EVALUATION OF FIT OF CAD/CAM RECORD BASES PRODUCED BY MILLED AND PRINTED METHODS

A Thesis

by

MOHAMMED RAWAS

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee, Seok-Hwan Cho
Committee Members, William W. Nagy
David F. Murchison
Elias D. Kontogiorgos
Head of Department, Larry L. Bellinger

May 2019

Major Subject: Oral Biology

ABSTRACT

Purpose: The purpose of the study was to evaluate the fit of two CAD/CAM record bases produced by milling and printing technology.

Material and Methods: A total of 20 record bases were fabricated on an edentulous maxillary cast by milled (n=10) and printed (n=10) methods, then the intaglio surfaces of the specimens were spray coated and scanned by a laboratory scanner. The intaglio surfaces of the specimens were superimposed on the intaglio surface of the CAD record base digital file as a control group by using an inspection software program. Twelve anatomic locations were selected, and the deviation values of each location were calculated. The deviation area (%) within 200 µm was also calculated. The twelve anatomic locations then were divided into four location groups (anterior alveolar ridge, tuberosity, posterior palatal seal, and mid-palatal) and compared within each milled and printed group. A student's t-test was performed for the percentage of the surface deviation and for the twelve anatomic locations. An ANOVA test was performed for the four location groups within each milled and printed group. A coefficient of variation test was done for the twelve location areas and for the four location groups.

Results: There was a statistically significant difference of mean deviation of twelve anatomic locations between the milled (-82.5 ± 6.28 µm) and printed (-100.2 ±16.48 µm) groups (*P*<.005). In terms of the deviation area within 200 µm, there was a significant difference between milled (91.6% ± 1.9) and printed (76.7% ± 3.7) groups (*P*< .001). The least fabrication distortion for the four location groups was the posterior palatal seal for both milled (56.2 ± 22 .2 μm) and printed (55.4 ± 76.6 μm) groups and the largest distortion location was in the anterior for both milled (-97.1 ± 35 μm) and printed (180.9 ± 60.3 μm) groups. The coefficient of variation for milled record bases is 7.6% and for printed record bases is 16.4%. The highest coefficient of variation was at tuberosity locations for milled record bases (43%) and in the posterior palatal seal location for printed record bases (138%). The lowest coefficient of variation was at the mid -palatal for milled record bases (26%) and in the anterior alveolar ridge for printed record bases (33%).

Conclusions: Within the limitations of this in vitro study, there was a significant difference of record base fit between milled and printed fabrication methods. The milled record bases exhibited a significantly better fit than printed record bases. The best adaptation fit was found at the posterior palatal seal for both milled and printed groups, while the poorest adaptation was found in the anterior area for both groups.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Seok-Hwan Cho, and my committee members Dr. William W. Nagy, Dr. David F. Murchison, and Dr. Elias D. Kontogiorgos for their guidance, enthusiasm, and support throughout the course of this research.

Special thanks to my lovely wife, Maylaa, for her patience, love, and support. Thanks to my parents for their encouragement and motivation. Thanks to my co-residents for their support.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supported by a thesis committee consisting of Dr. Seok-Hwan Cho, committee chair, Dr. William W. Nagy, and Dr. Elias D. Kontogiorgos of the Department of Restorative Sciences, and Dr. David F. Murchison of the Department of Diagnostic Sciences.

The data analyzed was conducted in part by Dr. Elias D. Kontogiorgos of the Department of Restorative Sciences.

All other work conducted for the thesis or dissertation was completed by the student independently.

Funding Sources

Graduate study was supported by a research grant from Texas A&M University.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

1. INTRODUCTION

As long as there have been removable dental prostheses, the denture base has undergone advances and evolution in material selection and fabrication techniques to better fit the oral cavity.[1] The first example of denture fabrication technique is known to be made by the Japanese in the early sixteenth century by means of sculpting a piece of wood to fabricate a record base.[1] Record bases have been made from many materials, including wood, ivory, porcelain, gold, chrome cobalt, and, in vogue today, poly-methyl-methacrylate (PMMA).[2, 3]

PMMA is a denture material that contains a liquid monomer component containing non-polymerized PMMA monomers with hydroquinone, which acts as an inhibitor to retard undesirable polymerization during shelf storage, and a powder component containing prepolymerized spheres of PMMA and benzoyl peroxide, which initiates the polymerization process.[3, 4] PMMA denture bases can be fabricated with different methods of polymerization, including heat-activated, chemically-activated, microwave-activated and visible light activated resins.[5] The chemically-activated resins have the chemical activator-like tertiary amine in the monomer, which can decompose the benzoyl peroxide.[4, 5] The main advantage of chemically-activated resins is less time consuming to the final polymerization. However, it has less favorable mechanical properties than the heat- activated resins.[5] The heat-activated resins need thermal energy for the polymerization process. Heat-activated fabrication technique includes traditional compression, injection molding, and poured molding. [4, 5] Heat activated PMMA resins are commonly used for record bases.[5] The advantage of the heat-activated fabrication method is that the equipment needed for fabrication is ubiquitous and used by many laboratories.[5] Material properties, such as flexural strength, modulus of elasticity, shear bond strength to denture teeth, residual monomer, and water sorption of heat activated PMMA denture resins have been well documented and understood to be clinically adequate for most applications in dentistry.[6, 7] The disadvantage of heat activated PMMA is polymerization shrinkage, which exists in two forms for removable prosthetics. Volumetric shrinkage occurs when polymerization occurs and the density changes. The change in density leads to volumetric shrinkage of approximately 21%. Because a significant amount of heat-cured denture resin is prepolymerized, the final volumetric shrinkage is usually around 7%.[8] This is acceptable due to the uniformity of the shrinkage as it relates to the denture bearing tissue surface, as long as the acrylic resin is handled correctly during fabrication. Linear shrinkage, measured between pre- and post-polymerized dentures at the second molar, is usually around 1%.[8] Because of these inaccuracies in the fabrication processes, recent fabrication techniques such as computer-aided designed and computer-aided manufactured (CAD/CAM) have been developed to decrease these disadvantages.

Milled CAD/CAM denture bases have been the subject of more research in the past few years as the technology has advanced and been refined. Studies have shown that Milled CAD/CAM dentures have less deviation, compared with the denture made by traditional denture processing method (compression molded, pour, injection techniques).[9, 10] Heat-polymerized resins have polymerization shrinkage that affects the denture base adaptation, but this problem is mitigated in CAD/CAM denture bases because they are milled from a puck of acrylic that has already undergone polymerization shrinkage. Milled denture bases have a better uniform quality of denture base fit over the entire soft tissue surface with significantly greater retention than traditional processing techniques.[11] Reduced chair time, better tissue adaptation, and the ability to expeditiously fabricate a backup prosthesis are the reported benefits of this technique.[12-15] Conversely, this technique is more expensive than conventional denture processing. Fewer laboratories can afford the proprietary equipment needed to produce these improved denture bases, and there is a limit as to the level of customization afforded by this technique, namely intrinsic denture tinting and precision in the trial denture.[16]

Denture fabrication methods in dentistry that formerly could only be milled, are now being incorporated into an additive manufacturing workflow, such as for surgical guides and indirect provisional restorations.[17, 18] Rapid prototyping is less expensive and wastes less material.[19] Additive manufacturing by using 3-D printing to execute fabrication and prototyping of provisional and denture prosthesis has recently been expanded in dentistry. Maeda et al[20] introduced the concept of applying rapid prototyping technology in the fabrication of complete dentures in 1994. Printing with digital light projection (DLP) or stereolithography (SLA) technology for rapid prototyping production has recently been incorporated into dentistry as well.[21] SLA technology is based upon a light-triggered reaction where ultraviolet light (UV) beams cure photosensitive liquid polymers on a printing bed, which moves in a z-direction on a cartesian axis after each layer has finished curing. Although expensive relative to other additive manufacturing techniques, such as fused deposition modeling (FDM), printing accuracy levels of the SLA printing method are higher compared to other printing methods. In addition, a smooth surface finish and fine details are achievable with this additive technology. Similarly, DLP printers use a digital micromirror device to simultaneously project ultraviolet light onto the specified surface of the build plate, where layers are sequentially added in a faster timeframe than SLA printing.[19, 22] Printing denture bases is a new area of study and innovation for additive manufacturing in that there are not many studies on the accuracy of the printing process or the material properties of the printed denture bases. The 3D dimensional accuracy of the object depends on the thickness of each layer, which varies from µm to millimeters, depending on the printer, the material, and the complexity of the object.[17] Objects printed with thinner layers are more dimensionally accurate, with the tradeoff of an increased print time.[23] Printed denture bases are fabricated with light-cured PMMA that is laid down by apposition onto a print bed, with layer upon layer that is polymerized, then is washed and cured in a separate light-curing step.[19]

Hwang et al[24] assessed adaption fit of maxillary denture bases from a standard edentulous cast by using DLP, milled and compression molded fabrication methods. The results showed that DLP denture bases have a better fit than milled denture bases. The DLP denture bases were printed at 100-degree build angle where the supporting structure was attached to the labial flange. Osman et al[25] showed that printing specimens at different build angles ranging from 90-degrees to 270-degrees for full coverage dental restorations resulted in varied dimensional accuracy. Tasaka et al[26] showed that additive manufacturing denture bases were more accurate and yielded significantly greater retentive force than traditional heat cured denture bases. Yoon et al[27] showed the milled mandibular denture bases have better adaption than DLP mandibular denture bases. However, Kalbere et al (2019)[28] published that CAD/CAM milled dentures had a better fit than additive manufacturing dentures.

A 3D printable acrylic resin and a corresponding DLP additive manufacturing system have recently become commercially available for a digitally fabricated complete denture, however, very little research has been done on the fit of these new resin systems. Therefore, the aim of this study was to evaluate the fabrication distortion of printed and milled denture bases The null hypothesis is that there is no fit difference between these two CAD/CAM fabrication techniques.

2. MATERIAL AND METHODS

2.1 Definitive cast fabrication

An edentulous maxillary definitive cast, closely approximating what is considered to be a typical American College of Prosthodontics Class I, type A residual ridge morphology presentation, was used for the present study. The cast was scanned by a laboratory scanner (D900; 3Shape), which has 7 µm accuracy, to build a virtual model as a reference. A standard tessellation language (STL) digital reference cast was generated. Then, spheres (0.5 mm radius) were embedded into the incisive papilla, left, and right tuberosity region by using 3D sculpting-based CAD (Meshmixer software; Autodesk) (Figure 1). The embedded spheres provided standardized positioning templates for annotation areas. The workflow for this study shows in Figure 2.

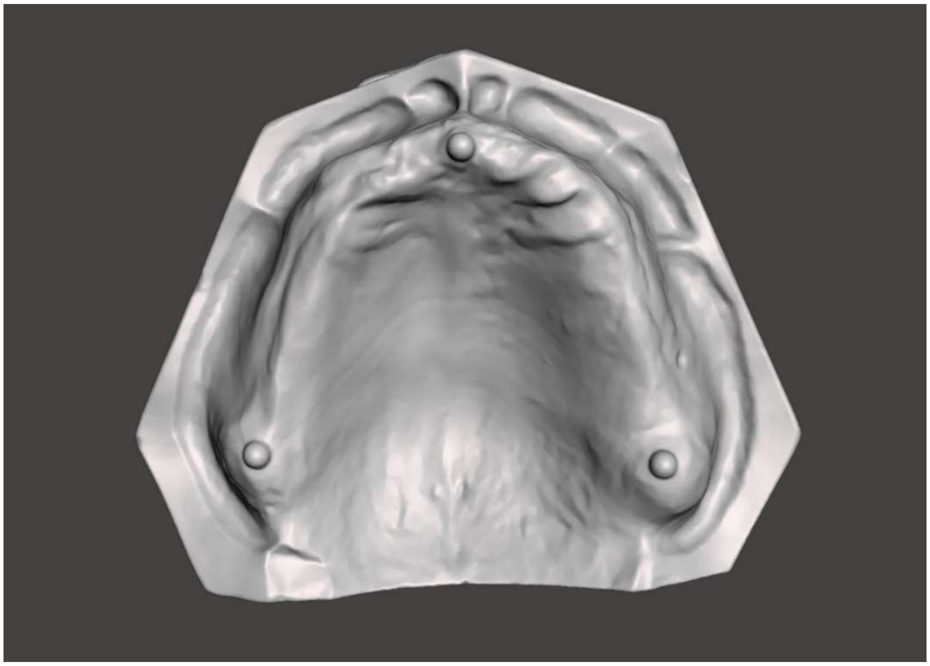

Figure 1. Reference cast shows three embedded spheres.

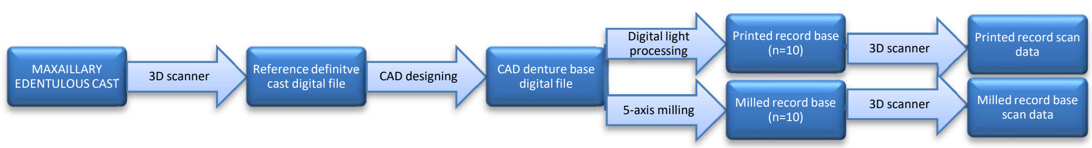

Figure 2. Study Workflow.

2.2 Specimen design and milled specimen fabrication

The reference definitive cast digital file was sent to AvaDent (Global Dental Sciences) and a record base (2 mm thick) was designed (Figure 3). Ten record base specimens were then milled from the CAD record base digital file using pre-polymerized PMMA resin (AvaDent Pucks; Global Dental Science) (Figure 4).

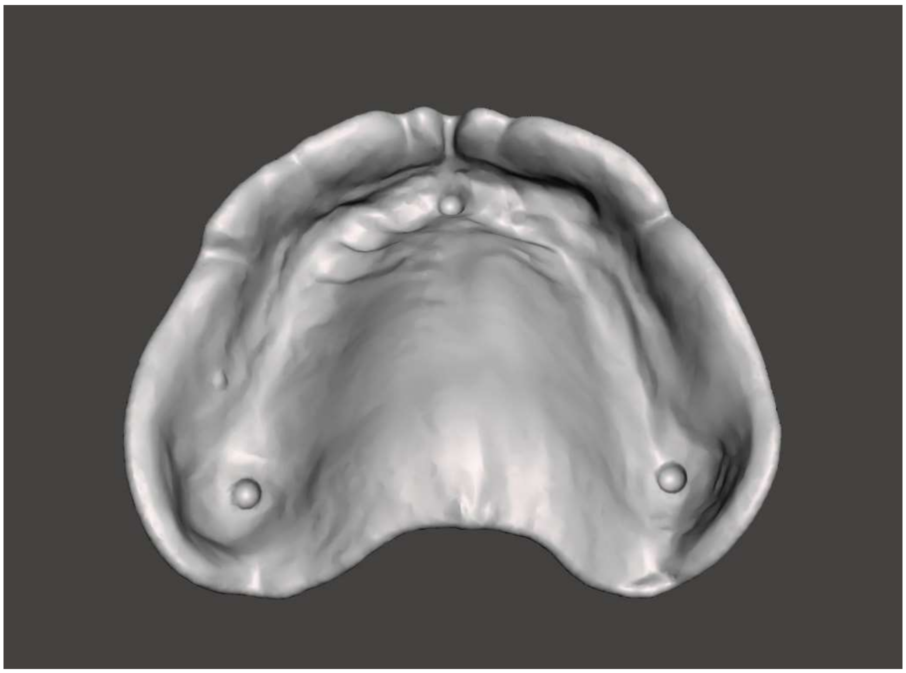

Figure 3. CAD record base digital file.

Figure 4. Milled record base specimens.

2.3 Printed specimen fabrication

The CAD record base digital file from AvaDent (Global Dental Sciences) was sent electronically to a 3D printing company (MedCAD). The printed record base was fabricated by a desktop 3D printer (Vida; EnvisionTEC) with first party denture resin (E-Denture 3D+ resin; EnvisionTEC). The Vida printer uses a high-resolution projector with custom ultraviolet light (UV) optics. It is a digital light processing (DLP) type printer that is commercially available. Specimens were printed vertically on the printing bed (Figure 5), then cleaned in an ultrasonic bath with 95% isopropyl alcohol solution, then the record bases were postpolymerized by using a UV light curing box (EnvisionTEC) according to manufacturer instructions.

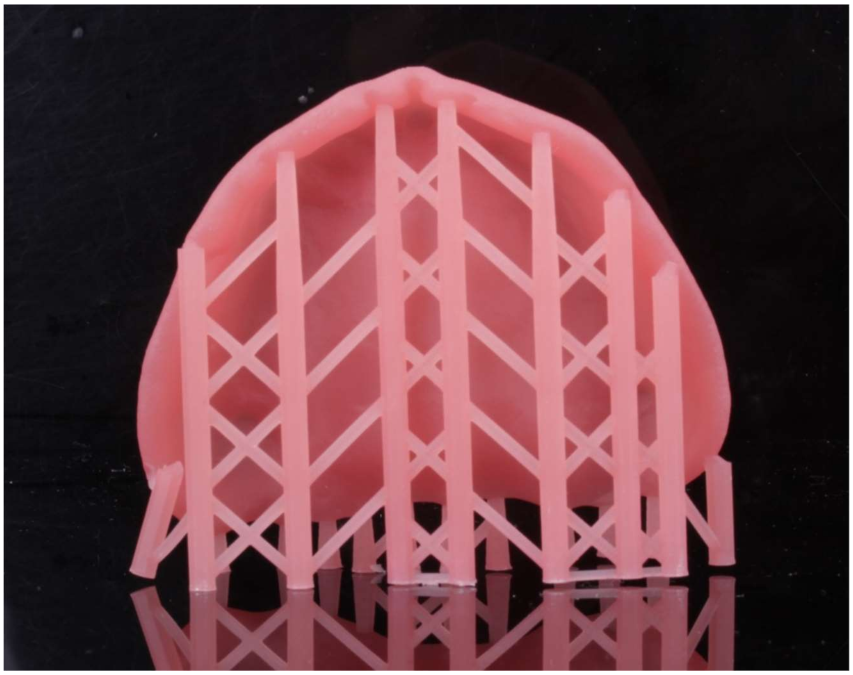

Figure 5. Printed record base with support struts.

2.4 Data acquisition and comparison

All the specimens were stored in water for three days. The intaglio surfaces of the milled and printed record bases as shown in Figure 6 were then spray coated with a thin layer of anti-glare CAD spray (CAD Spray; Whip-Mix) and scanned by using a highly accurate laboratory scanner rated for accuracy to 5 μm (D2000; 3Shape) to generate digital STL files of milled and printed record bases. Superimposition was performed by selecting only the tissue surface of the CAD record base digital file as a control group and the tissue surface of specimens with inspection software (Geomagic Control software; 3D system). Based on previous studies,[10, 29] the best fit alignment was then selected to employ the minimal average deviation for the whole surface. 3D comparison was used to create surface deviation color-coded mapped regions of the superimposed tissue surfaces and divided into 15 color mapped regions. The green zone represents the ideal adaption of the record base to the cast within ± 200 µm. The regions of yellow to red color indicate positive pressure of the record base which means the record base impinged on the definitive cast. Blue to dark blue colored regions indicate negative pressure of the record base to the tissue, which means a gap would exist between the record base and the definitive cast. The surface deviation color-coded mapped regions area is up to a maximum of ± 3000 µm. Figure 7 and 8 show the surface deviation of the printed and milled record base by the surface deviation color-coded mapped regions. The percentage of surface area within 200 µm (green zone) was also calculated.

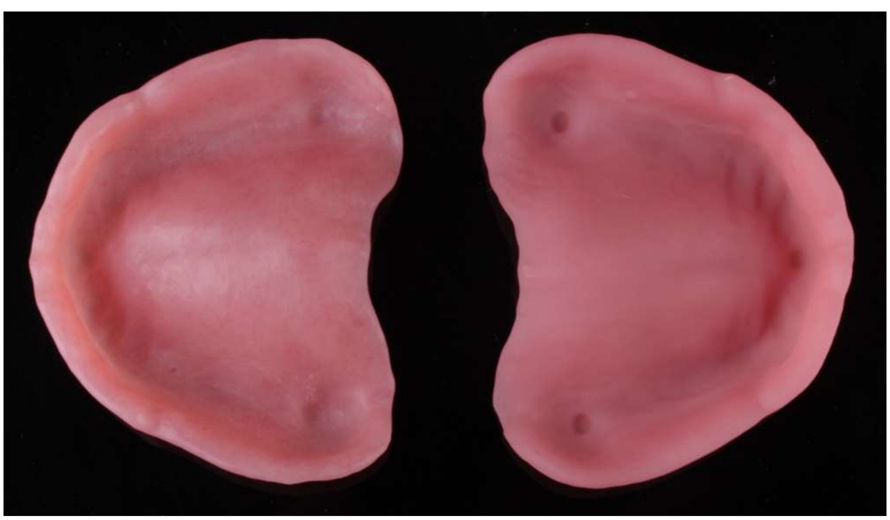

Figure 6. The intaglio surface of milled record base (left) compared with printed record base (right).

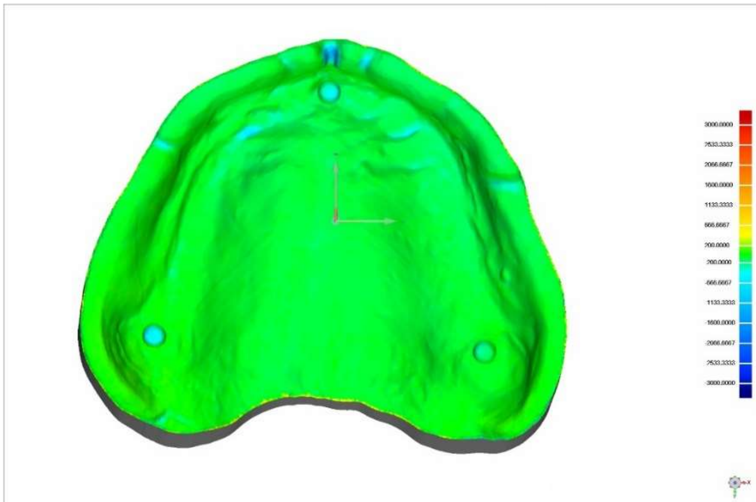

Figure 7. Surface deviation by color-coded of intaglio surface for milled specimen.

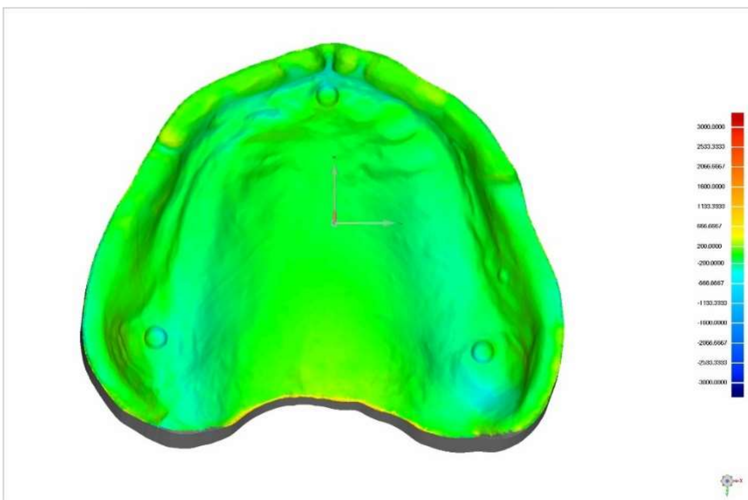

Figure 8. Surface deviation by color-coded map of intaglio surface for printed specimen.

The 3D analysis was also used to create an annotation of measurement employing multiple anatomical locations. The 1 mm spheres were used to superimpose a clear measurement positioning template on the computer screen to place annotation locations in similar regions for each specimen. There were twelve anatomic locations for annotations, which are the measured deviations from the two digital superimposed files, CAD record base, and the specimens. The twelve anatomic locations are as follows: left and right canine region on crest of ridge, left and right premolar region on crest of ridge, left and right tuberosity region on crest of ridge, left and right posterior palatal seal, left and right palatal vault, mid-palatal raphe posterior, and mid-palatal raphe anterior (Figure 9). Annotation locations selected had an exact diameter of 3 mm, which means that the algorithm took a consistent sampling of hundreds of specific locations in a 3 mm diameter and generated a location-specific average, based on those hundreds of deviations (Figure 10).

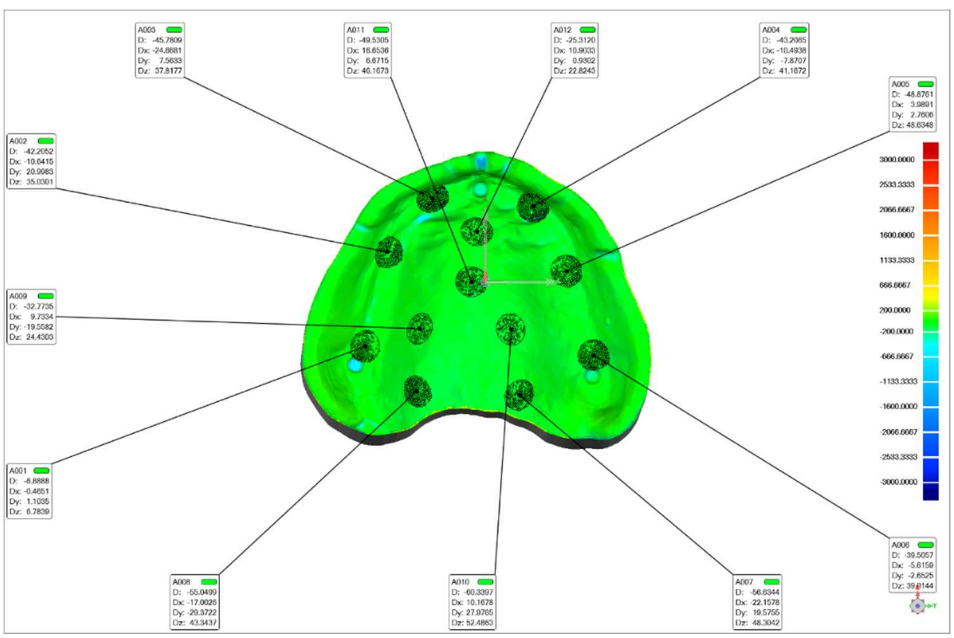

Figure 9. Twelve annotated areas by color-coded map.

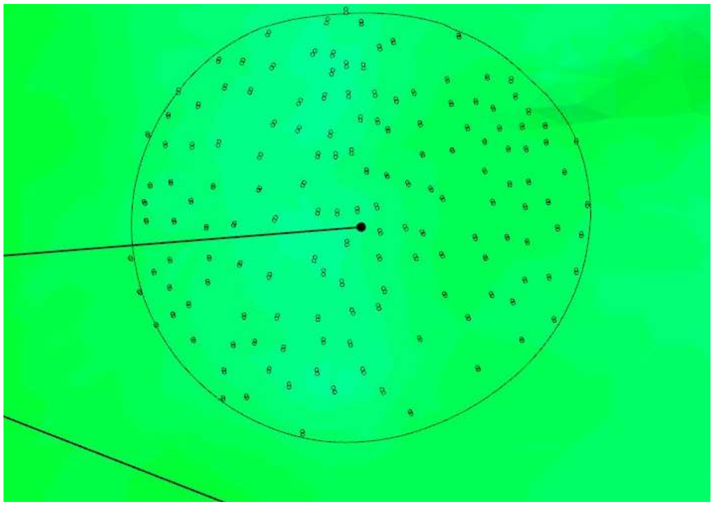

Figure 10. Hundreds of specific areas within each 3 mm diameter annotation location.

Then, these twelve anatomic locations for annotations were divided into four location groups: anterior alveolar ridge location (consisting of four anatomic locations for annotations), tuberosity location (consisting of two anatomic locations for annotations), posterior palatal seal location (consisting of two anatomic locations for annotations), and mid-palatal location (consisting of four anatomic locations for annotations) (Figure 11).

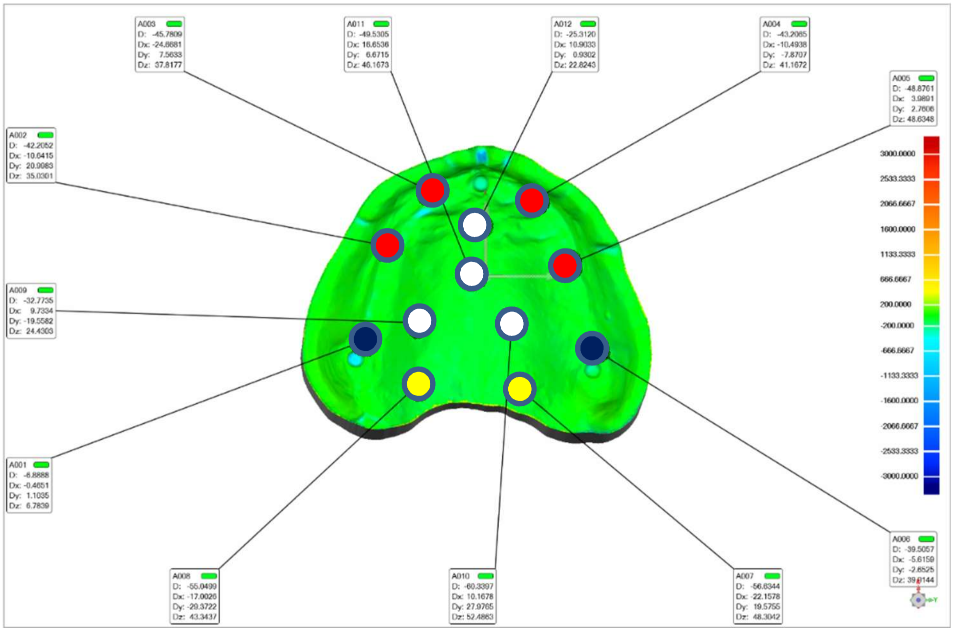

Figure 11. Anterior alveolar ridge location group (red color annotations), tuberosity location group (dark blue annotations), posterior palatal seal location group (yellow annotations), and mid palatal location group (white annotations).

2.5 Data analysis

Deviation values generated from the 3D comparison program were then recorded in Microsoft Excel and modeled in an appropriate statistics program software (IBM SPSS Statistics; IBM Corp). The surface deviation color-coded mapped region percentage of printed and milled record bases were summarized, then the mean deviation of all the annotation areas of each sample and of each four location groups was recorded. A student t-test was performed for the percentage of the surface deviation color coded mapped region zones and for the annotation areas. An ANOVA test was performed for the four location groups within each milled and printed group. mean, standard deviation, and *p*-value were recorded. A coefficient of variation was analyzed to evaluate the variability of fit for both milled and printed record bases.

3. RESULTS

Table 1 shows the area values (%) of record bases fit with ± 200 µm for two groups, milled and printed dentures. There is a statistically significant difference in the fit of the milled and printed record bases by a two-tailed Student's t-test (P<001). For the milled record bases 91.6% ± 1.9 of the areas fell into the green region (within ± 200 µm). Comparatively, 76.7% ± 3.7 of the printed record base area fell into the green zone (Figure 12). The color mapped regions of printed and milled record bases to the CAD record base digital file indicated that milled record bases have a better fit than printed record bases.

Table 1 Percentage value of record bases area fit within ± 200 µm (green zone) for two groups

GROUP	N	Mean (%)	Std. Deviation
MILLED	10	91.6	1.9
PRINTED	10	76.7	3.7

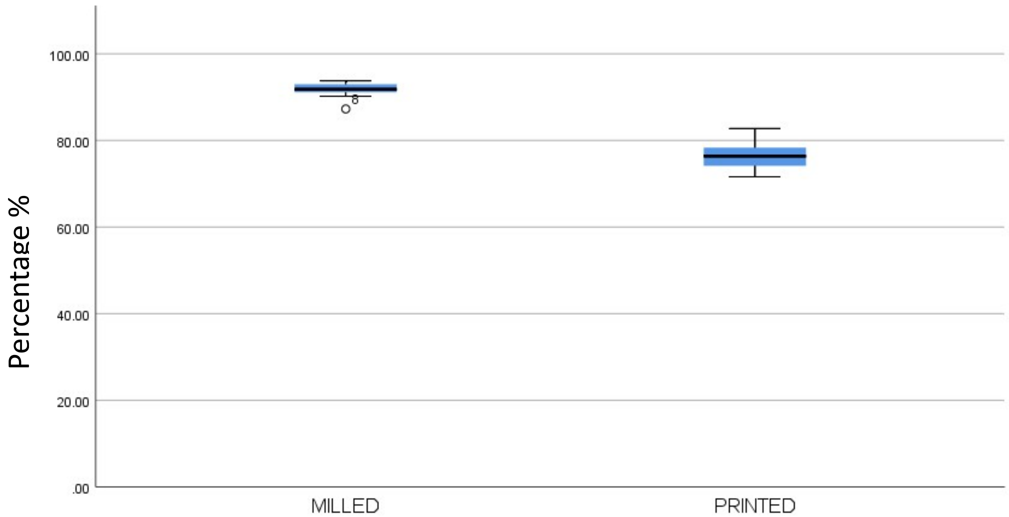

Figure 12. Boxplot for percentage value of record bases area fit within ± 200 µm for two groups

For the twelve annotation areas, there was a statistically significant difference in the fit values between the milled and printed record bases (P<.005). The milled record bases produced a better fit than printed record bases. Table 2 shows that the mean deviation value of the milled record base deviation was -82.5 ± 6.28 µm and the mean deviation value of the printed record base deviation was -100.2 ± 16.48 µm(Figure 13). The coefficient of variation for milled record bases is 7.6% and for printed record bases is 16.4%.

Table 2 Deviation values (mean and standard deviation) and coefficient of variation of two groups

Group	N	Mean (µm)	Std. Deviation	Coefficient of variation
Milled	10	-82.5	6.28	7.6%
Printed	10	-100.2	16.48	16.4%

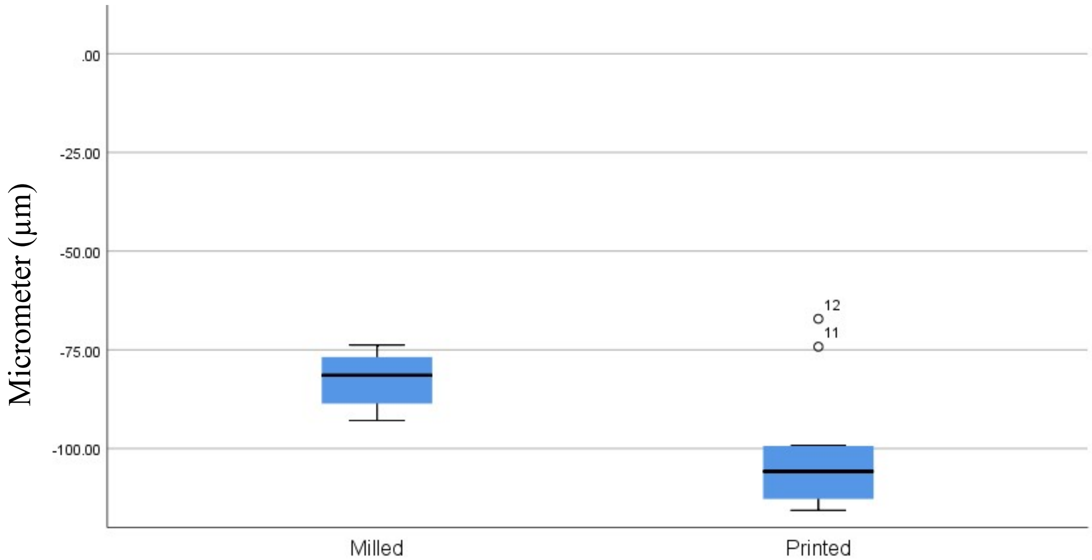

Figure 13. Boxplot for mean and standard deviation value (µm) of record base fit of two groups

Table 3 shows the mean, standard deviation and coefficient of variation of four locations of each milled and printed group. For the four location groups of the milled record bases, the lowest deviation location was the posterior palatal seal with a mean deviation of -56.2 ± 22.2 µm, and the highest deviation location was anterior alveolar ridge with a mean deviation of -97.1 ± 35 µm (Figure 14). For the printed record bases, the lowest deviation location was the posterior palatal seal with a mean deviation of 55.5 ± 76.6 µm, and the highest deviation location was anterior alveolar ridge with a mean deviation of -180.9 ± 60.3 µm (Figure 15). The highest coefficient of variation was in the tuberosity location for milled record bases (43%) and posterior palatal seal for printed record bases (138%). The lowest coefficient of variation was at mid palatal for milled record bases (26%) and at anterior alveolar ridge for printed record bases (33%). For the milled record bases, there was a statistically significant difference in the fit values among the location groups (P<.001) except between anterior and mid-palatal location groups, and between tuberosity and posterior palatal locations (P=1) using ANOVA test. For the printed group, there was a statistically significant difference in the fit values among the locations (P<.001) except between anterior and tuberosity locations (P=.124).

Table 3. Deviation comparison and coefficient of variation among four different locations for two groups

Location	MILLED (μm)	Std. Deviation (μm)	Coefficient of variation	PRINTED (μm)	Std. Deviation (μm)	Coefficient of variation
Anterior alveolar ridge	-97.1	35	36%	-180.9	60.3	33%
Tuberosity	-58.2	25.1	43%	-143.7	60.1	42%
Mid palatal	-93.1	24.3	26%	-61.8	45.3	73%
Posterior palatal seal	-56.2	22.2	40%	55.4	76.6	138%

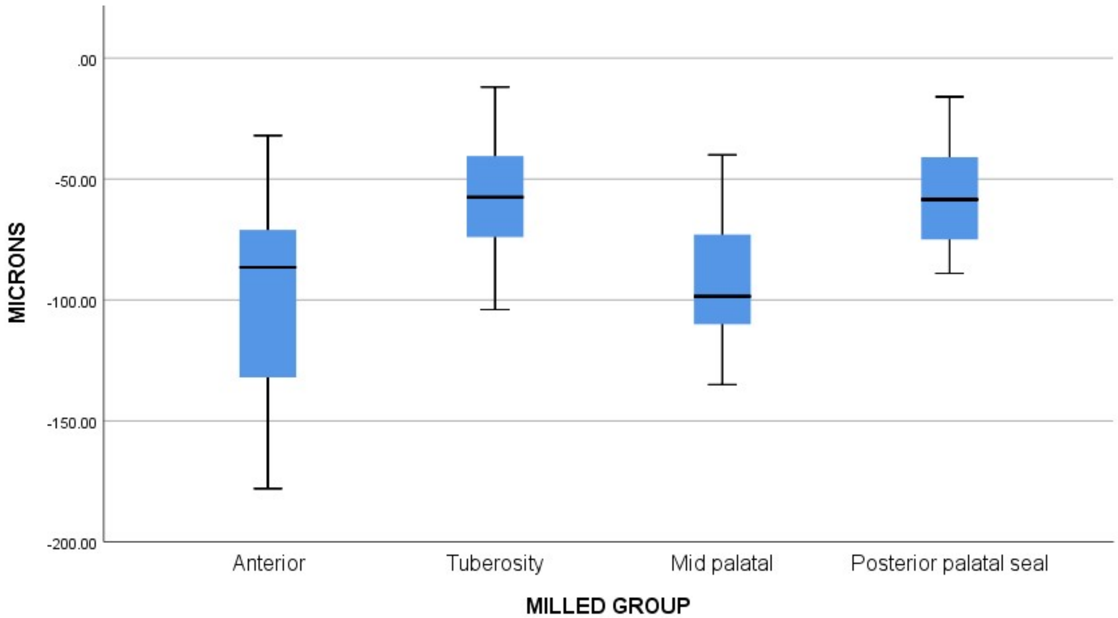

Figure 14. Boxplot for four location groups of milled record bases

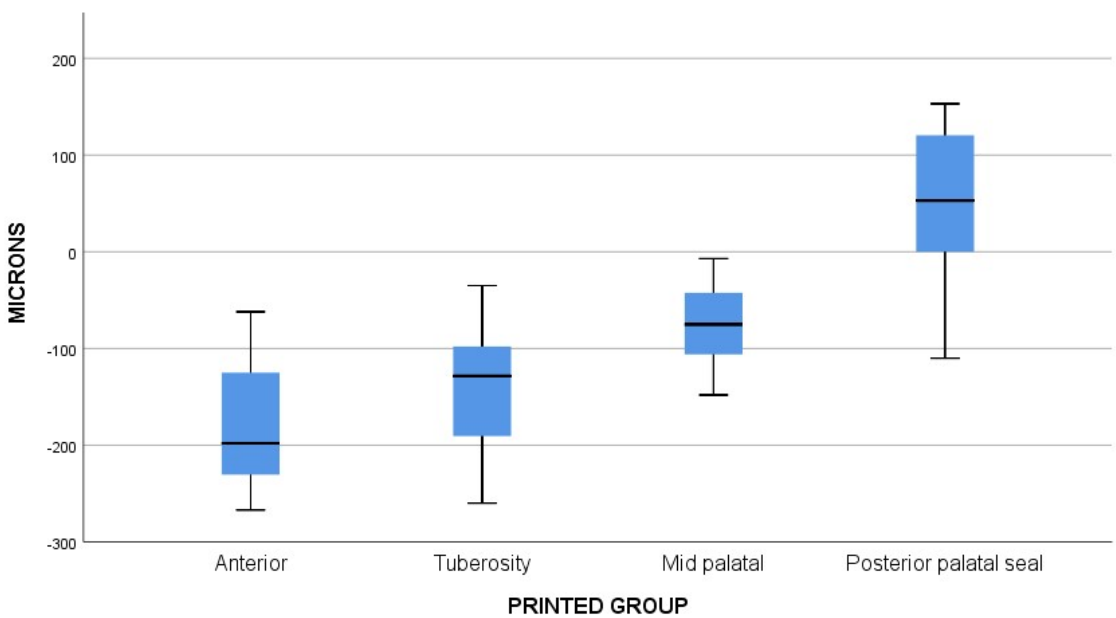

Figure 15. Boxplot for four location groups of printed record bases.

4. DISCUSSION

The present study investigated the fit of two CAD/CAM denture record bases, milled and printed. There was a statistically significant difference between the fit of two record base groups. Thus, the null hypothesis was rejected. For the deviation within 200 µm (green zone), milled record bases showed superior accuracy to the printed record bases. The area within ± 200 µm was used as a reasonable standard of denture deviation in the present study; above 200 µm, it can be unacceptable or marginally acceptable.[10] It is currently unknown as to which level of positive deviation will produce a sore spot. While the present study showed that significant differences existed between milled and printed record bases, this small dimensional discrepancy between the milled and printed record bases may not be clinically significant because studies have shown that clinically acceptable methods of denture fabrication lead to an average deviation of 270 µm in the posterior palatal seal area.[30]. The printed record bases showed approximately double the coefficient of variation for the twelve location areas compared to the milled record bases. Also, the highest coefficient of variation was at tuberosity locations for milled record bases and the posterior palatal seal for printed record bases. This indicates that printed record bases have more variability in fit than milled record bases. Possible explanations could be that printed record bases were exposed to different polymerization shrinkage rate during fabrication process. More research is needed to standardize a clinically acceptable amount of "misfit" of the denture base to the underlying soft tissue

Goodacre et al[10]demonstrated that milled record bases have higher accuracy of fit than traditional fabrication methods.[10] Yoon et al[27] showed that milled record bases have better adaption than DLP record bases. The present study agreed with other studies that the milled record bases showed a better fit than printed record bases.[27, 28] However, Hwang et al[24] showed that printed denture bases have a better fit than milled denture bases fabricated by definitive casts. They showed that milled bases were was mainly green except the labial flange, which indicated possible undercuts and a larger surface deviation from the definitive cast surface. Also, the DLP specimens were printed at 100-degree build angle where the supporting structure was attached to the labial flange. In the present study, the printed specimens were printed at 90-degree angle and the supporting structure was attached to the flange border according to the manufacturer's recommendation. The printing angulation method may affect the deviation of specimens. A previous study[25] showed that a printed crown at different build angles resulted in different fits. Further studies for record bases printed at different build angle will be needed to evaluate this variable. s

A well-fitted denture with minimum processing distortion provides good support, stability, and retention to minimize masticatory mucosa distortion and reduce residual ridge resorption. The denture retention depends on its resistance to the removal force that dislodges the denture and breaks the atmospheric pressure seal. The atmospheric pressure seal depends on a well adapted peripheral seal of the denture base and fit of the denture's intaglio surface to the tissue.[31] Well-fitted denture movements range from 0 to 1.4 mm on the chewing side and from 0.1 to 1.6 mm on the non-chewing side.[32]

According to a previous study[10], all deviation points for the milled and traditional processing denture bases ranged from - 241 to 224 μm measured with best-fit alignment using an inspection software program. While denture processing distortion should be held to a minimum, the may be little clinical significance of maxillary heat-activated dentures with a processing distortion in the range of 220 – 270 μm because tissue displacement of around 250 μm is needed for accurate denture seating.[30]

The anatomical region of greatest concern in removable prosthetics is usually the junction of the hard and soft palate, where the posterior palatal seal is scribed for traditional techniques. In the present study, the lowest deviation of annotation areas for the printed record bases was the right posterior palatal seal area (mean deviation of -13 μm). The lowest deviation group for the milled and printed record bases were also the posterior palatal seal groups. The mean deviation of the posterior palatal seal location of milled groups was negative value (-56.2 μm), indicating a negative pressure or a gap between the intaglio surface of record base and patient soft tissue The mean deviation of the posterior palatal seal location of the printed bases was a positive value (55.4 μm), indicating a positive pressure on the intaglio surface record base and the patient's soft tissue. This may result from the flatter surface of the posterior palatal seal area in contrast to undercut areas or deep concavities which may require many build layers for the 3D printer that could increase the fabrication distortion. Therefore, the results of this study agreed with other study results[10] that there might be no need to add a posterior palatal seal area for milled or printed denture bases tissue surface as standard practice.

In this in vitro study, the fit measurement was done through surface matching and best-fit alignments, so these results may not exhibit a clinically difference in vivo. Further studies are needed to evaluate the fit of different printed groups such as printing with different build angles. In addition, future studies are needed to evaluate the retention of milled and printed record bases in vivo. The results of the present study also do not take into account the next step in the patient workflow, which is to add wax to make an occlusal rim, then mount and set teeth, followed by traditional techniques and adding teeth upon the printed or milled denture bases. It is unknown as to whether milled and printed denture bases will distort significantly after re-processing, particularly in printed resins, which do not undergo a preliminary curing cycle for fabrication.

5. CONCLUSIONS

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

1. There was a significant difference in the fit between milled and printed record bases. The milled record bases exhibited a significantly better fit than printed record bases.
2. In terms of location comparison, the best adaptation fit was found at the posterior palatal seal for both groups, while the poorest adaptation was found in the anterior area for both groups.

REFERENCES

[1] Ring M.Dentistry : an Illustrated History, Abradale Press/Harry N. Abrams 1992.

[2] Engelmeier RL.The history and development of posterior denture teeth--introduction, Part II: Artificial tooth development in America through the nineteenth century. J Prosthodont 2003;12:288-301.

[3] Phoenix RD.Denture base materials. Dent Clin North Am 1996;40:113-120.

[4] Winkler S.Denture base resins. Dent Clin North Am 1984;28:287-97.

[5] Takamata T, Setcos JC.Resin denture bases: review of accuracy and methods of polymerization. Int J Prosthodont 1989;2:555-62.

[6] Phoenix RD, Mansueto MA, Ackerman NA, Jones RE.Evaluation of mechanical and thermal properties of commonly used denture base resins. J Prosthodont 2004;13:17-27.

[7] Bettencourt AF, Neves CB, de Almeida MS, Pinheiro LM, Oliveira SA, Lopes LP, Castro MF.Biodegradation of acrylic based resins: A review. Dent Mater 2010;26:e171-180.

[8] Anusavice KJ.Phillips' science of dental materials, St. Louis, Mo. : Elsevier/Saunders, St. Louis, Mo. 2013.

[9] El Bahra S, Ludwig K, Samran A, Freitag-Wolf S, Kern M.Linear and volumetric dimensional changes of injection-molded PMMA denture base resins. Dent Mater 2013;29:1091-7.

[10] Goodacre BJ, Goodacre CJ, Baba NZ, Kattadiyil MT.Comparison of denture base adaptation between CAD-CAM and conventional fabrication techniques. J Prosthet Dent 2016;116:249-256.

[11] AlHelal A, AlRumaih HS, Kattadiyil MT, Baba NZ, Goodacre CJ.Comparison of retention between maxillary milled and conventional denture bases: A clinical study. J Prosthet Dent 2017;117:233-8.

[12] Bidra AS, Farrell K, Burnham D, Dhingra A, Taylor TD, Kuo CL.Prospective cohort pilot study of 2-visit CAD/CAM monolithic complete dentures and implant-retained overdentures: Clinical and patient-centered outcomes. J Prosthet Dent 2016;115:578-586.e571.

[13] Goodacre CJ, Garbacea A, Naylor WP, Daher T, Marchack CB, Lowry J.CAD/CAM fabricated complete dentures: concepts and clinical methods of obtaining required morphological data. J Prosthet Dent 2012;107:34-46.

[14] Kattadiyil MT, AlHelal A.An update on computer-engineered complete dentures: A systematic review on clinical outcomes. J Prosthet Dent 2017;117:478-485.

[15] Thalji G, Jia-mahasap WJCOHR.CAD/CAM Removable Dental Prostheses: a Review of Digital Impression Techniques for Edentulous Arches and Advancements on Design and Manufacturing Systems. 2017;4:151-7.

[16] Kattadiyil MT, AlHelal A, Goodacre BJ.Clinical complications and quality assessments with computer-engineered complete dentures: A systematic review. J Prosthet Dent 2017;117:721-8.

[17] Bhargav A, Sanjairaj V, Rosa V, Feng LW, Fuh Yh J.Applications of additive manufacturing in dentistry: A review. J Biomed Mater Res B Appl Biomater 2018;106:2058-2064.

[18] Inokoshi M, Kanazawa M, Minakuchi S.Evaluation of a complete denture trial method applying rapid prototyping. Dent Mater J 2012;31:40-46.

[19] van Noort R.The future of dental devices is digital. Dent Mater 2012;28:3-12.

[20] Maeda Y, Minoura M, Tsutsumi S, Okada M, Nokubi T.A CAD/CAM system for removable denture. Part I: Fabrication of complete dentures. Int J Prosthodont 1994;7:17-21.

[21] Alharbi N, Wismeijer D, Osman RB.Additive Manufacturing Techniques in Prosthodontics: Where Do We Currently Stand? A Critical Review. Int J Prosthodont 2017;30:474-484.

[22] Stansbury JW, Idacavage MJ.3D printing with polymers: Challenges among expanding options and opportunities. Dent Mater 2016;32:54-64.

[23] Farzadi A, Waran V, Solati-Hashjin M, Rahman ZAA, Asadi M, Osman NAA.Effect of layer printing delay on mechanical properties and dimensional accuracy of 3D printed porous prototypes in bone tissue engineering. Ceramics Int 2015;41:8320-8330.

[24] Hwang HJ, Lee SJ, Park EJ, Yoon HI.Assessment of the trueness and tissue surface adaptation of CAD-CAM maxillary denture bases manufactured using digital light processing. J Prosthet Dent 2019;121:110-7.

[25] Osman RB, Alharbi N, Wismeijer D.Build Angle: Does It Influence the Accuracy of 3D-Printed Dental Restorations Using Digital Light-Processing Technology? Int J Prosthodont 2017;30:182-8.

[26] Tasaka A, Matsunaga S, Odaka K, Ishizaki K, Ueda T, Abe S, Yoshinari M, Yamashita S, Sakurai K.Accuracy and retention of denture base fabricated by heat curing and additive manufacturing. J Prosthodont Res 2019;63:85-89.

[27] Yoon HI, Hwang HJ, Ohkubo C, Han JS, Park EJ.Evaluation of the trueness and tissue surface adaptation of CAD-CAM mandibular denture bases manufactured using digital light processing. J Prosthet Dent 2018;120:919-926.

[28] Kalberer N, Mehl A, Schimmel M, Muller F, Srinivasan M.CAD-CAM milled versus rapidly prototyped (3D-printed) complete dentures: An in vitro evaluation of trueness. J Prosthet Dent 2019.

[29] Güth J-F, Keul C, Stimmelmayr M, Beuer F, Edelhoff D.Accuracy of digital models obtained by direct and indirect data capturing. Clin Oral Invest 2013;17:1201-8.

[30] Anthony DH, Peyton FA.Evaluating dimensional accuracy of denture bases with a modified comparator. J Prosthet Dent 1959;9:683-692.

[31] Boucher CO.Complete Denture Impressions Based Upon the Anatomy of the Mouth. J Am Dent Assoc 1944;31:1174-1181.

[32] Chong LC.Movement of maxillary complete dentures--a kinesiographic study. J Dent 1983;11:257-263.