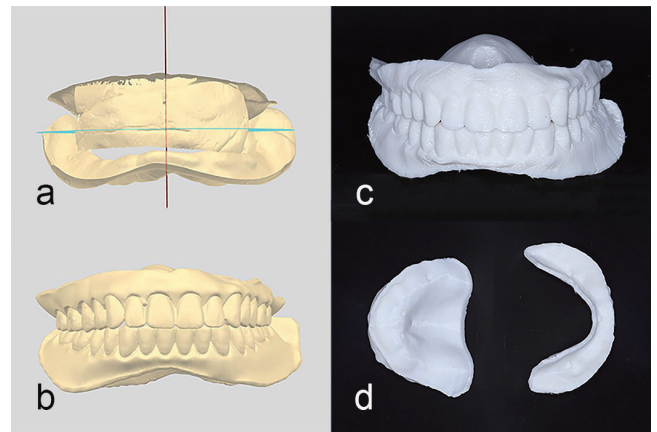

Fig. 3 Recording and 3D scanning of the maxillomandibular relationship recorded using diagnostic complete dentures. (a) front view of a definitive impression with the maxillomandibular relationship; (b) definitive impressions of the maxilla and mandible; (c) 3D scanning of definitive impressions of the maxilla and mandible with their maxillomandibular relationship; (d) maxillary and mandibular jaws with their maxillomandibular relationship

Fig. 4 3D construction of the maxillomandibular relationship for complete dentures

a Lingtong 3D printer with a nozzle diameter of 0.3 mm (Beijing Sinotech Co., Ltd., Beijing, P. R. China) (Fig. 2). The occlusal surfaces of 3D-printed teeth can be adjusted if necessary to balance the bilateral bite force. By using the closed-mouth technique and silicone impression material (Huge Dental Material Co., Ltd.), the diagnostic complete dentures were then used to acquire the definitive maxillomandibular relationships, definitive impressions, and esthetic results (Fig. 3a, b). The definitive impressions of the maxilla and mandible with their maxillomandibular relationships were scanned using a model 3D scanner (Fig. 3c) (Dentscan Y500; Nanjing Geosmart3D Information Technology Co., Ltd., Nanjing, P. R. China), and the maxillary and mandibular jaws with their maxillomandibular relationship in the DiaCD test group were obtained (Fig. 3d).

CD control group acquisition
The new complete dentures were made based on the impressions and maxillomandibular relationships for the DiaCD test group [15]. Balanced occlusion in the complete denture was obtained by adjusting the occlusal surface of artificial teeth through selective grinding at the first insertion, and the occlusion was checked and adjusted on subsequent visits. After being worn for at least 3 weeks, the complete denture was verified in terms of the maxillomandibular relationship, occlusion, lip support and tooth arrangement, and it was confirmed that the patients had no discomfort and were highly satisfied with their complete dentures. The artificial teeth of complete dentures in the intercuspal position were fixed in the patient's mouth, and extraoral scanning of the cameo and intaglio surfaces of the maxillary and mandibular dentures was performed using a Dentscan model 3D scanner. The scanned 3D data were imported into reverse engineering software (Geomagic Studio 2013; 3D Systems Inc., Rock Hill, CA, USA). Based on the common region of the primary and secondary stress-bearing areas, 3D data for the maxillary and mandibular jaws of complete dentures were registered in the intercuspal position (Fig. 4).
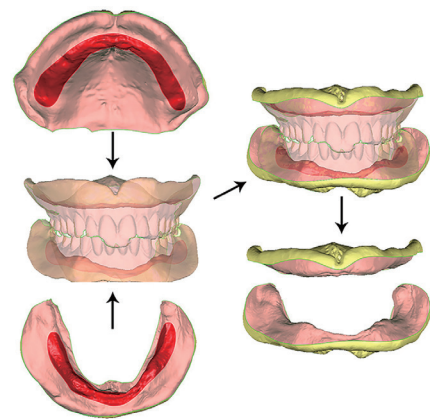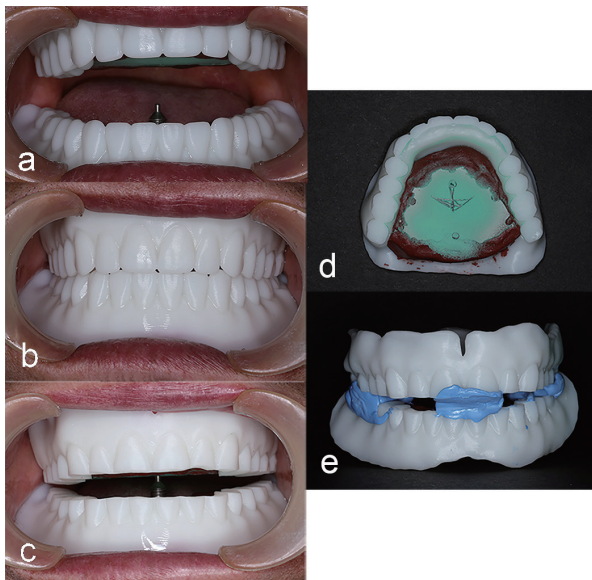
joint disorders, mental illness, highly resorbed ridges, flabby alveolar ridges, pharynx sensitivity, uncontrolled mucosal diseases, or systemic diseases. The following three maxillomandibular relationship records from each patient were obtained: those obtained using diagnostic complete dentures that had been fabricated using CAD and 3D printing (DiaCD test group), those obtained from new complete dentures with artificial teeth in the intercuspal position (CD control group), and centric relationship records obtained by gothic arch tracing (CR standard group). All of the procedures were performed by a single examiner under the guidance of the chief physician.

DiaCD test group acquisition
In principle, by repeating the previously reported study [15], data for the DiaCD test group were acquired from preliminary impressions of the maxilla and mandible obtained using an aluminum tray and plastic modeling impression compound (Shanghai Rong Xiang Dental Material Co., Ltd., Shanghai, P.R. China). The occlusal vertical dimension was determined by referring to the vertical dimension at rest, and the horizontal relationship was determined by neuromuscularly guided bite registration. With softened impression paste on the back of the maxillary tray, the patient was asked to bite until the occlusal vertical dimension was 2 mm shorter than the vertical dimension at rest. The silicone impression material (Huge Dental Material Co., Ltd., Shanghai, P. R. China) was applied to the impression paste to record the preliminary impression more accurately, and then the midline, maxillary canine line and upper lip line were marked. Based on the preliminary impressions and provisional maxillomandibular relationships (Fig. 1), diagnostic complete dentures were constructed using CAD software (Hoteamsoft Co., Ltd., Shandong, P. R. China) and printed using

Fig. 5 Acquisition of the centric relationship record. (a, b) 3D printed complete denture; (c) all of the contacts between the maxillary and mandibular teeth removed; (d) gothic arch tracing; (e) centric relationship position

Fig. 6 After 3D surface scanning of the centric relationship record, a CAD virtual gothic arch stylus and locating hole were attached to 3D data for the centric relationship, and the accuracy of the maxillomandibular relationship record was evaluated. (a) 3D surface scanning of the centric relationship record; (b) 3D construction of the centric relationship; (c) locating hole in the maxilla; (d) stylus in the mandible. (e) Based on the common region for the maxillary jaws, 3D data for the maxillomandibular relationships in the DiaCD test group and the CD control group were registered in the CR standard group; (f) displacements of the stylus vertices are shown.

Table 1 The displacements in the DiaCD test group and the CD control group compared with the CR standard group (unit: mm)

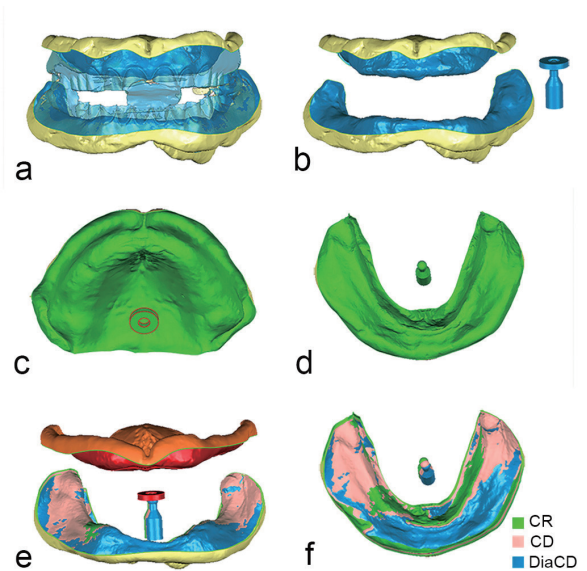|	DiaCD			CD		
	AP	LR	VD	AP	LR	VD
1	1.58	0.51	−0.26	1.26	0.24	−0.18
2	1.43	−0.56	−0.33	1.11	−0.38	0.12
3	1.73	0.01	−0.38	1.36	−0.40	0.18
4	1.74	0.23	−0.17	0.61	0.31	−1.05
5	0.26	0.08	−0.07	0.17	0.08	0.22
6	0.55	−0.70	−0.64	0.46	−0.71	−0.55
Median	1.51	0.05	−0.30	0.86	−0.15	−0.03
Lower 95% CI	0.54	−0.56	−0.52	0.32	−0.57	−0.74
Upper 95% CI	1.89	0.42	−0.10	1.34	0.29	0.32

DiaCD, maxillomandibular relationship recorded using diagnostic complete dentures; CD, maxillomandibular relationship for the complete denture; AP, anterior and posterior directions; LR, left and right directions; VD, vertical direction; CI, confidence interval

Fig. 7 Statistical analysis of differences in the maxillomandibular relationship records for the DiaCD test group and the CD control group using the Wilcoxon matched-pairs signed rank test. AP, anterior and posterior directions; LR, left and right directions; VD, vertical direction
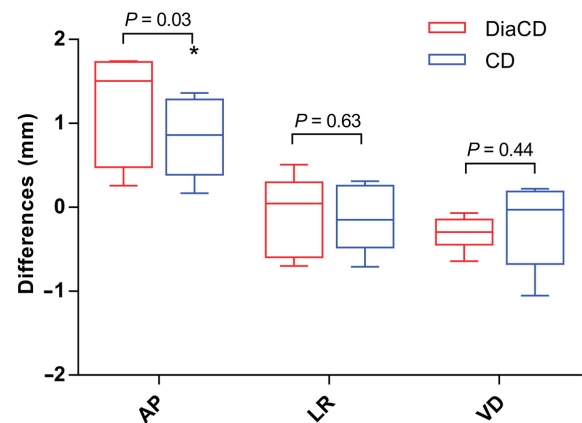
CR standard group acquisition

The CR standard group was obtained before using the new complete dentures. A gothic arch tracer was installed on a 3D printed complete denture (Beijing Sinotech Co., Ltd.), which was designed using the 3D data for impressions and maxillomandibular relationships in the DiaCD test group. The height between the tracing stylus in the mandible and the tracing plate in the maxilla was adjusted and fixed when the maxillary and mandibular teeth were in the intercuspal position (Fig. 5a, b). Then, the tracer was kept unchanged, and all the contacts between the maxillary and mandibular teeth were removed until only the tracing stylus was in contact with the tracing plate (Fig. 5c). The gothic arch tracer was applied to record protrusion, retrusion and right and left lateral movements without active intervention by the practitioner (Fig. 5d), to determine the centric relationship position, and to record the position with mandible in the tip of the arrowhead using silicone bite registration material (Huge Dental Material Co., Ltd.) (Fig. 5e). Finally, 3D surface scanning was performed using a Dentscan model 3D scanner (Fig. 6a). Based on the morphology of the intaglio surfaces of the dentures, 3D data for the maxillary and mandibular jaws were registered in the centric relationship record (Fig. 6b).

Data processing and quantitative accuracy evaluation

Using the centric relationship record determined by gothic arch tracing as a reference, the displacements in the vertical, horizontal antero-posterior, and horizontal right-and-left directions in the DiaCD test group and CD control group were measured. Using the 3D data for the centric relationship record, a 3D virtual gothic arch stylus and a locating hole were designed, with the locating hole in the maxilla and the stylus in the mandible (Fig. 6c, d). The 3D data for the maxillary and mandibular jaws in the DiaCD test group and CD control group were attached to the stylus and the locating

hole in the same way with no error by using coordinates transformed in Geomagic software. Based on the common region for the maxillary jaws, the 3D data for the maxillomandibular relationships in the DiaCD test group and CD control group were registered in the CR standard group (Fig. 6e). Displacements of the vertices of the stylus in the DiaCD test group and CD control group were assessed relative to the CR standard group (Fig. 6f). The displacement value was considered positive if it was in the forward, rightward, and upward directions; in other directions, the displacement value was considered negative.

Statistical analyses

All statistical analyses were performed using GraphPad Prism 7 (Graph-Pad Software Inc., San Diego, CA, USA). Differences in the displacements of the maxillomandibular relationships in the DiaCD test group and CD control group, and those in the horizontal antero-posterior, the horizontal right-and-left, and the vertical directions were subjected to the Wilcoxon matched-pairs signed rank test. Differences at $P < 0.05$ were considered statistically significant. Statistical power (1-β) was calculated by G*Power 3 (Heinrich-Heine-University Düsseldorf, North Rhine-Westphalia, Germany).

Results

Table 1 shows the results for displacements in the DiaCD test group and CD control group, compared with the centric relationship records. Figure 7 shows the statistical analysis of differences in the maxillomandibular relationship records in the DiaCD test group and CD control group using the Wilcoxon matched-pairs signed rank test. There were no significant inter-group differences in the horizontal right-and-left ($P = 0.63$) and vertical directions ($P = 0.44$). However, there was a significant difference in the horizontal antero-posterior direction ($P = 0.03$) with $1-\beta = 0.87$.

Discussion

Although there are many methods for quantifying the degree of satisfaction with a complete denture [16-18], a quantitative method for evaluating the maxillomandibular relationship record for complete dentures using CAD/CAM technology has been lacking. Li et al. [19] proposed a method for quantitative evaluation of 3D jaw casts in terms of the maxillomandibular relationship by using positioning cylinders adherent to gypsum casts, although the procedures for adhesion and contact measurement using the cylinders were complex and time-consuming. Later, [20] they developed a new method for evaluating displacements of the maxillomandibular relationship by referring to the complete denture with artificial teeth in the intercuspal position, but without consideration of the centric relationship position. In terms of the latter, which is the clinically repeatable reference position [21], it is convenient to assess and analyze the accuracy of maxillomandibular relationship records in a clinic by using a gothic arch tracer, which yields a visual display of displacements in the maxillomandibular relationship. In this study, based on the position of the centric relationship, the displacements of the maxillomandibular relationship obtained from diagnostic complete dentures and new complete dentures were measured.

For recording the edentulous maxillomandibular relationship, the first step is to determine the vertical dimension of occlusion, and then to record the horizontal relationship, which includes the horizontal antero-posterior, and horizontal right-and-left relationships. The vertical dimension of occlusion is traditionally determined by subtracting the interocclusal distance from the vertical dimension at rest. However, the interocclusal distance varies not only from person to person, but also in the same person due to different techniques used [22]. Therefore, to maintain the same selected vertical dimension of occlusion, the CD control group and CR standard group were derived from the DiaCD test group. However, occlusal adjustments in the CD control group caused slight modification of the mandibular position, and all the occlusal contacts were removed in the CR standard group. The results show that the displacements in the vertical dimension in the DiaCD test group and the CD control group were not significantly different. The 95% confidence interval for displacements in the horizontal antero-posterior direction in the CD control group was 0.32-1.34 mm, and in the horizontal right-and-left direction it was −0.57-0.29 mm. These discrepancies were within the tolerance range of horizontal discrepancy [23]. Therefore, the position of the maxillomandibular relationship obtained from complete dentures, adjacent to the intercuspal position of natural teeth, could be used as a control group to evaluate the accuracy of the maxillomandibular relationship records obtained using diagnostic complete dentures. The displacement in the horizontal antero-posterior direction was larger than that in the horizontal right-and-left direction in both the DiaCD test group and the CD control group, perhaps because during biting, the variation in the antero-posterior direction was larger than that in the right-and-left direction [24]. Besides, the displacements in the horizontal antero-posterior direction and the right-and-left direction in the CD control group were smaller than those in the DiaCD test group, and therefore the decrease of displacement in the CD control group may have been caused by occlusal adjustments [25].

The diagnostic complete denture, which was designed using CAD software and then 3D printed, can be used to obtain definitive impressions, and to record the maxillomandibular relationship and assess the degree of esthetic success. In the maxillomandibular relationship records, definitive impressions of the maxillomandibular jaws acquired using diagnostic complete dentures can easily stretch into the undercut portion, while manually recorded bases require block-out for the surface of the undercut portion. Therefore, diagnostic complete dentures, carrying definitive and elastic impressions, offer better retention and stability than those obtained using manually recorded bases. Moreover, the 3D printed teeth of a diagnostic complete denture can easily indicate displacement of the maxillomandibular relationship, and fully show the anterior teeth for esthetic evaluation. Furthermore, after occlusal adjustment of 3D printed teeth, the maxillomandibular relationship including the vertical and horizontal relationships can be further verified and recorded.

This study showed that it was feasible to record edentulous maxillomandibular relationships by using diagnostic complete dentures. However, there were some limitations: for this study, the same vertical dimensions were designed to evaluate the displacement of horizontal relations; thus, evaluation of the accuracy of maxillomandibular relationship records in different vertical dimensions requires further study. Besides, in edentulous patients, recording of maxillomandibular relationships using diagnostic complete dentures may not take protrusion into account. In such cases, measurements should be taken to guide patients to a retruded position, for instance by asking them to swallow several times while closing the jaw or to repeat opening-closing movements to fatigue the muscles.

Conflict of interest
The authors have no conflicts of interest to declare.

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