https://doi.org/10.4047/jap.2023.15.1.22

Analysis of the trueness and precision of complete denture bases manufactured using digital and analog technologies

Leonardo Ciocca[1]*, Mattia Maltauro[2], Valerio Cimini[1], Lorenzo Breschi[1], Angela Montanari[3], Laura Anderlucci[3], Roberto Meneghello[2]

[1]Oral and Maxillo-Facial Prosthodontics, Section of Prosthodontics, Department of Biomedical and Neuromotor Science, Alma Mater Studiorum University of Bologna, Bologna, Italy
[2]Department of Management and Engineering, University of Padova, Vicenza, Italy
[3]Department of Statistical Sciences, Alma Mater Studiorum University of Bologna, Bologna, Italy

ORCID
Leonardo Ciocca
https://orcid.org/0000-0002-2127-484X
Mattia Maltauro
https://orcid.org/0000-0002-8339-9306
Lorenzo Breschi
https://orcid.org/0000-0001-7621-226X
Angela Montanari
https://orcid.org/0000-0002-8369-1761
Laura Anderlucci
https://orcid.org/0000-0003-1161-6145
Roberto Meneghello
https://orcid.org/0000-0002-8099-9795

PURPOSE. Digital technology has enabled improvements in the fitting accuracy of denture bases via milling techniques. The aim of this study was to evaluate the trueness and precision of digital and analog techniques for manufacturing complete dentures (CDs). **MATERIALS AND METHODS.** Sixty identical CDs were manufactured using different production protocols. Digital and analog technologies were compared using the reference geometric approach, and the Δ-error values of eight areas of interest (AOI) were calculated. For each AOI, a precise number of measurement points was selected according to sensitivity analyses to compare the Δ-error of trueness and precision between the original model and manufactured prosthesis. Three types of statistical analysis were performed: to calculate the intergroup cumulative difference among the three protocols, the intergroup among the AOIs, and the intragroup difference among AOIs. **RESULTS.** There was a statistically significant difference between the dentures made using the oversize process and injection molding process ($P < .001$), but no significant difference between the other two manufacturing methods ($P = .1227$). There was also a statistically significant difference between the dentures made using the monolithic process and the other two processes for all AOIs ($P = .0061$), but there was no significant difference between the other two processes ($P = 1$). Within each group, significant differences among the AOIs were observed. **CONCLUSION.** The monolithic process yielded better results, in terms of accuracy (trueness and precision), than the other groups, although all three processes led to dentures with Δ-error values well within the clinical tolerance limit. [J Adv Prosthodont 2023;15:22-32]

KEYWORDS
Digital workflow; Digital denture; CAD-CAM; Complete denture; Reference geometry measurement

Corresponding author
Leonardo Ciocca
School of Dentistry, Alma Mater Studiorum University of Bologna
Via S. Vitale 59, 40125 Bologna
Italy
Tel +39 0512088186
E-mail leonardo.ciocca@unibo.it

Received October 24, 2022 / **Last Revision** January 17, 2023 / **Accepted** February 9, 2023

INTRODUCTION

Over the last decade, the increased use of digital technologies in dentistry has led to new techniques for producing complete dentures (CDs). New milling techniques and modern poly-methyl-methacrylate (PMMA) resins have improved the fitting accuracy of denture bases, which is a key factor for effective CDs. Goodacre *et al*.[1] demonstrated that milled denture bases produced using digital technology had better accuracy compared with conventionally manufactured CDs. Moreover, digital technologies have enabled improvements in the material properties of dentures.[2-5] For instance, the PMMA disks used for machine milling are polymerized under high temperature and pressure,[6] which enhances the production of longer polymer chains.[7] In turn, this promotes monomer conversion, leading to minimal residual monomers following free radical polymerization of the denture base resin.[8]

Several studies have described the advantages of digital technology for denture production. For instance, dentures made using the conventional pack-and-press technique had larger dimensional changes compared with milled denture bases, and the milling protocol was associated with minimal denture tooth movement compared with the conventional analog (mold) process.[9-11] Other studies evaluated patient satisfaction and reported higher clinical success rates for CDs manufactured using digital technology.[12,13] Studies on the trueness and precision of computer-aided design and computer-aided manufacturing (CAD-CAM) fabricated denture bases found that, according to the error (i.e., the difference between the surface of the design and the surface of the manufactured product), the bases were not inferior to conventional PMMA bases. Furthermore, they were always within the clinical tolerance limit.[14-16]

The aim of this study was to compare the accuracy, in terms of trueness and precision, of three different protocols for fabricating CDs. The surface of a metal reference model, equipped with conical landmarks for reference, was compared to the post-processing intaglio surface of the corresponding denture bases. All measurements were conducted based on the reference geometry approach, instead of using the automatic best-fit tools typically applied for superimposition and measurement. The null hypothesis of this *in vitro* study was that there would be no difference in mean error values between the bases made using different fabrication protocols. The secondary null hypotheses were that there would be no differences in the area of interest (AOI) among the different protocols, or among AOIs within each protocol.

MATERIALS AND METHODS

Sixty identical CDs were manufactured using three different resin-based techniques (n = 20 for each technique). The first technique involved the use of a monolithic disk of PMMA resin for simultaneous milling of the dental elements and denture base (Ivotion; Ivoclar Vivadent, Schaan, Liechtenstein). The second technique involved the use of different disks of monochrome pink and chromatic PMMA resin for the oversize process (Ivocap technique; Ivoclar AG, Schaan, Liechtenstein), to separately produce the denture base and dental resin, respectively. The third technique involved injection molding for direct molding of the PMMA resin (Ivobase High Impact; Ivoclar AG, Schaan, Liechtenstein).

Starting with the digitalization of a real edentulous maxillary model scanned using the E2 laboratory scanner (3Shape, Erlangen, Germany), five landmarks (conical surfaces) were created in the positions of the first molars, canines, and central papilla on the model mucosal surface (Fig. 1). All cones were equal in height and parallel to one another, enabling us to use them as a 3D reference system, i.e., a tridimensional xyz cartesian coordinate system. To define the origin and orientation of the Z-axis, the plane with the best fit with respect to all of the cone vertices was used. The five points were defined as V_{1-5}, and projected all of the cone vertices onto the plane. The origins of the second (X) and third (Y) axes were set at the intersection points of the V_1-V_4 and V_2-V_5 segments, respectively. The Y-axis orientation was coincident with the O_{XYZ}-V_3 segments. This process resulted in the complete definition of an xyz cartesian coordinate system (Fig. 2).

After establishing the RPS, a metal model was manufactured using a laser melting 3D printing process

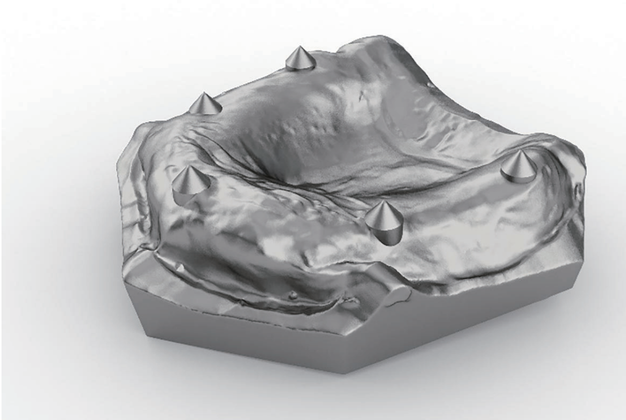

Fig. 1. The five landmarks (conical surfaces) created on the model mucosal surface.

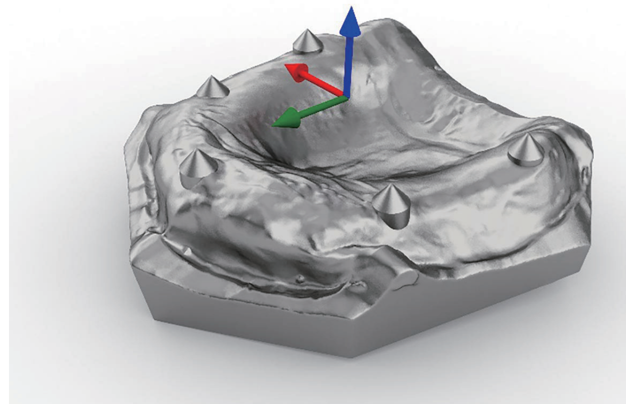

Fig. 2. Complete xyz Cartesian coordinate system.

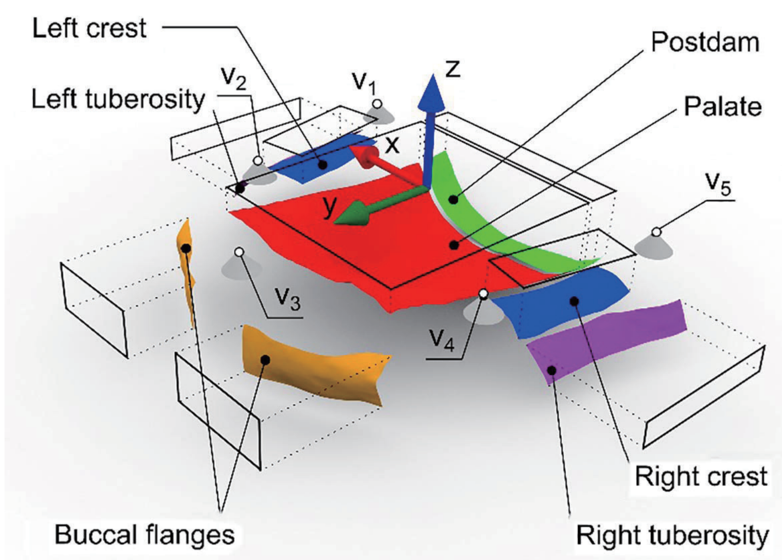

Fig. 3. The intaglio surface of the denture base was divided into eight areas of interest (AOIs).

(M280; EOS, Krailling, Germany) with titanium powder (Ti-6Al-4V grade 23) and buffed until the surface was smooth, to guarantee the integrity of the model during the multiple molding processes of group 3. This model was used as a reference for the initial scans of the specimens in groups 1 and 2. Then, the injection molding process was used to directly manufacture each specimen in group 3 (Fig. 3). This metal model was necessary to have a common starting point for all the manufacturing processes therefore avoid biases between groups.

After manufacturing the metal model, it was scanned using the E2 scanner (3Shape, Erlangen, Germany) to create an original STL file. This file was then used to construct the CD bases in all groups. A scanning preparation spray was used before scanning (Cerec Optispray; Dentsply Sirona, Charlotte, NC, USA), to simplify the acquisition of the digital impression.

Using the original STL file of the model mucosal surface, a CD was digitally planned and designed

(Ivotion; Ivoclar Vivadent, Schaan, Liechtenstein). In group 3, the metal model was used to manufacture the CDs according to the analog (conventional) injection molding procedure. The complete digital and analog denture bases were 360°-scanned using a laboratory scanner (Aurum3D; OpenTechnologies, Bergamo, Italy) to generate a second STL file for comparison between the intaglio and actual surface.

The intaglio surface of the denture base was divided into eight areas of interest (AOIs): the central palate, right and left edentulous crests, postdam region, right and left buccal flanges, and right and left tuberosities (Fig. 3). As these are curved surfaces, the anatomical evaluation was attempted to be simplified by considering the projection of each area in the three spatial planes (x, y, z). The central palate, postdam areas, and right and left crest areas were projected in the horizontal plane, while the right and left flanges and tuberosity areas were projected in the sagittal plane. This procedure made simpler to evaluate each curved surface as a linear rectangular area (Fig. 3). For each AOI, a specific number of measurement points were selected to calculate the Δ-error of trueness and precision between the original model and manufactured prosthesis. The point sampling (i.e., the point density or sampling distance) was determined via the sensitivity analysis, and was identical for all AOIs. Thus, the number of sampling points was related to the size of the AOI: 84 points for the right flange, 91 for the right and left crests, 78 for the left flange, 112 for the postdam, 88 for the left tuberosity area, and 63 for the right tuberosity area. For each point, the Δ-error represented the difference in position between the prosthesis and actual surfaces, and the distance was calculated along the normal direction. Table 1 gives the mean value for each linear deviation (Δ) and the standard deviation (SD). The landmark geometric features (i.e., cone vertices) allowed adopting this method, typically used only when they are available. This reference geometric approach is more efficient and effective than the superimposition method using the best-fit algorithm.[17]

For the statistical analysis, all values were considered as relative values. This would enable better representation of over- or under contouring, which would indicate a compressive spot on the mucosa or microcavity of the intaglio surface. Absolute values were also employed to account for both positive and negative Δ when evaluating the overall accuracy.

Table 1. Mean relative values for each area of interest (AOI) and group

Zona	Monolithic ΔN	Oversize ΔN	Injection molding ΔN
Left Crest	-0.0090	-0.1098	-0.0363
Left Flange	0.0223	0.0687	0.1494
Left Tuberosity	0.0055	-0.0460	0.0576
Palate	0.0122	-0.0870	-0.0841
Postdam	0.0349	-0.1074	-0.1044
Right Crest	0.0077	-0.1051	-0.0391
Right Flange	-0.0044	0.1014	0.1682
Right Tuberosity	0.0187	-0.0294	0.0670

The statistical analysis had three levels: the intergroup cumulative difference among the three protocols, intergroup difference among the AOIs, and intragroup differences in AOIs.

Level 1 (intergroup cumulative differences among protocols): the 60 specimens were made using the same reference model. Thus, the samples were considered as independent representations of the same information. Figures 4a and 4b display the distributions of the absolute and relative Δ values, respectively, according to the different protocols. The trueness among the three protocols were compared using the absolute differences. The null hypothesis, i.e., no treatment effect, was tested via the Kruskal-Wallis test. Post-hoc comparisons were carried out using the non-parametric Dwass-Steel-Critchlow-Fligner test. The chi-square test was used to compare the rates of positive and negative Δ among the different protocols.

Level 2 (intergroup differences in AOIs): to account for differences in AOIs among groups, the data were summarized by computing the mean of the absolute Δ for the different landmarks and items. Thus, the data matrix included one average measurement for each AOI and protocol. Treatment effects were tested related to the different materials via a non-parametric Friedman test, which accounted for variability due to the AOIs. Post-hoc comparisons were carried out with the non-parametric Wilcoxon-Nemenyi-McDon-

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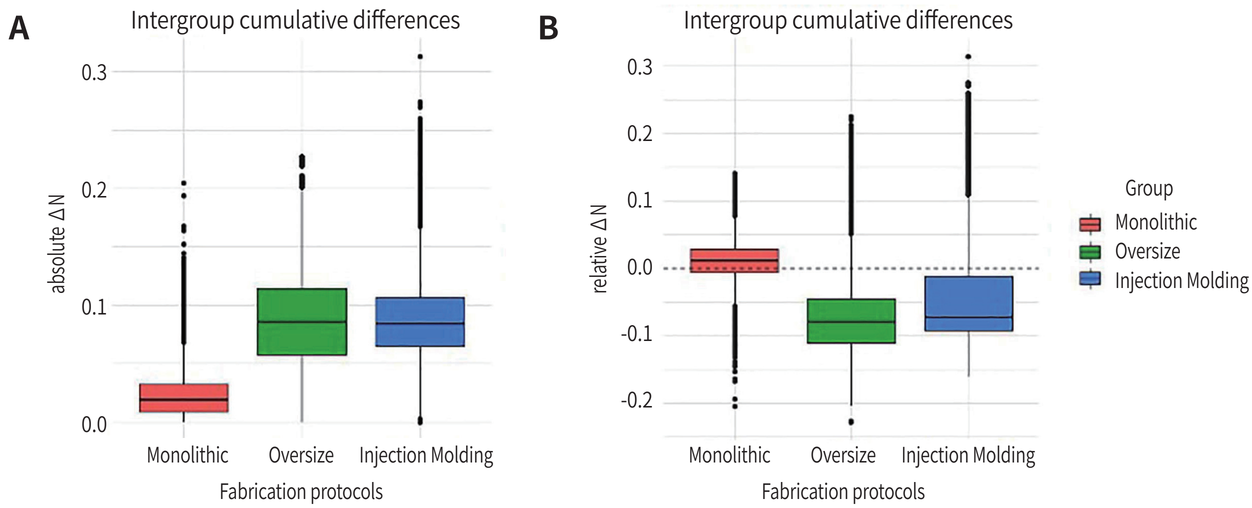

Fig. 4. Comparison among materials. (A) The absolute values, (B) The relative values.

ald-Thompson test.

Level 3 (intragroup difference in AOIs): treatment effects related to the individual AOIs were investigated using the Kruskal-Wallis nonparametric test. Post-hoc comparisons were carried out with the non-parametric Dwass-Steel-Critchlow-Fligner test.

RESULTS

In the level 1 analysis (intergroup cumulative differences among protocols), the absolute values of all measurements were significantly different (Kruskal-Wallis test, $P < .001$; Fig. 4A); thus, at least one group had a significantly different shift in the distribution of the absolute Δ values. According to the non-parametric Dwass-Steel-Critchlow-Fligner post-hoc test, the trueness of the monolithic process was statistically significantly different from that of the oversize ($P < .001$) and injection-molding ($P < .001$) processes. No significant difference ($P = .1227$) was found between the latter two methods. When considering the relative values of all measurements (Fig. 4b), the prevalence rate of negative values was significantly different among groups, and the monolithic process was statistically different from the oversize and injection molding processes ($P < .001$).

In the level 2 analysis (intergroup differences among AOIs), regarding the absolute mean values of all measurements (Fig. 5), a "treatment effect" was tested related to the different manufacturing processes using the non-parametric Friedman test. At least one process was significantly different from the others ($P = .0025$). The Wilcoxon-Nemenyi-McDonald-Thompson test for multiple comparisons revealed a statistically significant difference between the dentures made using the monolithic process and the other two processes for all AOIs ($P = .0061$), but there was no significant difference between the other two processes ($P = 1$).

In the level 3 analysis (intragroup difference in AOIs), regarding the absolute mean values of all measurements for specimens produced via the monolithic (Fig. 6), oversize (Fig. 7), and injection molding (Fig. 8) processes, the Kruskal-Wallis test indicated a "treatment effect" in terms of the AOIs ($P < .001$). The Dwass-Steel-Critchlow-Fligner test revealed significant intra group differences in AOIs (Table 2, Table 3, Table 4).

DISCUSSION

The null hypothesis was rejected, i.e., that no difference exists among the manufacturing processes, as well as the secondary null hypotheses, i.e., that there would be no differences in AOI among the protocols,

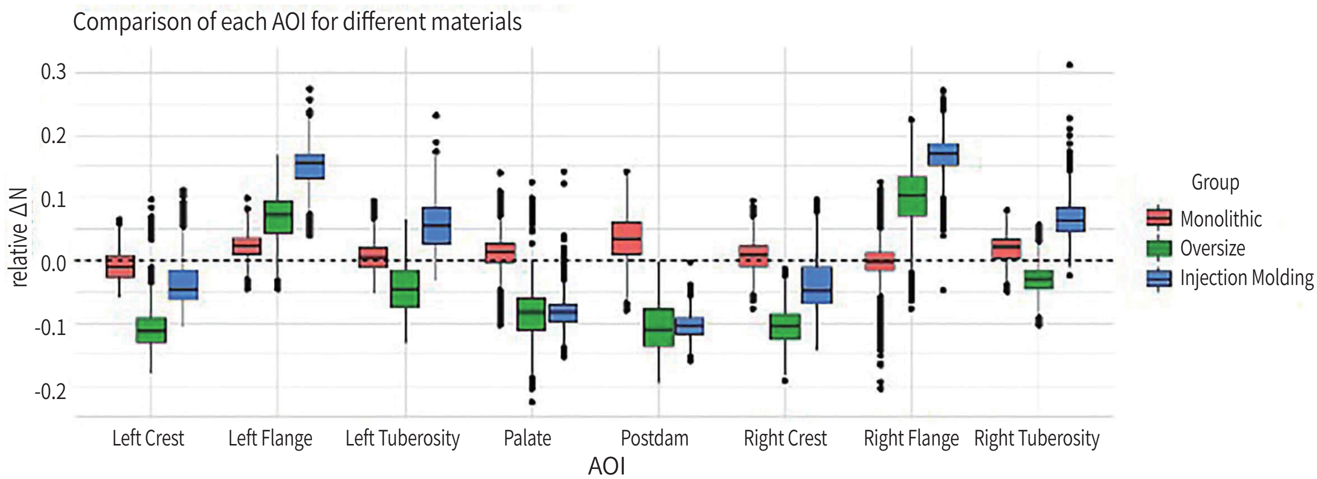

Fig. 5. Comparison of AOIs among the different materials.

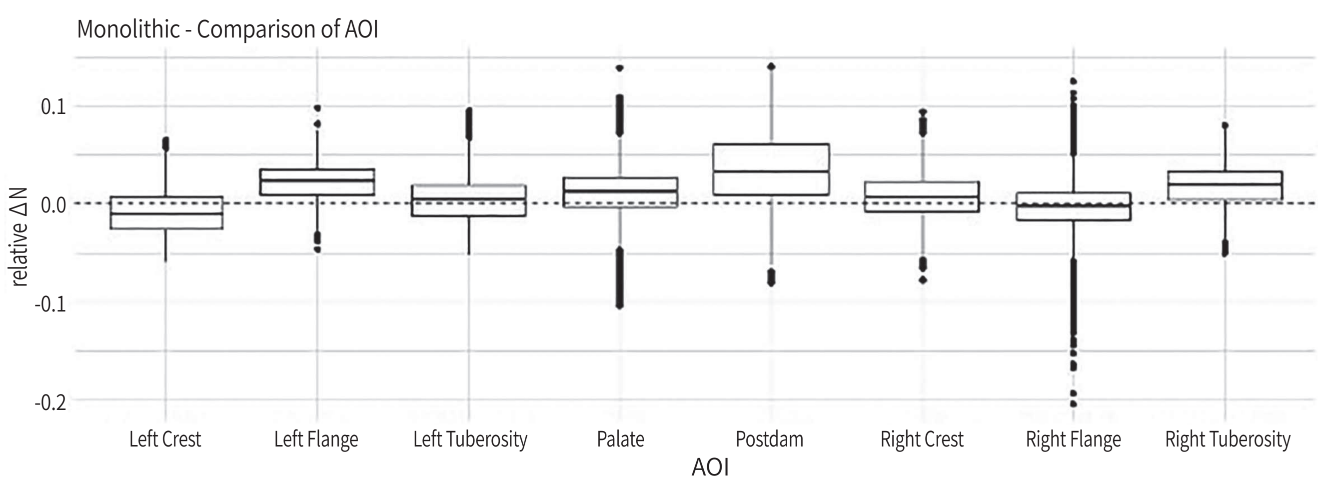

Fig. 6. Comparison of AOIs within the monolithic group (relative values).

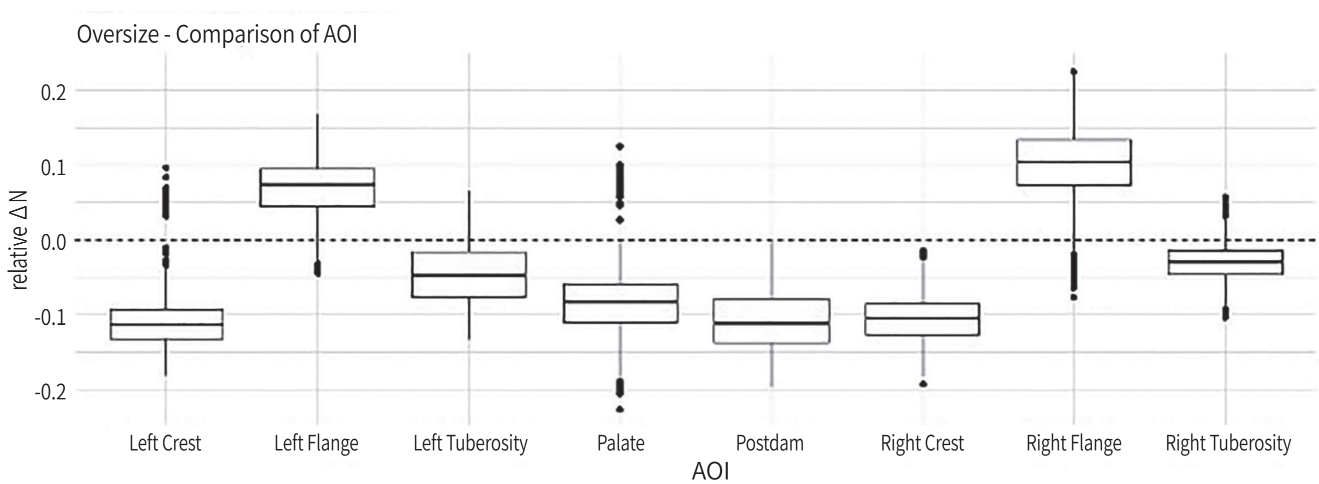

Fig. 7. Comparison of AOIs within the oversize group (relative values).

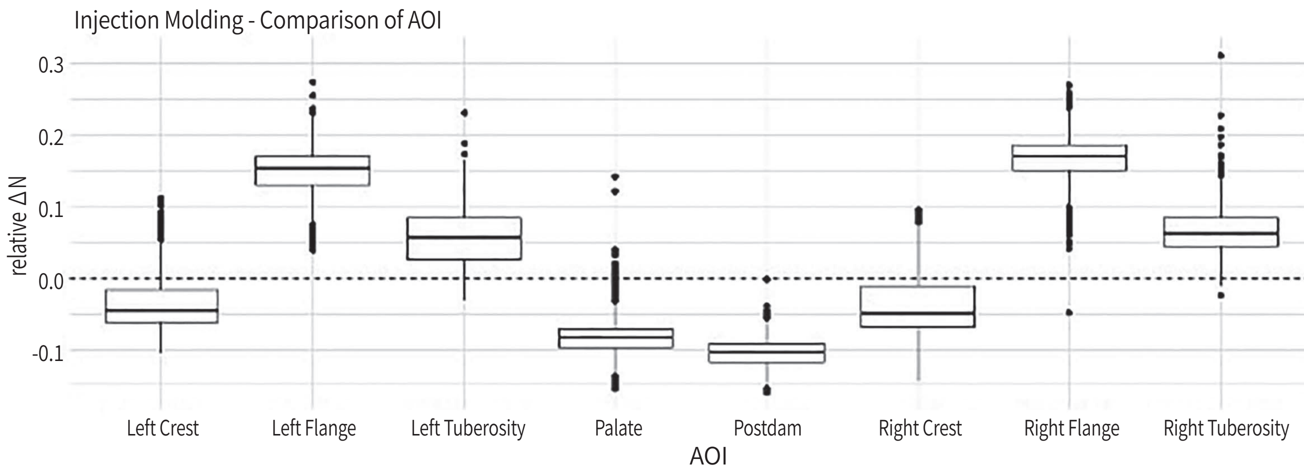

Fig. 8. Comparison of AOIs within the injection molding group (relative values).

Table 2. Comparison of AOIs within the monolithic group

Monolithic comparison	*P* value	Sig
Left Crest - Left Flange	< .001	*
- Left Tuberosity	.5163	
- Palate	.6624	
- Postdam	< .001	*
- Right Crest	.5334	
- Right Flange	< .001	*
- Right Tuberosity	< .001	*
Left Flange - Left Tuberosity	< .001	*
- Palate	< .001	*
- Postdam	< .001	*
- Right Crest	< .001	*
- Right Flange	< .001	*
- Right Tuberosity	.0355	*
Left Tuberosity - Palate	.0013	*
- Postdam	< .001	*
- Right Crest	1.0000	
- Right Flange	.1890	
- Right Tuberosity	< .001	*
Palate - Postdam	< .001	*
- Right Crest	.0016	*
- Right Flange	< .001	*
- Right Tuberosity	< .001	*
Postdam - Right Crest	< .001	*
- Right Flange	< .001	*
- Right Tuberosity	< .001	*
Right Crest - Right Flange	.0901	
- Right Tuberosity	< .001	*
Right Flange - Right Tuberosity	< .001	*

Table 3. Comparison of AOIs within the oversize group

Oversize comparison	*P* value	Sig
Left Crest - Left Flange	< .001	*
- Left Tuberosity	< .001	*
- Palate	< .001	*
- Postdam	.1556	
- Right Crest	< .001	*
- Right Flange	< .001	*
- Right Tuberosity	< .001	*
Left Flange - Left Tuberosity	< .001	*
- Palate	< .001	*
- Postdam	< .001	*
- Right Crest	< .001	*
- Right Flange	< .001	*
- Right Tuberosity	< .001	*
Left Tuberosity - Palate	< .001	*
- Postdam	< .001	*
- Right Crest	< .001	*
- Right Flange	< .001	*
- Right Tuberosity	< .001	*
Palate - Postdam	< .001	*
- Right Crest	< .001	*
- Right Flange	< .001	*
- Right Tuberosity	< .001	*
Postdam - Right Crest	.0715	
- Right Flange	.0066	*
- Right Tuberosity	< .001	*
Right Crest - Right Flange	.7307	
- Right Tuberosity	< .001	*
Right Flange - Right Tuberosity	< .001	*

Table 4. Comparison of AOIs within the injection molding group

Injection molding comparison	*P* value	Sig
Left Crest - Left Flange	< .001	*
- Left Tuberosity	< .001	*
- Palate	< .001	*
- Postdam	< .001	*
- Right Crest	< .001	*
- Right Flange	< .001	*
- Right Tuberosity	< .001	*
Left Flange - Left Tuberosity	< .001	*
- Palate	< .001	*
- Postdam	< .001	*
- Right Crest	< .001	*
- Right Flange	< .001	*
- Right Tuberosity	< .001	*
Left Tuberosity - Palate	< .001	*
- Postdam	< .001	*
- Right Crest	< .001	*
- Right Flange	< .001	*
- Right Tuberosity	< .001	*
Palate - Postdam	< .001	*
- Right Crest	< .001	*
- Right Flange	< .001	*
- Right Tuberosity	< .001	*
Postdam - Right Crest	< .001	*
- Right Flange	< .001	*
- Right Tuberosity	< .001	*
Right Crest - Right Flange	< .001	*
- Right Tuberosity	< .001	*
Right Flange - Right Tuberosity	< .001	*

or in the AOIs within each protocol.

Over the last two decades, several studies[18-24] have investigated the denture base adaptation of CDs fabricated via milling or digital printing technology, and compared it with that of dentures made using the conventional fabrication technique.

The results of this study were consistent with the literature, and the null hypothesis that there is no difference among the examined manufacturing techniques, was rejected. For the analysis, a novel methodology was used, i.e., the reference geometry approach. Briefly, for each AOI, a specific number of points were selected depending on the extent of the AOI on the surface. This was used to calculate the difference in Δ-error between the intaglio surface of digitally manufactured CDs and the original model. The sampling distance (density of points) for the AOIs was kept constant. This reference geometry approach was used instead of the superimposing procedures used by the best-fit tools of commercial software.

When comparing the relative values among the three protocols (Fig. 4B), the monolithic material showed the best mean Δ-error difference: it had a positive value near zero (0.0118 mm), SD of 0.0284 mm, and extremal values ranged from -0.2 to 1.5 mm. The other processes (oversize and injection molding) had larger negative differences (-0.0668 and -0.0374 mm, respectively), although the extreme values of the distribution were positive (0.3 mm). Table 5 shows the mean values for each material. Goodacre *et al.*[1] compared four different CD fabrication processes: pour, pack and press, CAD-CAM, and injection molding. They concluded that no technique resulted in perfect denture base adaptation. However, in their study, when the absolute mean values were assessed, the digital fabrication technique was the most reproducible (precision) and accurate (trueness). Meanwhile, Kalberer *et al.*[20] confirmed that CAD-CAM CD fabrication was significantly superior to 3D-printed fabrication in terms of AOIs in the posterior palatal seal, posterior crest, tuberosity, palatal vault, and anterior ridge. The accuracy of CD fabrication was compared among the 3D-printing, milling, and injection molding techniques by Lee *et al.*[21] They concluded that 3D-printing had low reproducibility, and was less time- and cost-effective. Moreover, the 3D-printing and milling processes were more accurate than injection molding.

Table 5. Comparison of relative mean values among the different materials

Material	Mean ΔN	SD ΔN
Monolithic	0.0118	0.0284
Oversize	-0.0668	0.0680
Injection Molding	-0.0374	0.0880

SD: Standard Deviation.

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In this study, the non-parametric Dwass-Steel-Critchlow-Fligner test revealed a significant difference in the trueness of specimens created using the monolithic protocol and the other two protocols ($P < .001$). However, no statistically significant difference was found between the oversize and injection molding processes. This result suggests that the milled monolithic block process is superior for manufacturing CDs compared with the injection molding process, as well as recomposition by cementing two milled parts (base and teeth) with PMMA resin. However, inaccuracies for the protocol with the poorest performance remain well under the clinical tolerance limit of 300 mm.[26-28]

Similarly, Steinmassl *et al*.[25] compared the fit between CAD-CAM and conventionally fabricated dentures. When scans of cast dentures were superimposed onto STL files of the intaglio surface of the corresponding CDs, the CAD-CAM dentures showed a better fit than the conventionally fabricated ones, as well as enhanced retention and a lower incidence of sore spots. Another study[14] compared different AOIs from CDs (palatal vault, posterior palatal seal, vestibular flange, alveolar crest, tuberosity) in terms of the fit of the intaglio surface. The authors showed that digital manufacturing and injection molding techniques improved the fit in the postdam and palatal areas relative to the conventional technique. However, the outcomes for all fabricating techniques were clinically tolerable and confirmed the results of this study.

Interestingly, both positive (overcontouring) and negative (undercontouring) errors were observed; although overcontouring is not likely to lead to sore spots (i.e., < 300 mm) and thus does not constitute a clinical problem, undercontouring reflects superficial porosity that may enhance plaque retention at the intaglio surface, which could in turn lead to mycosis or tissue inflammation. The Pearson chi-square test with Yates' continuity correction revealed a statistically significant difference among the processes; there were a major number of negative differences between the oversize and injection molding processes, and a higher rate of positive errors for the monolithic process. Other studies[24] compared 3D-printing to conventional processes for the fabrication of CDs. Authors demonstrated that 3D-printed CDs had a better fit than heat-polymerized CDs, although both exhibited some material shrinkage. Yoon *et al*.[22] evaluated CD mandibular bases, manufactured via 3D-printing and milling, according to the same parameters (tissue adaptation and trueness). Although milling resulted in superior tissue adaptation, no statistically significant differences were found. The authors reported that 3D-printed bases led to more tissue compression at the posterior ridge crest and buccal shelf, which required some clinical adjustment during delivery.

To identify the AOI most responsible for the inaccuracies of the different protocols, the Δ-error for each AOI was compared among the protocols (Fig. 5). Table 1 shows the mean values for each AOI.

For the monolithic process, all AOIs were statistically significantly different from the corresponding of the other materials. The highest Δ-error was observed at the postdam AOI for the monolithic process ($\Delta N = 0.034$ mm), at the left crest for the oversize process ($\Delta N = -0.110$ mm), and at the right flange for the injection molding process ($\Delta N = 0.168$ mm). The monolithic process had the best ΔN values for all AOIs. However, these results do not have negative impact on the clinical performance of the CD, being the Δ-error values well within the tolerance limit of the mucosa for generating sore spots.

The AOIs was also compared within each group. For the monolithic process, the worst AOIs were the left and right crests and the postdam. For the oversize process, the worst AOIs were the right and left crests, right flange, and postdam. For the injection molding process, the worst AOIs were the right and left crests. This analysis leads to conclude which manufacturing technique is worst in a specific AOI of the CD, but further studies will be necessary to understand the reason why a specific technological process generates Δ-error values in that specific AOI.

Limitations of this study are the absence of a clinical trial to test results in terms of plaque accumulation and sore spots absence, and the usage of a single commercial producer that may limit the comparison between different manufacturing processes. Further studies will be necessary to test the trueness and precision of the dental surface as well.

CONCLUSION

Modern technologies to digitally manufacture CD investigated in this study are reliable in terms of trueness and precision of the denture base, and all the Δ-error values of the intaglio surface are well within of the tolerance limit of the mucosa. However, the manufacturing process of the monolithic disks showed a significant difference of accuracy in comparison to the oversize and injection molding processes.

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