THE JOURNAL OF PROSTHETIC DENTISTRY

RESEARCH AND EDUCATION

CAD-CAM milled versus rapidly prototyped (3D-printed) complete dentures: An in vitro evaluation of trueness

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ABSTRACT

Statement of problem. Complete dentures fabricated by computer-aided design and computer-aided manufacturing (CAD-CAM) techniques have become popular. The 2 principal CAD-CAM techniques, milling and rapid prototyping (3D printing), used in the fabrication of complete dentures have been reported to yield clinically acceptable results. However, clinical trials or in vitro studies that evaluated the accuracy of the 2 manufacturing techniques are lacking.

Purpose. The purpose of this in vitro study was to compare the differences in trueness between the CAD-CAM milled and 3D-printed complete dentures.

Material and methods. Two groups of identical maxillary complete dentures were fabricated. A 3D-printed denture group (3DPD) (n=10) and a milled denture group (MDG) (n=10) from a reference maxillary edentulous model. The intaglio surfaces of the fabricated complete dentures were scanned at baseline using a laboratory scanner. The complete dentures were then immersed in an artificial saliva solution for a period of 21 days, followed by a second scan (after immersion in saliva). A third scan (after the wet-dry cycle) was then made after 21 days, during which the complete dentures were maintained in the artificial saliva solution during the day and stored dry at night. A purpose-built 3D comparison software program was used to analyze the differences in the trueness of the complete dentures. The analyses were performed for the entire intaglio surface and specific regions of interest: posterior crest, palatal vault, posterior palatal seal area, tuberosity, anterior ridge, vestibular flange, and mid-palatal raphae. Independent *t* tests, ANOVA, and post hoc tests were used for statistical analyses (α=.05).

Results. The trueness of the milled prostheses was significantly better than that of the rapid prototyping group with regard to the entire intaglio surface (P<.001), posterior crest (P<.001), palatal vault (P<.001), posterior palatal seal area (P<.001), tuberosity (P<.001), anterior ridge (baseline: P<.001; after immersion in saliva: P=.001; after the wet-dry cycle: P=.011), vestibular flange (P<.001), and mid-palatal raphae (P<.001).

Conclusions. The CAD-CAM, milled complete dentures, under the present manufacturing standards, were superior to the rapidly prototyped complete dentures in terms of trueness of the intaglio surfaces. However, further research is needed on the biomechanical, clinical, and patient-centered outcome measures to determine the true superiority of one technique over the other with regard to fabricating complete dentures by CAD-CAM techniques. (J Prosthet Dent 2019;121:637-43)

The fabrication of complete dentures by computer-aided design and computer-aided manufacturing (CAD-CAM) methods has become popular in both clinical and laboratory practices in recent years.[1] This increased popularity may be attributed to the improvements in the CAD-CAM techniques and the growing awareness of dental practitioners and laboratory technicians, along with an increasing flexibility to combine parts of the digital workflow with

The authors gratefully acknowledge the sponsorship from the Swiss Dental Association (SSO) for the acquisition of the IScan D103i, Imetric 3D SA, Courgenay, Switzerland.

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Clinical Implications

This study provides evidence to help in the clinical selection of appropriate CAD-CAM manufacturing techniques for fabricating complete dentures. Currently, complete dentures manufactured by CAD-CAM milling technique should be preferred over complete dentures using the rapid prototyping method.

conventional clinical and laboratory protocols. Two CAD-CAM techniques, a computerized numeric control subtractive milling process and a system of rapid prototyping (RP) that is commonly known as 3D printing, an additive manufacturing process, are available to fabricate CAD-CAM complete dentures. Most providers currently use the milling technique for commercial production of complete dentures, whereas the RP method is mainly used for fabricating interim or evaluation complete dentures and, rarely, definitive complete dentures. However, the milling process wastes large quantities of denture base material, and more recent 3D prototyping promises a more sustainable additive approach by using less denture resin.

Complete dentures fabricated with either of the CAD-CAM techniques have been evaluated. When compared with conventional complete dentures, CAD-CAM, milled complete dentures show similar or better fit of the intaglio surfaces, equal biocompatibility, and improved mechanical properties.[2–7] High patient and clinician satisfaction have also been reported with CAD-CAM, milled complete dentures.[8,9] The clinical protocols considerably reduce the chairside time, whereas the manufacturing process may reduce the laboratory fees in some countries.

Complete dentures fabricated using the RP technique have also elicited patient satisfaction comparable with that for conventional complete dentures.[10,11] RP has been further used in complete denture fabrication for the precise reproduction of denture bases and printed wax patterns.[12,13] Although both the techniques are successful in fabricating clinically acceptable complete dentures, the authors are unaware of a study that has compared the accuracy of the intaglio surface of complete dentures manufactured by RP (3D printing) and a milled technique.

The International Standards Organization uses the terms “trueness” and “precision” to describe the accuracy of a measurement method. Trueness is defined as the closeness of agreement between the arithmetic mean of many test results and the true or accepted reference value. Precision refers to the closeness of agreement between test results.[14] The purpose of this in vitro study was to compare the trueness of the intaglio surfaces of complete dentures fabricated using the CAD-CAM milling technique with that of those fabricated with the RP (3D printing) technology. The null hypothesis was that no difference would be found in the trueness of the intaglio surfaces of complete dentures fabricated either by CAD-CAM RP or milling techniques.

MATERIAL AND METHODS

This in vitro study was conducted in the Division of Gerodontology and Removable Prosthodontics, University Clinics of Dental Medicine, University of Geneva, Switzerland. Ethical approval was not required because no patient records or data were used. The best-fit 3D-superimposition color mapping and analysis of the differences were performed at the Division of Computerized Restorative Dentistry, Clinic for Preventive Dentistry, Periodontology and Cariology, Center for Dental Medicine, University of Zurich, Switzerland.

The sample size was calculated using a freeware program (G*Power 3.1.9.3 for Mac OS X)[15] from the results of a previously published study.[3] The effect size (dz=1.5004) and the required sample size were calculated for α=.05 and a power of .95 (1−β error probability), assuming a normal distribution. For this study, a sample size of 9 was obtained, which subsequently increased to 10 per group to remain consistent with similar previously published studies and to minimize errors.[2,3]

A completely edentulous maxillary cobalt-chromium model used in a previous experiment[3] served as the master reference model. All the complete denture specimens were fabricated using the scan of this reference model. A master scan of the reference model was performed using a laboratory scanner (IScan D103i; Imetric 3D SA). The high-resolution scanner was calibrated to a precision of 6 μm,[16] with a manufacturer-specified nominal point spacing of 6 to 8 μm and a repeatability of 10 μm at an accuracy of 20 μm. The bundle scanner software was equipped with an auto-align function that aligned multiple scan sets, and the resultant complete surface was stored in 3D standard tessellation language (STL) format.

The file of this master scan in STL format was transmitted to the CAD-CAM complete denture provider using a purpose-built software program (AvaDent Connect software; AvaDent Digital Dental Solutions Europe, Global Dental Science Europe BV). The anatomic landmarks were identified, and the peripheral limits were marked on a virtual model in the design software, which then served to design the definitive complete denture. A digital preview was generated and sent for approval to the investigators before fabrication. Both milled and 3D-printed complete dentures used the same design.

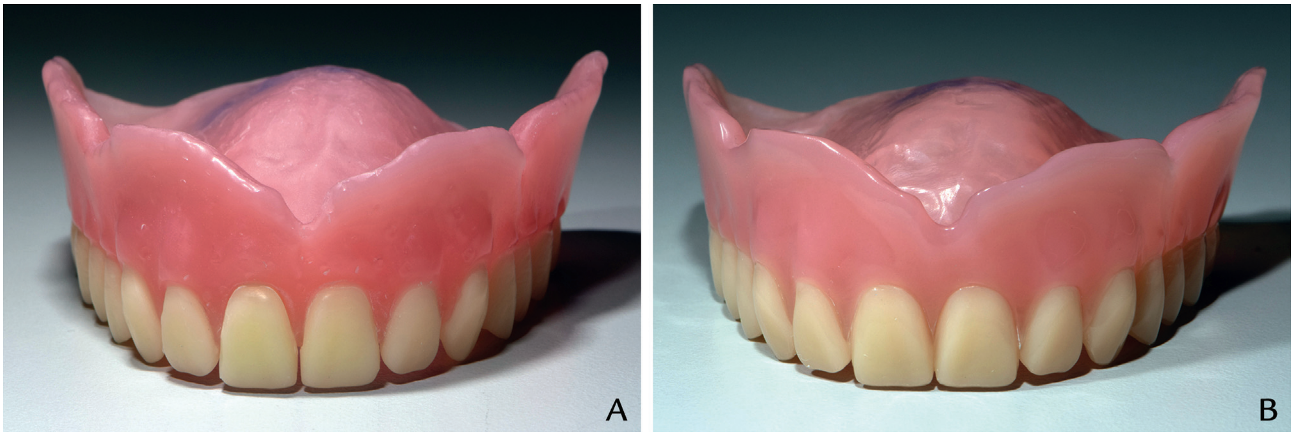

Figure 1. Representative denture specimens. A, Rapidly prototyped (3D printed). B, Milled.

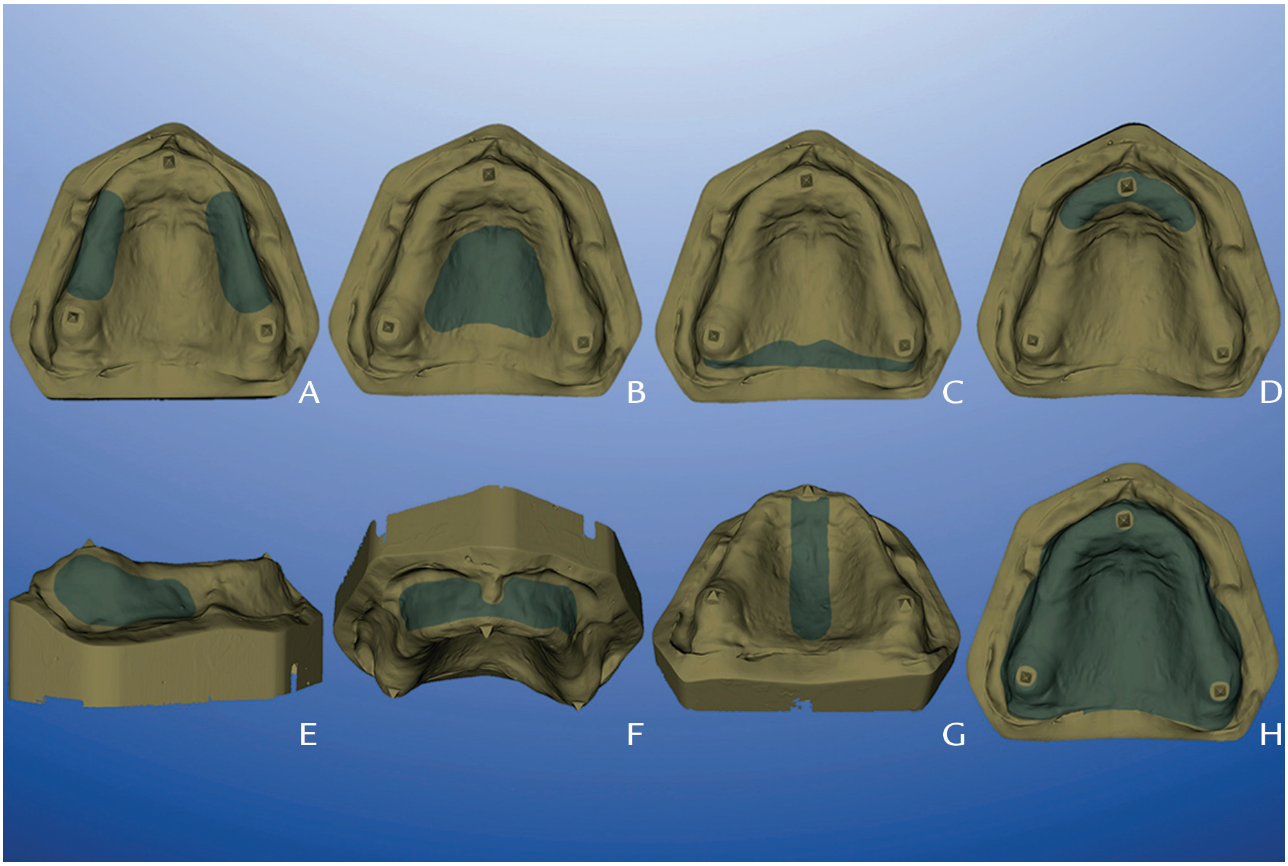

Figure 2. Regions of interests investigated. A, Posterior crest. B, Palatal vault. C, Posterior palatal seal area. D, Anterior ridge. E, Tuberosity. F, Vestibular flange. G, Mid-palatal raphae. H, Total intaglio surface.

A total of 20 complete dentures were fabricated using the scan of the master reference model by applying the 2 CAD-CAM manufacturing techniques (Fig. 1). The 3DPD group (n=10) comprised complete dentures fabricated by an RP technique in a 3D printer with a build platform of 110×62 mm using a native pixel 29-μm 405 LED light source (RapidShape D30; Rapid Shape GmbH, Generative Production Systems). The liquid printing material used was a monomer based on acrylic resin esters for fabricating denture bases (NextDent Denture 3+; NextDent B.V.). The denture bases were printed in a vertical orientation with a layer thickness of 100 μm per layer, with the location and number of supports being automatically designed by the software. After printing, the complete dentures were separated from the build platform with a putty knife, and the supports were removed.

Table 1. Statistical significance of differences (mean ±standard deviations in µm) in trueness of 2 groups of complete dentures shown in intergroup analyses

Regions	Time-point	3D Printed	Milled	P*
Total surface	BL	95.3 ±7.5	34.9 ±4.7	<.001
	IS	76.6 ±7.2	33.3 ±2.1	<.001
	WDC	83.0 ±7.9	33.7 ±2.6	<.001
Posterior crest	BL	58.1 ±12.8	32.5 ±2.5	<.001
	IS	47.6 ±8.0	36.0 ±2.2	<.001
	WDC	47.8 ±5.5	36.7 ±4.3	<.001
Palatal vault	BL	64.4 ±9.1	17.7 ±2.9	<.001
	IS	60.0 ±7.2	16.0 ±0.8	<.001
	WDC	64.5 ±13.3	17.0 ±1.4	<.001
PPS area	BL	118.0 ±22.4	30.0 ±7.2	<.001
	IS	72.0 ±9.3	29.6 ±2.1	<.001
	WDC	87.9 ±24.7	23.9 ±1.9	<.001
Tuberosity	BL	100.8 ±17.9	31.8 ±5.0	<.001
	IS	83.7 ±19.1	31.7 ±2.5	<.001
	WDC	89.6 ±16.8	30.8 ±2.6	<.001
Anterior ridge	BL	43.3 ±7.1	32.7 ±2.3	<.001
	IS	42.0 ±4.9	34.1 ±3.7	.001
	WDC	45.5 ±7.9	37.2 ±4.9	.011
Vestibular flange	BL	76.2 ±10.7	41.9 ±6.4	<.001
	IS	72.7 ±8.7	39.8 ±4.5	<.001
	WDC	80.7 ±17.0	38.7 ±3.3	<.001
MPR	BL	95.3 ±9.2	22.8 ±3.1	<.001
	IS	87.5 ±13.9	19.9 ±.73	<.001
	WDC	86.7 ±11.5	20.5 ±1.3	<.001

BL, baseline; IS, immersion in artificial saliva solution; MPR, mid-palatal raphae; PPS, posterior palatal seal; WDC, wet-dry cycle. *Student *t* tests.

The printed complete dentures were rinsed twice in a 96% ethanol solution in an ultrasonic bath to remove excess material. A first rinse of 3 minutes was followed by a second rinse in clean 96% ethanol solution for approximately 2 minutes. The manufacturer specifies a maximum 5-minute alcohol rinse, as excessive rinsing could lead to surface defects in the printed complete dentures.

The complete dentures were then cleaned, dried, and placed in an ultraviolet light box (LC-3DPrint Box; NextDent B.V.) for 10 minutes for additional polymerizations. The light box had 4 Dulux Blue UV-A lamps and four 18W/71 lamps (Dulux L blue) delivering a wavelength of blue UV-A 315 to 400 nm and an output of 43.2 kJ.

The MDG group (n=10) consisted of fully milled complete dentures (AvaDent Digital Dental Solutions Europe, Global Dental Science Europe BV), for which the denture base and teeth were milled from prepolymerized acrylic resin pucks. This system differs from other types of milled complete dentures in which only the denture base is milled and then commercially available prefabricated teeth are bonded into the milled socket spaces in the milled denture base.

Based on clinical relevance for denture function, the entire intaglio surface and certain regions of interests were selected for analysis (Fig. 2): posterior crest, palatal vault, posterior palatal seal area (PPS), anterior ridge, tuberosity, vestibular flange, and mid-palatal raphae (MPR). The master reference model was first scanned to form the master scan data STL file, which was used to manufacture the complete dentures. This master scan was also subsequently used for data analysis and comparison. After fabrication, the specimens were examined for any defects. At baseline, the intaglio surfaces of the complete denture specimens (N=20 specimens; 3DPD: n=10, MDG: n=10) were scanned. Subsequently, the specimens were immersed in an artificial saliva solution for a period of 21 days at room temperature. The artificial saliva solution was made solely for these in vitro experiments. The composition of this medium has been described in detail in previously published studies.[3,17,18] At the end of this period, a second scan of the intaglio surface was performed (after immersion in saliva). In the following 21 days, the specimens were immersed during the day in the artificial saliva solution and stored dry during the night. The intaglio surface was then scanned a third and last time (after the wet-dry cycle).

All the intaglio surfaces were scanned (IScan D103i; Imetric 3D SA) by a single investigator (N.K.) following the laboratory scanning procedures recommended by the manufacturer. For comparative analyses, a 3D comparison software program was used (OraCheck 2.10; Cyfex AG). The scan file of the master reference model was inverted, and the intaglio surface scans were superimposed with a best-fit alignment.[3,19] The software computed the distances between the superimpositions. As a measure of trueness for each superimposition, both the median and half the amount of quantile80%-quantile20% of the distribution of the distance values were computed. Then, for each group, the mean values and standard deviations of these measures were calculated for the entire intaglio surface and for the regions of interest.

Normal distribution was confirmed with the Kolmogorov-Smirnov test (α=.05) and homogeneity of variance with the Levene test (α=.05) before Student *t* tests and 1-way ANOVA were used. Bonferroni post hoc statistical tests were used to demonstrate any significant differences between the groups with respect to the entire intaglio surfaces and the specified regions of interest. All statistical analyses were performed using a statistical software program (IBM SPSS Statistics, v24; IBM Corp).

RESULTS

Intergroup results (3DPD versus MDG) at the given time points (baseline, after immersion in saliva, and after the wet-dry cycle) showed that the trueness of the entire intaglio surface was significantly better in the MDG complete dentures than that in the 3DPDs (P<.001)

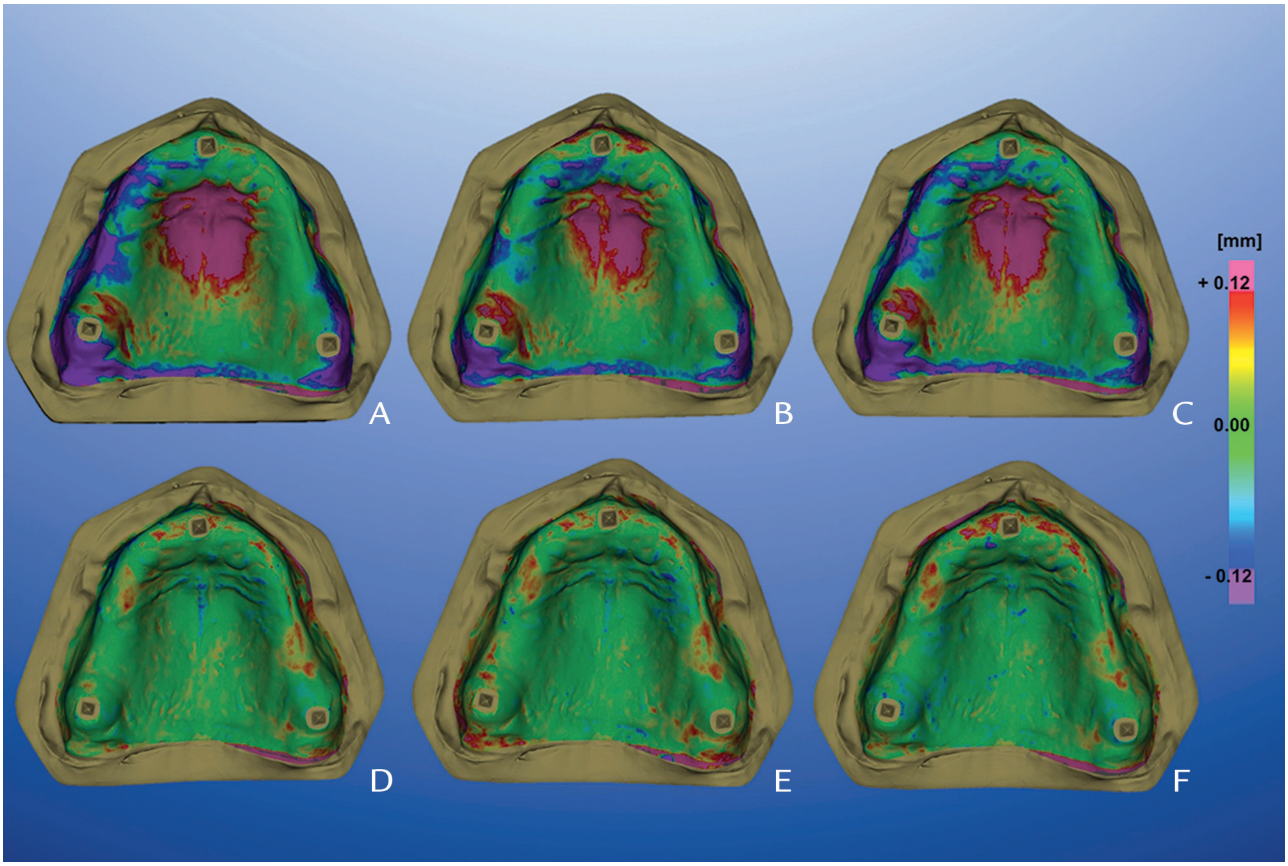

Figure 3. Color maps of representative specimens from each group: A, 3DPD at baseline; B, 3DPD after immersion in artificial saliva solution; C, 3DPD after wet-dry simulation cycle. D, MDG at baseline; E, MDG after immersion in artificial saliva solution; F, MDP after wet-dry simulation cycle. Precision scale between −0.12 and +0.12 mm. 3DPD, 3D-printed denture; MDG, milled denture group.

(Table 1; Fig. 3). Intragroup results within group analysis (Table 2) revealed a significant difference in the trueness of the entire intaglio surface in 3DPD when compared between baseline and after immersion in saliva (*P*<.001) and between baseline and after the wet-dry cycle (*P*=.003), but not between after immersion in saliva and after the wet-dry cycle (*P*=.205). MDG did not show any statistically significant differences in trueness among the 3 evaluated time points (Fig. 3).

Intergroup results (3DPD versus MDG) concluded that the trueness of the complete dentures in MDG was significantly better at baseline, after immersion in saliva, and after the wet-dry cycle, with regard to the posterior crest (*P*<.001), palatal vault (*P*<.001), PPS (*P*<.001), anterior ridge (baseline: *P*<.001; after immersion in saliva: *P*=.001; after the wet-dry cycle: *P*=.011), the tuberosity (*P*<.001), vestibular flange (*P*<.001), and MPR (*P*<.001) (Table 1). Intragroup results in 3DPD showed a significant difference for the PPS area when compared between baseline and after immersion in saliva (*P*<.001) as well as between baseline and after the wet-dry cycle (*P*=.007), but no difference between after immersion in saliva and after the wet-dry cycle (*P*=.261). The trueness in the PPS area improved after immersion in saliva. No significant differences were observed in the trueness of the other investigated regions of interest for 3DPD dentures (Table 2). MDG dentures demonstrated significant differences in the posterior crest (baseline versus after the wet-dry cycle: *P*=.020), PPS area (baseline versus after the wet-dry cycle: *P*=.015; after immersion in saliva versus after the wet-dry cycle: *P*=.023), anterior ridge (baseline versus after the wet-dry cycle: *P*=.037), and in the MPR area (baseline versus after immersion in saliva: *P*=.010; baseline versus after the wet-dry cycle: *P*=.045).

DISCUSSION

The fabrication of complete dentures by subtractive milling or by additive RP is a recent development. Although, both the techniques use a digital 3D-image file designed by CAD software to manufacture the complete dentures, the 2 modes of fabrication are entirely different. In the milling method, the complete denture is fabricated at a milling station using a prepolymerized polymethylmethacrylate puck manufactured under high pressure. The RP technique uses photosensitive liquid

Table 2. Statistical significance of differences (*P*) in trueness of 2 groups of complete dentures shown in intragroup analyses

		P	
Regions	**Comparison**	**3D Printed**	**Milled**
Total surface	BL versus IS	<.001*	.815
	BL versus WDC	.003*	1.000
	IS versus WDC	.205	1.000
Posterior crest	BL versus IS	.054	.057
	BL versus WDC	.059	.020*
	IS versus WDC	1.000	1.000
Palatal vault	BL versus IS	1.000	.158
	BL versus WDC	1.000	1.000
	IS versus WDC	.999	.713
PPS area	BL versus IS	<.001*	1.000
	BL versus WDC	.007*	.015*
	IS versus WDC	.261	.023*
Tuberosity	BL versus IS	.125	1.000
	BL versus WDC	.519	1.000
	IS versus WDC	1.000	1.000
Anterior ridge	BL versus IS	1.000	1.000
	BL versus WDC	1.000	.037*
	IS versus WDC	.771	.222
Vestibular flange	BL versus IS	1.000	1.000
	BL versus WDC	1.000	.483
	IS versus WDC	.515	1.000
MPR	BL versus IS	.443	.010*
	BL versus WDC	.339	.045*
	IS versus WDC	1.000	1.000

BL, baseline; IS, immersion in artificial saliva solution; WDC, wet-dry cycle; PPS, posterior palatal seal; MPR, mid-palatal raphae. *Statistically significant ($P<.05$).

resins, repetitively layered on a support structure and polymerized by an ultraviolet or a visible light source. Distinct advantages and disadvantages for each of the 2 techniques exist. Manufacturing complete dentures from a prepolymerized polymethylmethacrylate puck may eliminate the shrinkage and porosities caused by the packing and polymerization process. Also, the dentures should contain lower levels of residual monomer and have better material properties. However, the residual monomer content of the milled complete dentures has been reported to be not markedly reduced when compared with conventional heat-polymerized complete dentures and significantly lower than that of complete dentures manufactured from autopolymerizing resin.[6]

The RP technique uses unpolymerized resins for manufacturing complete dentures, and once processed, it requires an additional final light-polymerization step to complete the process. During the RP workflow, polymerization shrinkage is theoretically possible, as complete dentures are not completely polymerized before the final light-polymerization procedure. A deformation of the prostheses can occur when demounting the partially polymerized complete denture from the build platform. Furthermore, a residual layer of unpolymerized resin invariably remains on the finished prostheses, which must be eliminated by thorough rinsing with a suitable solvent. The claimed advantages of an additive manufacturing process include higher accuracy, less material wastage, and low infrastructure costs; however, these have not yet been scientifically proven with regard to complete denture fabrication.

Theoretically, the accuracy of the fabricated complete dentures should be different with the different manufacturing processes, but both the techniques have been documented to be clinically acceptable and better than conventional methods.[2–12] The authors are unaware of previous studies comparing the accuracy of these 2 CAD-CAM techniques. The results of this in vitro study demonstrated that the trueness of the CAD-CAM milled complete dentures was statistically better than that of the rapidly prototyped complete dentures, both for the entire intaglio surface and specific regions of interest. Therefore, the null hypothesis was rejected. Whether this difference in trueness is clinically relevant is unclear as studies have demonstrated that the accuracy of rapidly prototyped complete dentures has clinically acceptable levels of precision and have also reported good patient and clinician satisfaction.[10–13]

An additional consideration is whether rapidly prototyped complete dentures are dimensionally stable during long-term service as they are being manufactured from light-polymerizing resins. The authors are unaware of studies that have elucidated this aspect. Despite the inferior trueness found in the present study, the RP techniques should be perfected as they present advantages over the CAD-CAM milling techniques. Milling units are expensive and may be suitable for commercial manufacturing centers but not practical for individual practices or smaller dental laboratories. Furthermore, these units consume a considerable amount of energy during the manufacturing process. Moreover, the subtractive manufacturing technique of milling leads to a considerable amount of material wastage. With a projected estimate of 61 million dentures to be made in 2020 for the United States alone,[20] a substantial reduction of environmental pollution with plastic particles may be achieved if judicious manufacturing techniques are adopted.

Tabletop 3D printers are much less expensive than a milling center and could be afforded by individual dentists and dental laboratories or in lower-income nations where edentulism is prevalent and skilled dental laboratory technicians are scarce. On-site manufacturing would also avoid delays in delivery and reduce shipping costs. Technical improvements in terms of trueness can be expected in the near future, as CAD-CAM techniques are developing rapidly. However, before recommending RP as a standard manufacturing procedure for the fabrication of complete dentures, more research is needed.

Studies are lacking on the monomer-based ester compounds that are used in RP with regard to allergenic potential, residual monomer levels, material and color stability, material compatibility with conventional relines, mechanical properties, and biocompatibility. The appearance of the 2 different denture types requires evaluation as esthetics are of increasing importance. In addition, patient-centered outcome measures have to be considered before validating this evolving technique.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn;

1. CAD-CAM milled complete dentures were better than rapidly prototyped complete dentures in terms of trueness of the intaglio surfaces.
2. Further research is needed on the biomechanical, clinical, and patient-centered outcome measures to determine the superiority of one technique over the other with regard to manufacturing complete dentures by CAD-CAM techniques.

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https://doi.org/10.1016/j.prosdent.2018.09.001