# EVALUATION OF ACCURACY AND DIMENSIONAL STABILITY OVER TIME OF 3D PRINTED CUSTOM TRAYS, USING TWO DIFFERENT TYPES OF PRINTING RESINS

A Thesis

by

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ABSTRACT

Statement of problem: Taking an accurate edentulous impression is the first step in complete denture restoration and is key to ensuring that the complete dentures will have good support, retention, and stabilization functions. To ensure intra-oral stability the retention of the denture, the custom tray should be closely adapted to the intraoral tissues and should be dimensionally stable from printing time to impression appointment. In the clinical setting, the accuracy of custom trays manufactured by traditional methods may be related to the experience of the operators, the change of uneven wax thickness, and the deformation of custom trays in the whole process. 3D printed custom tray workflows have been introduced and are continuing to emerge in modern dentistry.

Purpose: The aim of this study is to investigate the intaglio surface trueness and dimensional stability of the digitally designed and 3D printed custom trays using two different types of printing resins over a 21-day period.

Materials & Methods: Two maxillary and mandibular arches were scanned in a laboratory scanner to create a master file. Maxillary and mandibular custom trays were digitally designed, and 40 trays were printed in an LCD 3D printer. Four separate groups (n = 10) were fabricated using two different types of resin. Specimens were scanned at five-time intervals time “0” (t0), on the 3rd day (t1), on the 7$^{th}$ (t2), on the 14$^{th}$ (t3) and on the 28$^{th}$ (t4). Scans were measured for deviations from the reference trays. Statistical analysis was performed using Kruskal-Wallis with Bonferroni corrections ($\alpha$= 0.05).

Results: Group comparisons showed statistically significant differences between the Keytray mandibular trays, Keytray maxillary, Raydent mandibular, and Raydent maxillary.

Conclusions: Maxillary trays showed more distortion than the respective mandibular trays of the same resin over time. Keytray printed trays were more accurate than the Raydent trays at all times regardless of the arch. Keytray mandibular trays remain stable at 21 days. Keytray maxillary trays remain dimensionally stable until 7 days. Raydent mandibular and maxillary trays show no dimensional changes up to 3 days after printing.

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## CONTRIBUTORS AND FUNDING SOURCES


### Contributors

This work was supervised by a thesis committee consisting of Dr. Matthew Kesterke, Assistant Professor of the Department of Orthodontics; Dr. Elias D. Kontogiorgos, Director of the Department of Prosthodontics; Dr. Jenn Hwan Chen, Assistant Professor of the Department of Prosthodontics and Dr. Bernard J. Hennessy, Head of Department of Comprehensive Dentistry.

The data analysis was provided by Dr. Matthew Kesterke. All other work conducted for the thesis was completed by the student independently.

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# NOMENCLATURE

| | |
|---|---|
| VLC | Visible light cure |
| LED | Light emitting diode |
| 3D | 3-dimensional |
| CAD | Computer Aided Design |
| CAM | Computer Aided Manufacture |
| DLP | Digital light processing |
| DMD | Digital micromirror device |
| IPA | Isopropyl alcohol |
| LCD | Liquid crystal display |
| SLA | Stereolithography |
| STL | Standard Tessellation Language |

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# 1. INTRODUCTION

In recent years, with an aging population leading to increased life spans, the loss of dentition challenges a large proportion of the population. The demand for comfortable prosthetic options, such as treatment with complete dentures, which entails a convenient and timely fabrication process, is growing more and more over time. In spite of the fact that implant restorations are widely popular because of their considerable advantages, complete dentures are still a routine treatment and an affordable prosthodontic solution for edentulous patients[2]. The first step in complete denture restoration is taking an accurate impression of the existing ridges to ensure that the final prostheses will have sufficient support, retention, and stabilization for functional purposes. The two-step technique involves making two different impressions, a primary and a final. The final is taken with the aid of a custom tray in order to obtain an accurate representation of the morphology and have a moderate flange extension, compared to the one-step technique with a prefabricated / stock tray. First, the primary impression is taken with the use of a stock tray with impression material. Second, the primary plaster model is used to fabricate the custom tray from which the final impression is obtained[3].

An impression can achieve most accuracy when the distance between the impression and the impressed area is minimal and also when the impression material is evenly distributed and has uniform thickness. The use of prefabricated trays, independent of tray material, results in an uneven bulk thickness of the impression material, which leads to more likelihood of distortion[4]. Therefore, custom trays are preferable to stock trays, since they create a thin and homogenous space between the tray and the oral mucosa to control the impression material thickness. Studies have shown that custom trays contribute to the accuracy of impressions relative to the anatomical characteristics of the oral tissues, by providing a uniform space of 2 mm for the elastomeric impression materials.[4,5] In addition, a precise adaptation of custom trays to the patient's oral structures can eliminate the patient's discomfort while making the impression[6].

However, some problems appear in the application of the method: the operation of manual custom trays is tedious, and the primary gypsum is difficult to preserve for extended periods of time and repeated use.[2] Another common problem in the fabrication of custom trays is the lack of dimensional stability and subsequent deformation[6]. In the past, various materials were used to fabricate custom trays, such as Shellac, Thermoform, Polycaproilaitone, Self-Cure Acrylic Resin, and Heat Cure Acrylic Resin, Visible Light Cure (VLC) resin.[7] The dimensional changes of these materials may be caused by many different factors with the most prominent being the shrinkage or expansion according to the method of curing.[7] Many studies have suggested that the trays made of auto-polymerizing acrylic resin should be made at least 20 to 24 h in advance to avoid major dimensional changes in the material[8]. In addition, previous research on VLC resin documented that the material closest to the light emitting diode (LED) light of the curing unit would get polymerized first and the resulting internal stresses would lead to transformation, contraction, and shrinkage while cooling, resulting in gap formation. [8] Consequently, the produced space of the custom tray on the tissue surface of the master cast is commonly observed at the margins and the posterior palatal seal area of the maxillary trays. This distorted custom tray prevents correct impression- taking and border molding, leading to poor retention of the final dentures.[6]

With the progress of digital technology, the application of computer-aided design and computer-aided manufacturing (CAD-CAM) rendered prosthodontic procedures more convenient, accurate, efficient, and less time-consuming. 3D printing is technology based on computer-aided design digital data that allows the fabrication of a physical object via an additive manufacturing technique. Using CAD-CAM technology to digitally design and print custom trays seems to address the previously mentioned issues, since the hands-on labor to manually fabricate and adjust the trays made in the traditional approach can be saved. Also, there is no need to keep the gypsum casts since they can be scanned and saved as digital files (STL). Additionally, there is no direct contact of the operator with volatile substances or dust that is potentially harmful.

Moreover, a high level of precision and trueness in the production of custom trays can be easily achieved.[3] Chen et al. compared the conventional and digital methods of making custom trays of the mandibular arch, reporting that although the difference between the two techniques was not statistically significant, the 3D printed custom tray exhibited a higher precision compared to the handmade tray.[9] Similarly, Sun et al. examined the thickness of the impressions taken with digital and conventional trays. They concluded that custom trays fabricated with the use of 3D printing technology provided a more even space for the impression material compared to the conventionally made trays.[10]

In the manufacturing of different dental prostheses using 3D printing technology with photosensitive resin, there are many different types of printing methods that can be employed.[11] The first to introduce three-dimensional printing technology in the dental world was Charles Hull in 1986. He introduced stereolithography (SLA), the first type of three-dimensional printing technology. Scott Crump introduced the fused deposition modeling (FDM) three-dimensional printing technology four years later. The most commonly used 3D technologies in dentistry, because of their great success, are the Stereolithography Apparatus (SLA), Direct Light Processing (DLP), and Liquid Crystal Display (LCD). The basis of the above-mentioned technologies is a vat polymerization method. The liquid photopolymer resin used by these printers is cured with the aid of a light source. DLP technology has a digital light projector which serves as the source of light to photo-polymerize the resin. This projector works by flashing an image of a layer at a time and in this way all points of each layer are light cured simultaneously, thus reducing the printing time. A DLP printer has a light emitting diode (LED) screen which is composed of a digital micromirror device (DMD). These tiny micromirrors concentrate the light coming from the source and form the structure of each layer on the bottom part of the resin tank.[12] With LCD 3D printers, the printing resins are polymerized after being irradiated with light. The light source in this case is a LED light emitted from a lamp and the LCD screen controls the light pattern. LCD 3D printers use LCD panels that shine directly to the build area in a parallel fashion.[13] In this technology, there is no need of lenses. Also, possible pixel distortion cannot affect the printing result which gives LCD printers an extra asset.[12] It is worth mentioning that the LCD technique is more affordable than other vat polymerization 3D printers and has similar resolution. The reported short service life though can be considered as a drawback of this printing technique.[14]

Among the available resins to produce custom trays via 3D printing for intraoral use, are the isopropyl alcohol (IPA) washable custom tray resins and the water-washable resins. Most kinds of uncured liquid 3D printing resins are not soluble in water and postprocessing of the printed objects includes cleaning with >99% IPA to rinse off extra resin. IPA solvent has a high vapor pressure that makes the IPA very volatile with a propensity to evaporate. Furthermore, IPA is a flammable liquid that requires specific safety precautions[15,16]. Fairly new to the market, the water washable resins contain hydrophilic groups and can be cleaned simply using water, thus eliminating risks associated with the use of IPA. Because the water-washable photopolymer resin is insoluble when cured, only the uncured water-washable photopolymer resin is washed away.

Water is readily available, safe, cheap, easy to use, and creates minimal waste compared to IPA washable[17].

Previous studies have investigated the dimensional deformation of 3D printed models and denture bases according to their storage time period.[18] They indicated that dimensional changes may occur continuously when a prosthesis is fabricated using 3D printing technology with photopolymer printing resin.[19] Specifically in a private practice setting, the possible rescheduling of the patients may affect the dimensions of the intaglio surface of the 3D printed custom trays resulting in inaccurate final impressions.

The maxillary impression is very important for capturing the closure of the edge and anterior and posterior palatal seal area, while the mandibular impression must capture the retromolar pad area and the lingual floor of the mouth as well as having good border molded closed edges. In addition, when compared to maxillary impressions, the extension of the borderline of the mandibular impression is much longer and because of the difficulty of achieving suction at the mandibular arch, the impression requires higher sealing of the entire edge. Because of these differences in the anatomic structures and important key points that must be considered when taking maxillary and mandibular edentulous final impressions, these might have an effect on the clinical use of 3D printed individual trays, and it is necessary to study the 3D printed custom trays of both maxillary and mandibular arches[2].

To the author's knowledge, there is no published data on the effectiveness of water-washable resins for the 3D printing of custom trays. Additionally, no research results have been reported on the guidelines for a storage time of maxillary and mandibular custom trays printed with water washable resins and IPA washable resins, thus potentially affecting the fit of the trays at the appointment date. Therefore, it is crucial to establish an exact protocol on the recommended type of resin for 3D printing custom trays and the suggested storage time after post-curing, to prevent significant dimensional changes.

The aim of this study is to investigate the intaglio surface trueness and dimensional stability of the digitally designed and 3D printed custom trays using two different types of printing resins (water washable and IPA washable) over 21 days period.

The null hypotheses of this study are as follows:

(1) the different types of 3D printing resin (Water washable/IPA washable) of custom trays do not affect their accuracy and their dimensional stability over time

(2) there is no difference in the dimensional stability of the maxillary and mandibular 3D printed custom trays over time

(3) the period of storage time has no significant influence on the accuracy of printed custom trays

# 2. MATERIALS AND METHODS

The flowchart of this study protocol is presented in Figure 1. A total of 40 samples - custom trays were used in the study. The samples were divided into 4 groups and each group had 10 samples. Groups were divided based on the arch (maxillary/mandibular) and the printing resin (Keytay -IPA washable / Raydent -water washable). All maxillary and mandibular sample trays were designed using one master cast for each arch. Trueness and precision of the intaglio surface of the custom trays were evaluated in Geomagic Control Software (3D systems) after they were compared to the reference virtual custom tray design.

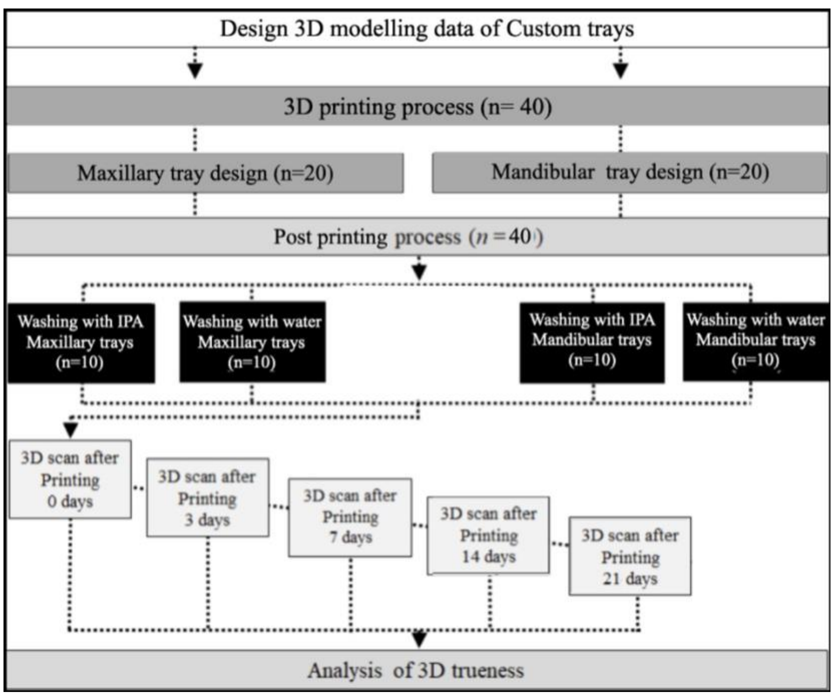



**Figure 1. Flowchart of the study design. n = number of specimens**

## 2.1 Specimen preparation

Two dental models (1560 Articulated Dentoform, Columbia Dentoform) (Figure 2) of maxillary and mandibular edentulous arches closely approximating residual ridge morphology of class I-type A according to the American College of Prosthodontics [20] were selected and scanned with a dental intraoral scanner (TRIOS, 3Shape). A standard tessellation language (STL) file of each model was generated and exported (Figure 3). These STL files were then imported into CAD software (Exocad GmbH) to generate a custom tray for each model. On Exocad at the step of the Virtual wax up bottom design, the offset was set at 2 mm along the master cast surface to form the inner surface of the custom trays. Also, the base thickness was set to 2 mm to obtain a 2-mm–thick entity.

The STL files of the maxillary and mandibular trays, which served as the reference virtual custom trays, were imported into Meshmixer to create the handles and to visually inspect and identify any scanning errors (Figure 4). This final version of the digitized custom trays, or master STL files, was exported.

**Figure 2. Standard edentulous dental models for maxilla and mandible**

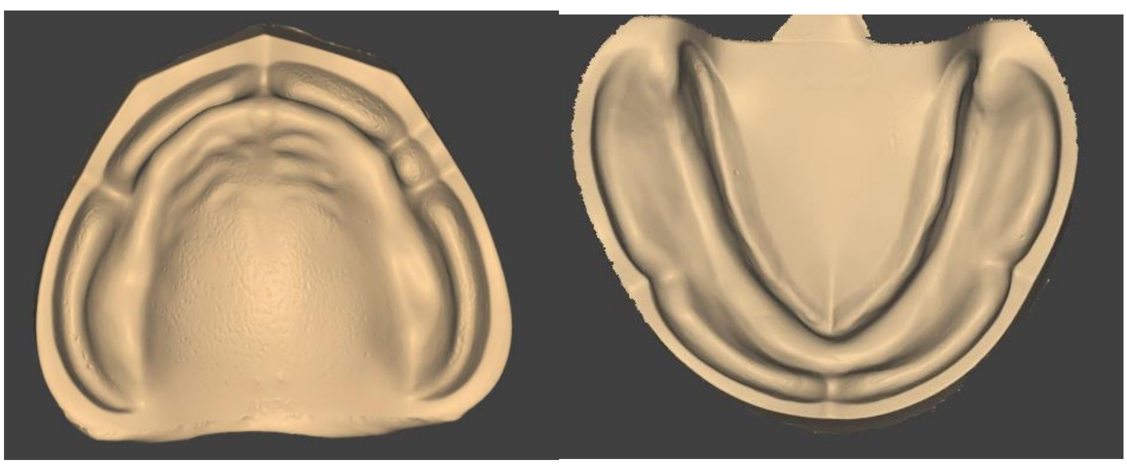


**Figure 3. Scanned data of tissue surface of maxillary and mandibular arches**

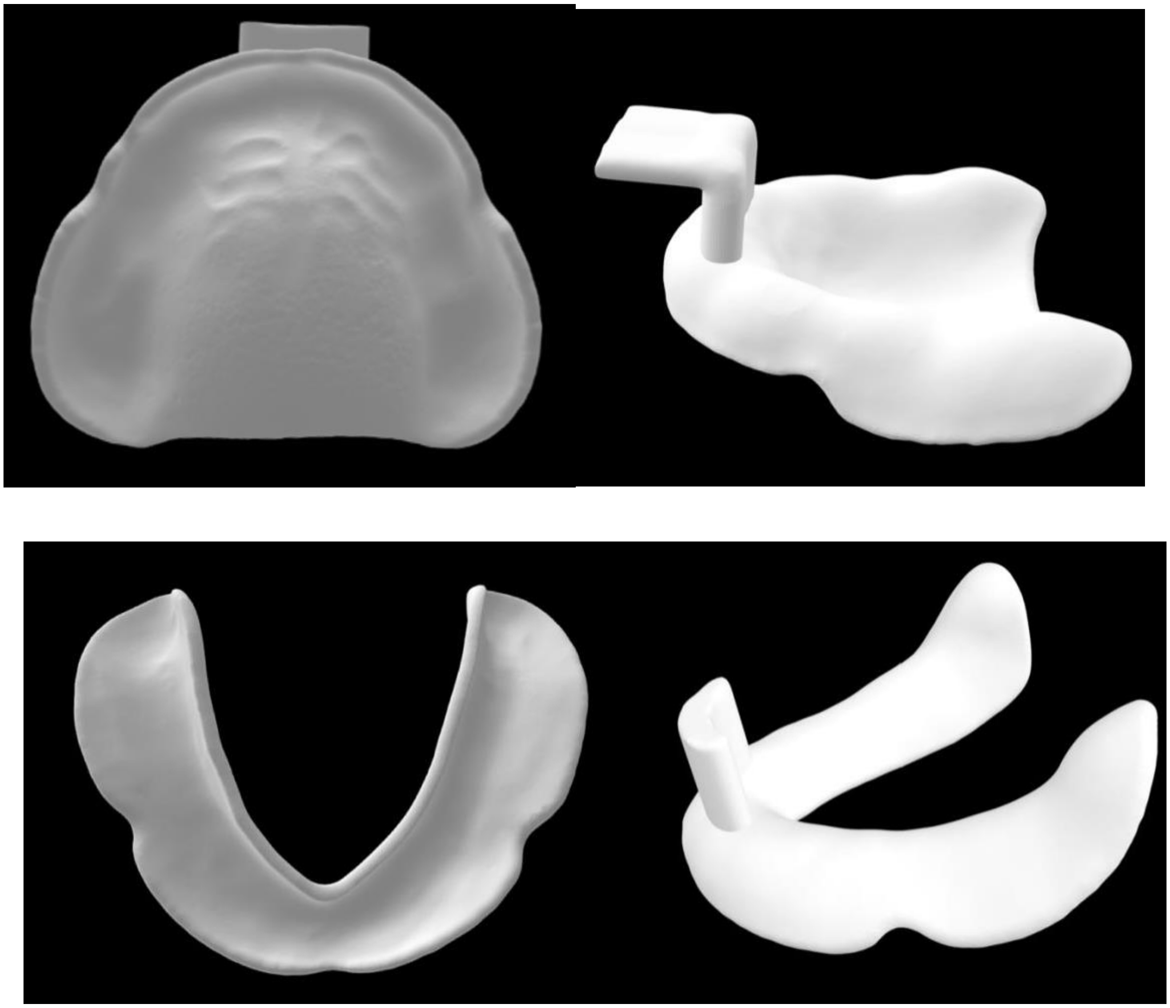
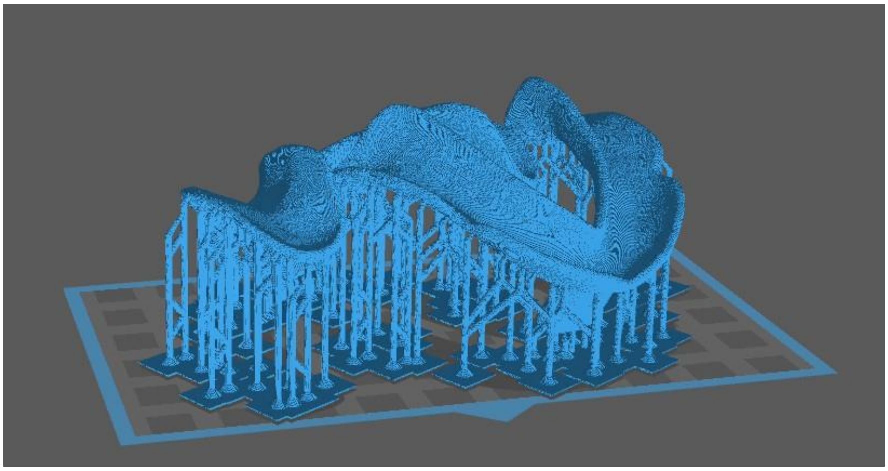


**Figure 4. Finished virtual design of maxillary and mandibular custom trays (master STLs)**

2.2 Print file preparation

An LCD 3D printer (Sonic Mini 4K; Phrozen) was used to print the custom trays and a slicing software (Chitubox v1.9.4) was used to prepare the Chitubox file (.ctb).

The light source (a light-emitting diode) of the printer had a 405 nm wavelength, and each building layer was 100 mm thick. The master STL files were imported into Chitubox and duplicated once to fit two models on the printing bed with a 45-degree build angle. Two types of resins were used to print the trays; the KeyPrint® KeyTray™, a light curing and IPA washable resin (by Keystone Industries), and the RAYDENT Dental Model Resin, a water washable biocompatible resin (Raydent DM; Ray) which was suggested by the company after communication. The print precision was set at 100 microns for all print jobs and the settings were manually set according to the manufacturer's specifications. Medium supports were added on the cameo surface of the custom trays, making sure no support structure was located on the intaglio surface (Figure 5). The following parameters were used according to the manufacturer's instructions; Keytray resin: layer thickness 0.1 mm, exposure time 16.75 s, bottom exposure time 16.75 s, lifting distance 5 mm. Raydent resin: layer thickness 0.1 mm, exposure time 4.5 s, bottom exposure time 35 s, lifting distance 6 mm. The trays were sliced and four CTB files were generated and saved to a flash drive.



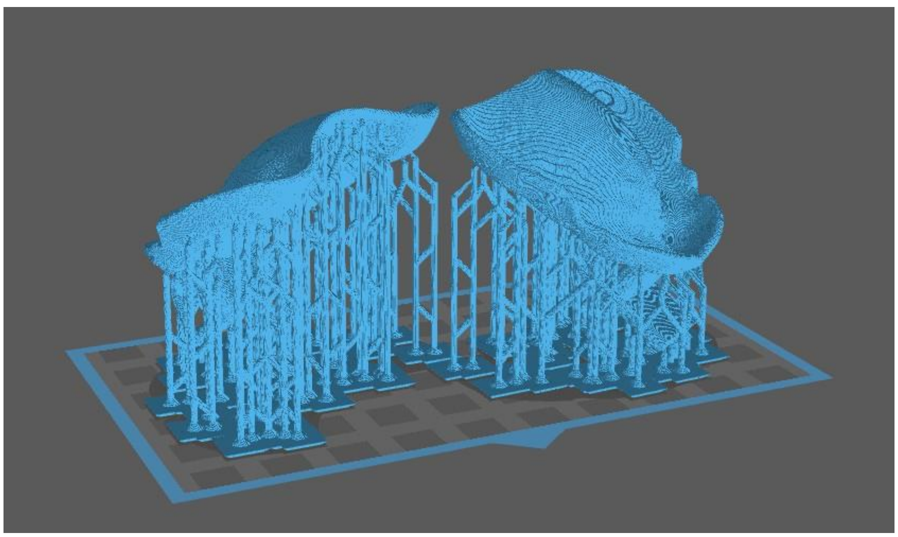


**Figure 5. Chitubox slicing software**

2.3 Experimental group fabrication

The four CTB files were loaded directly to the LCD 3D printer's external USB port to the Sonic Mini 4K. Each print job consisted of two identical custom trays either mandibular or maxillary with different settings according to the resin used. Each print job was printed 5 times for a total of 40 samples (Figure 6).

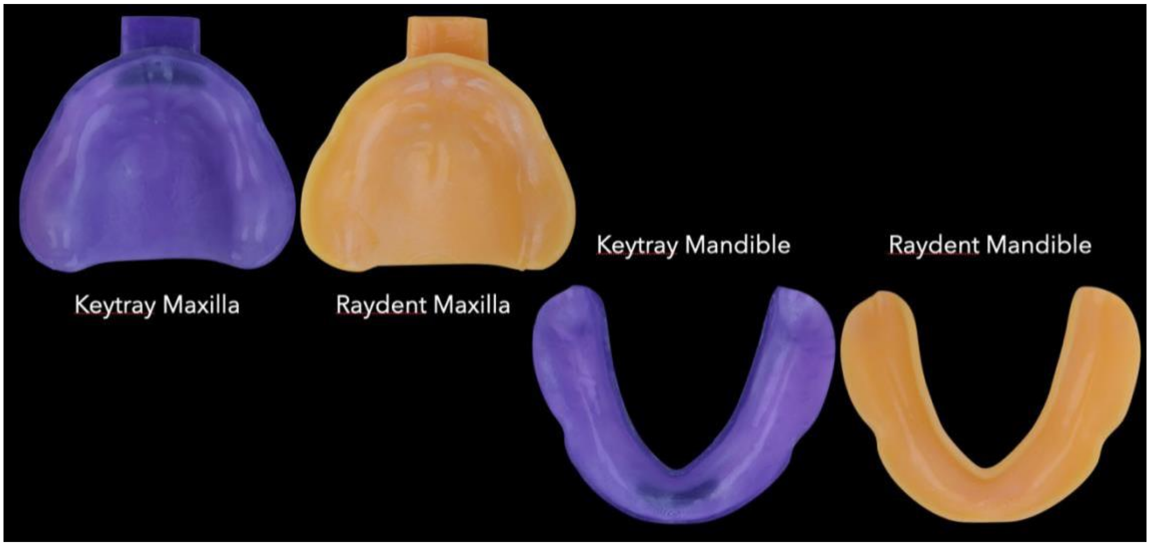



**Figure 6. Groups of the 3D printed custom trays**

## 2.4 Post-processing

Two different washing agents were used for each group of 20 resins for the two resin groups: 99% isopropyl alcohol for the Keytray resin group and tap water for the Raydent resin group.

The 20 trays made from KeyPrint® KeyTray™ IPA washable resin were rinsed with isopropyl alcohol (IPA, 99%). This bath was used for the first wash of the trays coming from the printer and swishing or vibrating with the trays submerged in the IPA bath was done, as proposed by the company. The parts were then transferred into a Stage 2 IPA ultrasonic bath for 5 min. To achieve optimal final print quality, fresh IPA with a lower concentration of contaminants was used according to the manufacturer's recommendation.

The 20 specimens made from the Raydent water washable resin were cleaned using running tap water for 1 min. Then a neutral detergent was used with a soft toothbrush to clean them. The remaining soapy water and residues were rinsed off. With the aid of a soft toothbrush excess resin was thoroughly removed.

All samples were then dried with a compressed lab air gun to dry all surfaces of the printout making also sure there is no residual liquid resin, which is visible as it remains glossy. All the Keytray and Raydent trays were post-cured for 15 and 10 minutes respectively at 50◦C in the Sprint Ray Pro Cure (Sprint Ray) according to the manufacturers' specifications. Finally, the supports were cut at the points where they attach to the trays. After the custom trays were cured, they were stored in a dark box until they were scanned.

## 2.5 Scanning printed trays

All 40 custom trays were scanned with a dental laboratory scanner (3Shape D900 laboratory scanner). Each tray was scanned once within 24h (t0) of the printing and post-curing process and then in the order of the printing day: $3^{rd}$ (t1), $7^{th}$ (t2), $14^{th}$ (t3), and $21^{st}$ (t4). In order to control scanning errors, the scanning orientation (location and angulation) of each sample was standardized by a positioning index. A customized matrix for the maxillary and the mandibular trays respectively were made of GC Pattern Resin, which held the handle of the trays at the same position. These two matrices had a magnetic disc at the bottom side so that they can be placed on the magnet of the scanning plate of the 3Shape laboratory scanner (Figure 7). The intaglio surfaces of the trays were coated using a scanning spray (Renfert Scanning Spray, Hilzingen, Germany). Each scan was exported as an STL file for 3D comparison to the maxillary or mandibular custom tray master STL file.

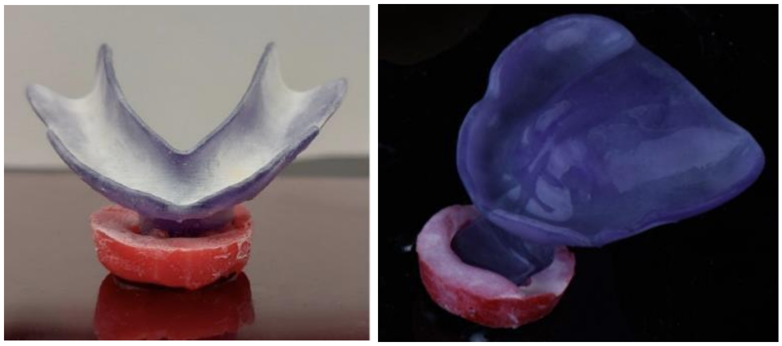


**Figure 7. Mandibular and maxillary indices made of GC Pattern Resin for scanning standardization purposes**

2.6 3D comparison

According to the International Organization for Standardization 5725 "Accuracy (Trueness and Precision) of Measurement Methods and Results", 'trueness' is the closeness of agreement between the expectation of a measurement result and a true value[21,22]. Each STL file of the scanned custom trays was superimposed on the STL file of the reference virtual design of the maxillary and mandibular custom tray with surface matching software to evaluate the trueness of each 3D printed custom tray. This 3D comparison was performed on a 3D quality inspection software (Geomagic Control X; Artec 3D). All STL files were imported into the software. After the reference files were imported into Geomagic, one file from the working groups was imported at a time. The intaglio surfaces of the maxillary and mandibular trays were selected after the segmentation of the entire tray to have an exact region for each 3D comparison. The trays were aligned using the Alignment and Best Fit Matching tools. Overall 3D deviations (x, y, and z) between datasets obtained from the reference maxillary and mandibular trays and from trays printed with different resins (trueness) as well as deviations between datasets obtained from the same resin group (precision) were calculated. All measurements were recorded by the same investigator. The 3D comparison software provided positive and negative discrepancies and visualized the deviations in a color-coded image of the superimposition, representing expansions or contraction, respectively (Figure 8). The 3D Compare function was used to calculate the differences between each scan and the original STl master file. A report was generated with metrics and the output files were compiled into Excel spreadsheets reporting all report variables.

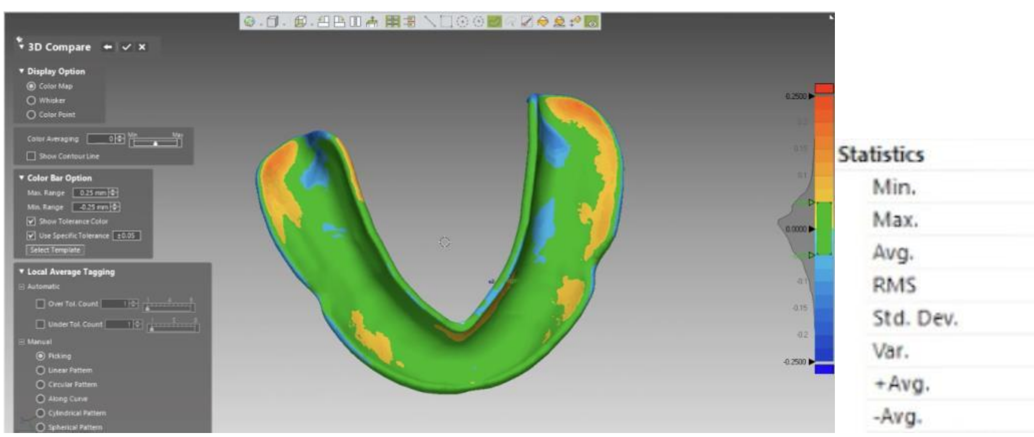



**Figure 8. Geomagic Control X model alignment. Intaglio surface was cut and selected for 3D comparison**

## 2.7 Study variables

All measurements of volume differences between the master files and sample files were reported in millimeters (Min, Max, Avg, RMS, Std. Dev., Var., + Avg, - Avg) (Figure 8). The 3D comparisons report average shape distances across all surfaces of the two scanned objects, resulting in averaged deviations from the master files. After the maxillary and mandibular custom trays were included in the scan data corresponding to the virtual design trays' reference data and storage time of the trays. The root-mean- square error (RMSE) was used in order to calculate the surface-deviation values and thus assess and compare the trueness values. RMSE is a mean calculated as the square root of the mean square by which an error index can be identified in units similar to the actual value and is applied to measure the dimensional and shape variability of a surface[23]. The present study determined RMSE as error values of trueness, as follows:

$$RMSE = \sqrt{\frac{\sum(O_i - E_i)^2}{n}}$$

where Oi represents the observed values; Ei the expected values. ∑ represents 'sum'; and n is the sample size.

A low RMS value points to excellent 3D agreement of the virtual designed tray and printed trays. An RMSE farther from zero indicates larger dimensional errors relative to the reference model. All scan data used to calculate the RMSE values were statistically analyzed to determine the trueness values of each group, and the average discrepancy value obtained from comparing surface RMSE data set was used for the statistical analysis.

## 2.8 Statistical analysis

For each group, a priori power analysis was performed as part of the research planning process revealing that a sample size of 8-10 in each group had a 95% power to detect the difference in dimensional deformations between the reference design and the 3D scan file with the highest effect[2]. All data were checked for normality. The Levene test revealed a significant difference in variances between the techniques and the Kruskal-Wallis procedure was used to analyze the differences between the custom tray discrepancies recorded in each processing technique. The median value of the data represents the accuracy of the technique while the interquartile range can be used to interpret the reproducibility. Discrepancy values generated from the 3D comparison program were then recorded in Microsoft Excel and modeled in an appropriate statistics program suite (SPSS 28.0; IBM, Amonk, NY). Differences in accuracy and dimensional discrepancies between different groups were evaluated with the Mann-Whitney U test. Significance was set at $\alpha = 0.05$ and was adjusted with Bonferroni correction for multiple tests, where appropriate.

# 3. RESULTS

For each group (Keytray Maxilla, Keytray Mandible, Raydent Maxilla, and Raydent Mandible) that consisted of 10 samples, a total of 50 measurements were collected from Geomagic Control X software for the 5 timepoints (t0, t1, t2, t3, t4). The root mean square (RMS) measurements were used for statistical analyses. The mean, median, standard deviation, and interquartile range (IQR) of the dimensional change of the 4 different groups during the different timelines are shown in Tables 1 and 2.

**Table 1. Overall median and interquartile range values of the mandibular trays over the 21-day period**

| MANDIBLE | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Printer | n | mean | stdev | median | IQR | Levenes | t-test p-value | Mann-whitney p-value |
| Keytray | 50 | 0,0992 | 0,0518 | 0,0811 | 0,0535 | <0.001 | <0.001 | <0.001 |
| Raydent | 50 | 0,1602 | 0,0185 | 0,1551 | 0,0229 | | | |

**Table 2. Overall median and interquartile range values of the maxillary trays over the 21-day period**

| MAXILLA | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Printer | n | mean | stdev | median | IQR | Levenes | t-test p-value | Mann-whitney p-value |
| Keytray | 50 | 0,1117 | 0,0159 | 0,1103 | 0,0237 | <0.001 | <0.001 | <0.001 |
| Raydent | 50 | 0,2157 | 0,042 | 0,2181 | 0,066 | | | |

The mandibular custom trays for the entire investigation period show significant differences in the dimensional accuracy between the Keytray and Raydent trays ($p<0.001$). The Keytray trays demonstrate lower RMS values and better stability over time (median= 0.08) compared to the Raydent trays (median= 0.156). In addition, the maxillary custom trays for the entire investigation period indicate significantly more stable dimensions of the Keytray printed trays over the 21 days than the Raydent maxillary trays ($p<0.001$). The Keytray trays demonstrate lower RMS values and better stability over time (Keytray trays median= 0.11, Raydent trays median= 0.22).

Therefore, the accuracy among the 4 groups had the following ranking from most accurate to least accurate: Keytray mandibular (median= 0.08), Keytray maxillary (median= 0.11), Raydent mandibular (median= 0.16), Raydent maxillary (median= 0.21) (Figure 9). A Kruskal-Wallis pairwise comparison of overall results demonstrated statistically significant differences ($P<.05$) among all groups. Overall, the Keytray printed trays demonstrate better trueness to the reference virtual design of the trays across the time points compared to the Raydent trays, indicating higher dimensional stability of the Keytray resin regardless of the arch (maxillary or mandibular) ($p<.001$, post hoc power=0.99). The Raydent groups had overall the largest errors. Within the same resin group, the mandibular trays had a significantly lower RMS value than the maxillary ones over time (Figures 10 and 11). Regarding the precision across the time points, the following ranking was shown from most to least reproducible by interquartile range values: Raydent Mandible (IQR= 0.0229), Keytray Maxilla (IQR= 0.0237), Keytray Mandible (IQR= 0.0535), Raydent Maxilla (IQR= 0.066) (Table 1 and 2).

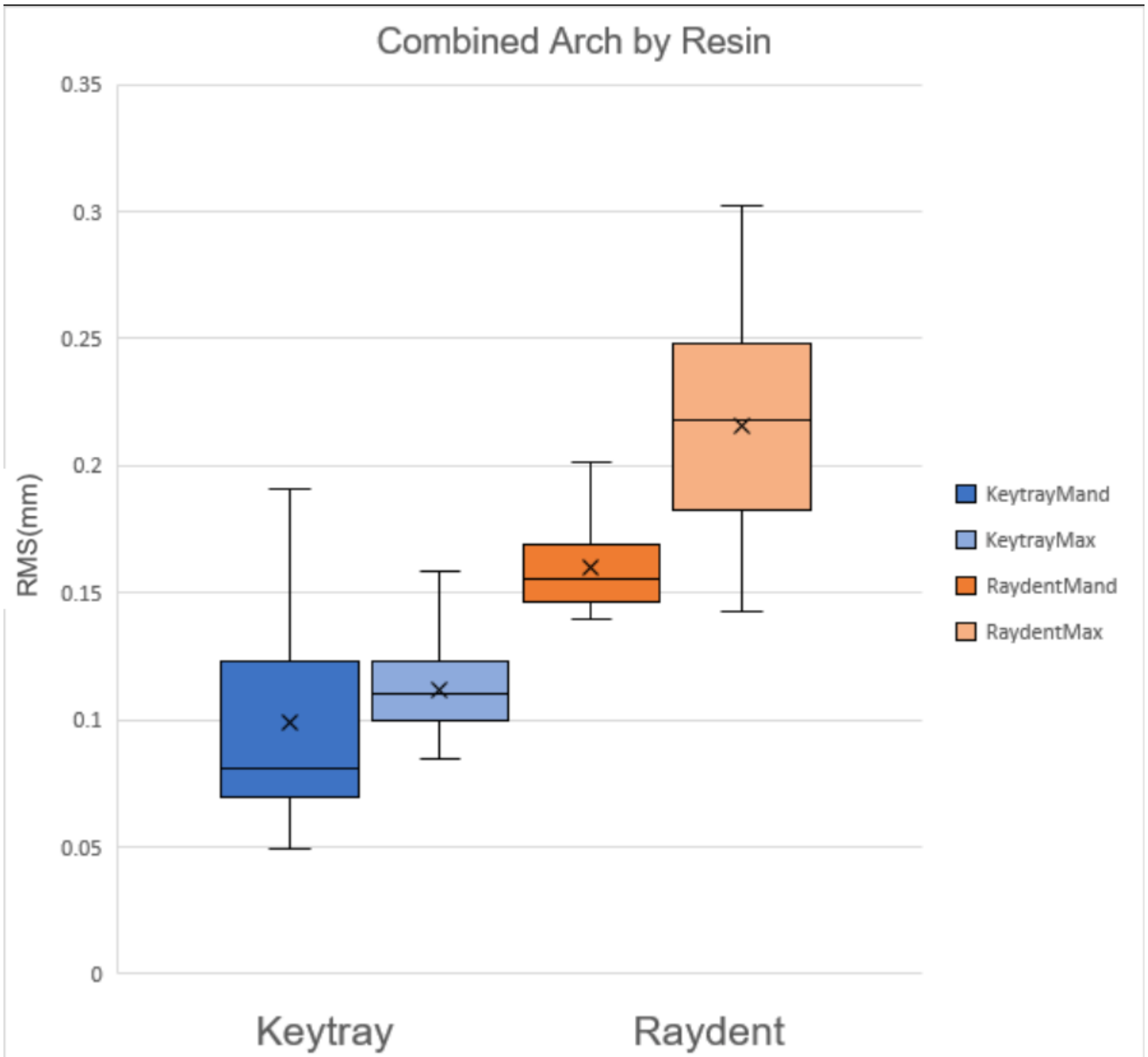



**Figure 9. Trueness of intaglio surfaces of 3D printed custom trays for the full investigation period. Line X represents the median. The bottom of the boxes is the first quartile, top of the boxes is the third quartile. Both ends of whiskers represent minimum and maximum of measured data. *Significant difference (P<.05).**

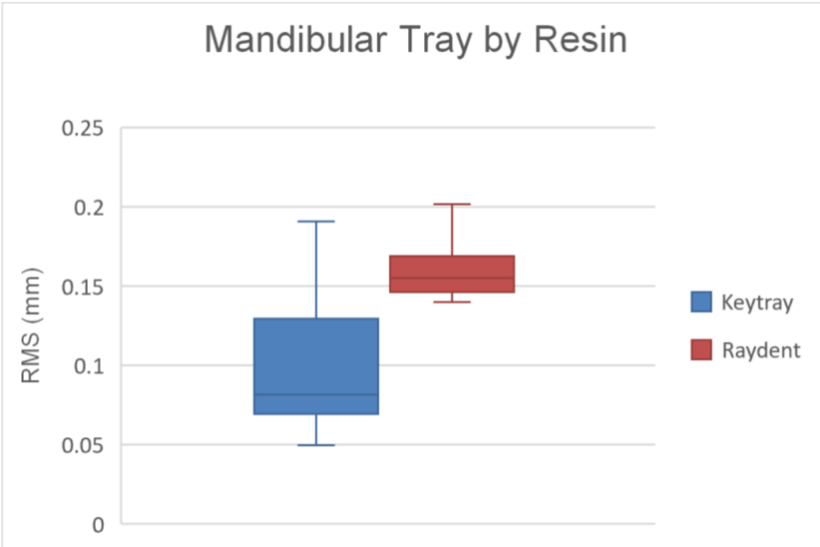



**Figure 10. Overall results comparing accuracy and precision of the mandibular trays at all time intervals**

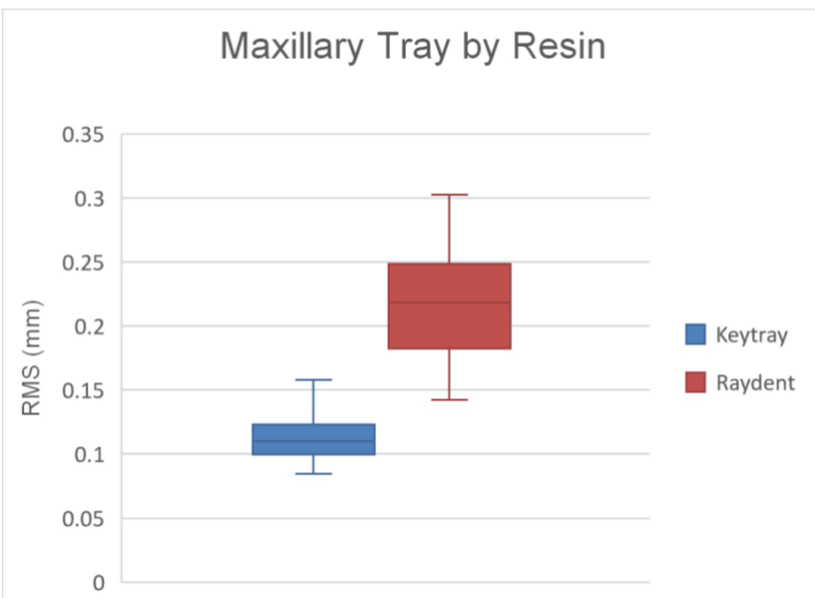



**Figure 11. Overall results comparing accuracy and precision of the maxillary trays at all time intervals**

In the error graph, (Figure 12), and pairwise comparison for each elapsed period after printing there were no statistically significant volumetric changes at the Keytray mandibular trays (p=0.217) (Table 3). On the other hand, there were significant dimensional changes at the Raydent custom mandibular trays, specifically between t1-t2 (3 -7 days) (p=0.04) and t2-t3 (7 - 14 days) (p=0.011), so the error appeared to gradually increase from day 3 (Table 3 and 4).

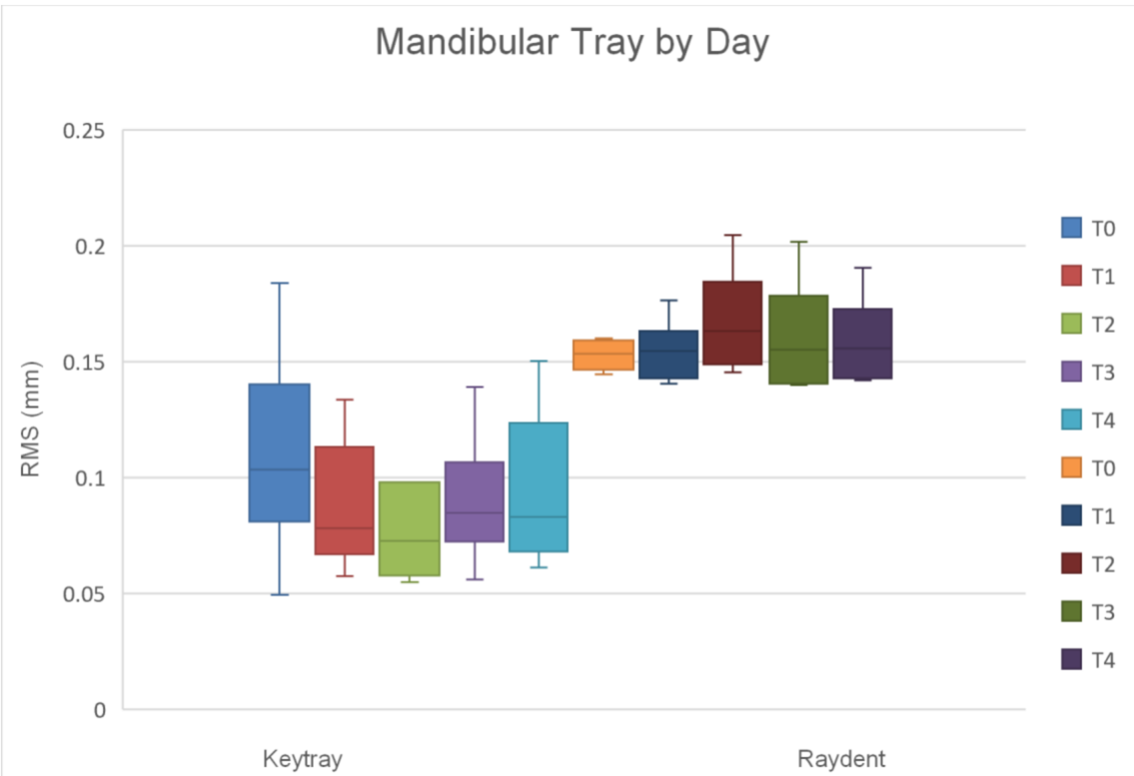



**Figure 12. Comparison of intaglio surface deviations (Root-mean-square estimates) of mandibular Keytray and Raydent custom trays over time**

**Table 3. Pairwise comparisons for mandibular custom trays between different time points, showing only the statistically significant changes**

**MANDIBLE**

| Keytray |
|---|
| Friedman's related sample p=0.217, no need for pairwise |

| Raydent | |
|---|---|
| Pairwise Comparisons | |
| Sample 1-Sample 2 | Adj. Sig.[a] |
| T1-T2 | 0,037 |
| T3-T2 | 0,011 |

**Table 4. Pairwise comparisons for Raydent mandibular custom trays between different time points**

Raydent

**Pairwise Comparisons**

| Sample 1-Sample 2 | Test Statistic | Std. Error | Std. Test Statistic | Sig. | Adj. Sig.a |
|---|---|---|---|---|---|
| T3-T1 | 0,250 | 0,707 | 0,354 | 0,724 | 1,000 |
| T3-T0 | 0,400 | 0,707 | 0,566 | 0,572 | 1,000 |
| T3-T4 | -1,050 | 0,707 | -1,485 | 0,138 | 1,000 |
| T3-T2 | 2,300 | 0,707 | 3,253 | 0,001 | 0,011 |
| T1-T0 | 0,150 | 0,707 | 0,212 | 0,832 | 1,000 |
| T1-T4 | -0,800 | 0,707 | -1,131 | 0,258 | 1,000 |
| T1-T2 | -2,050 | 0,707 | -2,899 | 0,004 | 0,037 |
| T0-T4 | -0,650 | 0,707 | -0,919 | 0,358 | 1,000 |
| T0-T2 | -1,900 | 0,707 | -2,687 | 0,007 | 0,072 |
| T4-T2 | 1,250 | 0,707 | 1,768 | 0,077 | 0,771 |

Graphs of the individual aging periods in the groups for the maxilla showed that over the 21-day period, the Keytray maxillary custom trays are more stable (RMS median =0.1103) than the Raydent maxillary trays (RMS =0.2181) and the difference is statistically significant ($p<0.01$) (Figure 13). More specifically, the Keytray custom maxillary trays are stable / not statistically significant changes at the RMS values over the 7-day (t0-t2) aging period, but present significant changes that gradually increase as the aging period increases till the t3 time point (14-days) (t0-t3: $p<0.001$) and t4 timepoint (21-days) (t0-t4: $P=0.019<0.05$) (Tables 5 and 6). Regarding the maxillary custom trays printed with Raydent resin, they show more trueness, without any statistically significant changes from t0 (within 24h after printing) through t1(3 days) ($p=0.20$), but then significant change over the rest time period of 21-days (t0-t2: $p<0.001$, t0-t3: $p=0.001$, t0-t4: $p=0.004$) (Tables 5 and 7).

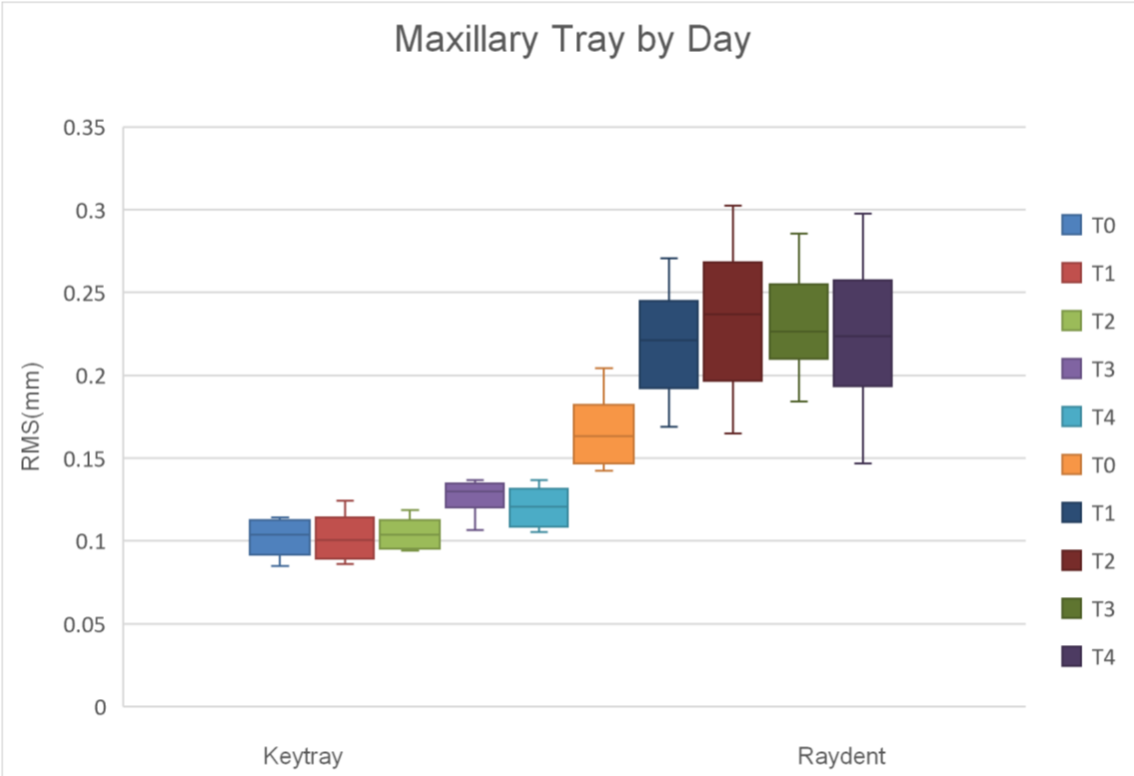



**Figure 13. Comparison of intaglio surface deviations (Root-mean-square estimates) of maxillary Keytray and Raydent custom trays over time**

**Table 5. Pairwise comparisons for maxillary custom trays between different time points, showing only the statistically significant changes**

**MAXILLA**

| Keytray | |
|---|---|
| **Pairwise Comparisons** | |
| Sample 1-Sample 2 | Adj. Sig.[a] |
| T0-T3 | 0,000 |
| T0-T4 | 0,019 |
| T1-T3 | 0,001 |
| T2-T3 | 0,004 |

| Raydent | |
|---|---|
| **Pairwise Comparisons** | |
| Sample 1-Sample 2 | Adj. Sig.[a] |
| T0-T2 | 0,000 |
| T0-T3 | 0,007 |
| T0-T4 | 0,004 |
| | |

**Table 6. Pairwise comparisons for maxillary Keytray custom trays between different time points, highlights showing only the statistically significant changes**

Keytray

**Pairwise Comparisons**

| Sample 1-Sample 2 | Test Statistic | Std. Error | Std. Test Statistic | Sig. | Adj. Sig.a |
|---|---|---|---|---|---|
| T0-T1 | -0,400 | 0,707 | -0,566 | 0,572 | 1,000 |
| T0-T2 | -0,700 | 0,707 | -0,990 | 0,322 | 1,000 |
| T0-T4 | -2,200 | 0,707 | -3,111 | 0,002 | 0,019 |
| T0-T3 | -3,200 | 0,707 | -4,525 | 0,000 | 0,000 |
| T1-T2 | -0,300 | 0,707 | -0,424 | 0,671 | 1,000 |
| T1-T4 | -1,800 | 0,707 | -2,546 | 0,011 | 0,109 |
| T1-T3 | -2,800 | 0,707 | -3,960 | 0,000 | 0,001 |
| T2-T4 | -1,500 | 0,707 | -2,121 | 0,034 | 0,339 |
| T2-T3 | -2,500 | 0,707 | -3,536 | 0,000 | 0,004 |
| T4-T3 | 1,000 | 0,707 | 1,414 | 0,157 | 1,000 |

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.

Asymptotic significances (2-sided tests) are displayed. The significance level is .050.

a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

**Table 7. Pairwise comparisons for maxillary Raydent custom trays between different time points, highlights showing only the statistically significant changes**

Raydent

**Pairwise Comparisons**

| Sample 1-Sample 2 | Test Statistic | Std. Error | Std. Test Statistic | Sig. | Adj. Sig.a |
|---|---|---|---|---|---|
| T0-T1 | -1,600 | 0,707 | -2,263 | 0,024 | 0,237 |
| T0-T3 | -2,400 | 0,707 | -3,394 | 0,001 | 0,007 |
| T0-T4 | -2,500 | 0,707 | -3,536 | 0,000 | 0,004 |
| T0-T2 | -3,500 | 0,707 | -4,950 | 0,000 | 0,000 |
| T1-T3 | -0,800 | 0,707 | -1,131 | 0,258 | 1,000 |
| T1-T4 | -0,900 | 0,707 | -1,273 | 0,203 | 1,000 |
| T1-T2 | -1,900 | 0,707 | -2,687 | 0,007 | 0,072 |
| T3-T4 | -0,100 | 0,707 | -0,141 | 0,888 | 1,000 |
| T3-T2 | 1,100 | 0,707 | 1,556 | 0,120 | 1,000 |
| T4-T2 | 1,000 | 0,707 | 1,414 | 0,157 | 1,000 |

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are the same.
Asymptotic significances (2-sided tests) are displayed. The significance level is .050.
a. Significance values have been adjusted by the Bonferroni correction for multiple tests.

Figure 14 and Table 8 demonstrate the results for precision / reproducibility at t0 (printing consistency) by the values of median and interquartile range of all the printed trays when compared to the reference STLs (virtual design of the maxillary and mandibular trays). The Keytray mandibular trays had the highest amount of variation, but the group with the smallest IQR was the most consistent at t0 (Figures 12 and 13).

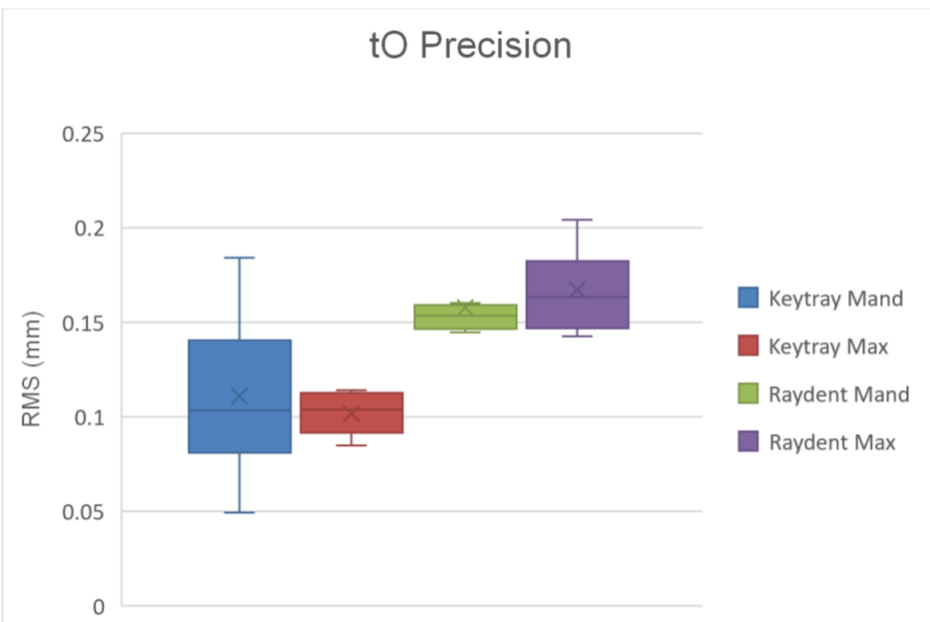



**Figure 14. Precision/reproducibility of the 3D printed trays at t0 (within 24 hours after printing)**

**Table 8. Median and IQR values of all the 3D printed trays at t0 (within 24 hours after printing)**

| Keytray Mandible | | | | | |
|---|---|---|---|---|---|
| | n | mean | StDev | Median | IQR |
| tO | 10 | 0,1107 | 0,0411 | 0,1033 | 0,0594 |
| Keytray Maxilla | | | | | |
| | n | mean | StDev | Median | IQR |
| tO | 10 | 0,1977 | 0,3059 | 0,1038 | 0,0221 |
| Raydent Mandible | | | | | |
| | n | mean | StDev | Median | IQR |
| tO | 10 | 0,1575 | 0,0184 | 0,1534 | 0,0129 |
| Raydent Maxilla | | | | | |
| | n | mean | StDev | Median | IQR |
| tO | 10 | 0,1673 | 0,0214 | 0,1635 | 0,0355 |

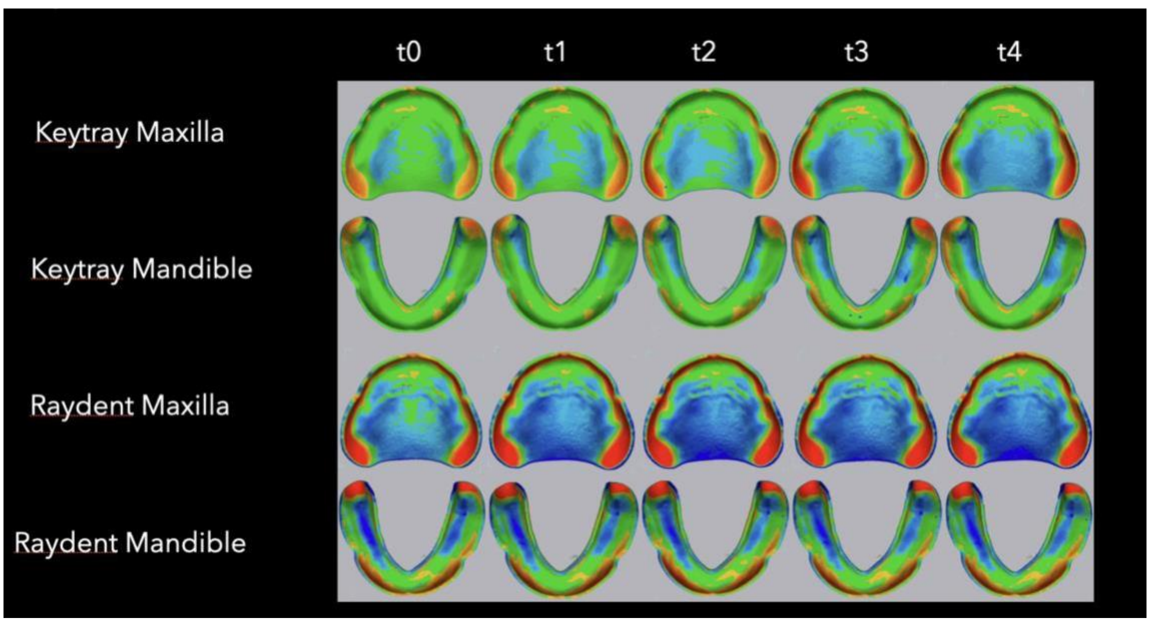



**Figure 15. Qualitative evaluation of 4 groups at t0, t1, t2, t3, t4**

Figure 15 shows the qualitative analysis result of the four groups (KeyTray maxilla, KeyTray mandible, Raydent maxilla, and Raydent mandible) with color maps for the five time points investigated. Blue color mapping (negative discrepancies) shows areas of the test object that are underneath or behind the reference virtual design of the tray, while yellow to red color mapping (positive discrepancies) shows areas that are above or in front of the reference object. Overall the Keytray and Raydent groups showed similar types of deviations region-wise but they were more pronounced in the Raydent groups.

The Keytray mandibular group showed positive distortion at retromolar pads, labial slope of the anterior ridge and buccal slope area. The posterior alveolar ridge crest presented negative deviation. The Raydent mandibular group showed the same type of deviations at the same regions but more intense distortions at the retromolar pads, posterior ridge crest and labial slope of anterior ridge. In the maxilla, the lingual contraction of the palatal region and shape deformation around the maxillary tuberosity and hamular notch were observed for both groups. For the Raydent maxillary group, there were more intense blue color marks on the palatal surface, which means that the Raydent maxillary trays moved further below the reference tray than the Keytray group. Similarly, there were stronger red marks on the tuberosities and hamular notches, indicating the maxillary trays had positive discrepancies on the intaglio surface and also at the labial slope of the anterior ridge.

# 4. DISCUSSION

This study evaluated the intaglio surface accuracy and dimensional stability of digitally designed and 3D printed maxillary and mandibular custom trays using two different types of printing resins having two different washing methods (water washable and IPA washable). The samples were further studied for set times after printing to determine the optimal clinical use time of these trays to minimize dimensional changes. A sample size of 10 was used for the dimensional deformations' evaluation. Many printing parameters can have an effect on 3D printing accuracy. Each stage of the 3D printing procedure might have an additive error, that can result in clinically unacceptable trays. Therefore, the printing parameters for each resin were kept constant. The build angle was kept at 100 degrees, which exhibites accurate results and allows comparability between the outcomes of this study with those of previous in vitro studies[1,24,25]. Based on the size of the platform of the printer, two trays could be accommodated at the same time while simultaneously allowing accurate printing of the intaglio surface. In this study, the thickness of the printing layer was 100 μm, according to the manufacturer's recommendations, with previous studies showing this produces highly precise and detailed trays. [26,27] The evaluation of the trueness and dimensional stability of the intaglio surface of the trays revealed that the maxillary trays had a larger dimensional change over 21 days than the mandibular trays between the groups printed with the same resin. Dimensional changes across all time points were smaller for the Keytray resin, but precision was higher in one of the Raydent groups. Therefore, all three null hypotheses were rejected. It was concluded that the two types of printing resins were significantly different regarding the accuracy and dimensional stability of the 3D printed trays over 21 days. In addition, the period of storage time significantly affected the long- term dimensional stability and precision of the printed trays. Lastly, significant differences were found between the mandibular and maxillary custom trays regardless of resin.

Based on the results obtained in this study, the type of 3D printing resins significantly influenced the manufacturing trueness of the printed trays and their stability over time. The Keytray printed trays were more accurate than the Raydent trays at all times regardless of which arch wsa evaluated. Also, at t0, the Raydent mandibular trays had the most precise sample, followed by the Keytray maxillary, Raydent maxillary, and finally Keytray mandibular. There are no previous report in the dental literature regarding trays being printed with water-washable resin to compare the results obtained. However, the same type of water washable resin of the same brand (Raydent C&B for temporary crown & bridge) was used in a similar study by Atria et al, who evaluated the color stability and surface roughness at baseline and after water thermocycling of multiple provisional restoration materials: acrylic resin, bisacrylic resin, PMMA CAD/CAM block, and 3D printed water washable resin. Water washable 3D printed provisionals showed the least reliable values which are also getting worse over time for both thicknesses tested (0.6 mm, 1.3 mm) among the materials examined.[26] Similarly, Sampaio et al, evaluated the film thicknesses of provisional crowns fabricated by the conventional acrylic materials and the Raydent C&B resin water washable 3D printingresin. This resin had the worst adaptation, or the thicker film, which was significantly different than all other materials ($p < .05$), while the other materials were not significantly different from each other.[27] One of the possible explanations for the results obtained in the present study for the 3D printed Raydent trays could be the incomplete polymerization, derived from either the curing time or the hand washing post-processing technique. A possible insufficient degree of polymerization and conversion could lead to a lower elastic modulus and to more residual monomers that evaporate, thus affecting the overall properties of the material. Interestingly, the printing reproducibility of the Raydent mandibular trays was very high, helping to eliminate any unexpected misfit errors at dental appointments even after mass production of these trays. However, the authors recognize this resin's print jobs may be more susceptible to change over time than the Keytray resin which seems to have more stable results. It can be speculated that once the Keytray resin is fully cured, the hardness and high elastic modulus of the material reduce the residual stress accumulation and distortion of the printed trays. These results support suggestions by Atria et al that newer water-washable 3D printed resins present some disadvantages, one of them being that manufacturers do not provide clinicians with sufficient information regarding the manipulation of these new products, which directly affects the immediate and long-term results.

This study also indicated that dimensional changes may occur continuously when a custom tray is manufactured using 3D printing technology with photopolymer resin.

Joda et al. printed 10 full-arch tooth dental models with a Digital Light Processing type 3D printer and after post-curing and aging, they stored them for 1 to 4 weeks at a constant 20C and 50% humidity. After the resulting dimensional deformations were analyzed, it was revealed that 1 week after printing, the storage group had a dimensional deformation of around 4.0 μm, the 3-week group had an average RMS error of 6.4 μm, and the 4-week group had an average error of 8.9 μm. A statistically significant change ($p < .05$) occurred after 3 weeks of printing. Therefore, if a 3D printed model is used to produce prostheses, it is suggested that it should be used as soon as possible, and for no longer than 3–4 weeks after printing[18]. However, the present study indicates that the dimensional error of the trays was larger over time than those seen in prior studies. The dimensional change after 21 days exceeded the minimum value of 100 μm and the maximum value of 200 μm, which was thought to have occurred due to the custom tray being generally thin, and therefore, having a weaker resistance to shrinkage and distortion, compared to a model[19]. At the same time-change concept, Shin et al. evaluated the trueness of 3D printed denture bases over 28 days after the post-curing processes using the same LCD printer that was used in the present study (Phrozen Mini 4K) and similar IPA washable photopolymer resin. They concluded that for both the maxillary and mandibular 3D printed denture bases, the largest dimensional deformations occurred between days 0 and 1 and the degree of change decreased as the period increased[19]. The results of the present study were contradictory to the above-mentioned conclusions since the pairwise comparisons (Tables 3, 5) showed statistically significant changes only after day 3 of storage for the two more unstable groups (Raydent groups), while a continuous decrease in accuracy was found with each further time-storage stage of the tested 3D printed trays. This might be contributed to many different factors affecting the print jobs, such as the resin itself, the printing parameters, and post-processes (washing and post-curing). It is worth noting that the RMS values of the Keytray groups and Raydent mandibular tray group over the evaluated period ranged from 50 μm to 200 μm and Raydent maxillary tray group exhibited 300μm discrepancy after 3 storage days. The range of 40 to 200 μm has been reported as a clinically acceptable discrepancy between stone models and digital models[28,29]. Also, according to previous studies, the average discrepancy of marginal fit has been reported to range from 100 μm to 200 μm for definitive prostheses. [30] Given that internal and marginal fits are generally more crucial for a definitive crown than the fit of a custom tray, the results of our experiment for all 21 days for the 3 groups and the first 3 days for the Raydent maxillary tray group are within the clinically acceptable range. It has been highlighted in the literature that deformed trays may lead to distortion of the final impressions, which seems to be acceptable on visual examination and is proved deficient only during insertion of the respective dental prosthesis[31]. In this principle, a significant distortion is noted for the Keytray maxillary trays after 7 days (t2), which may still be within the clinically permitted range, but their intraoral use is recommended to be avoided if possible. Likewise, the Raydent mandibular printed trays shall be used, since they remain largely unchanged, up to the first 3 days (t1), whereas Raydent maxillary trays within the first 24h (t0) before large shape deformations are identified.

Furthermore, as it can be seen from the trueness analysis, it is shown that there are significant differences between the mandibular and maxillary custom trays, regardless of the printing resin. The dimensional deformation of the maxillary custom trays of the same resin was larger than that of the mandibular trays over time (110 μm over 80 μm for Keytray and 210 μm over 160 μm for Raydent). Also, the mandibular printed trays present more trueness at each time point than the respective maxillary trays. This comes in conflict with Shin et al's study where even with different post-curing times they found that the 3D printed mandibular denture bases had lower output trueness than the maxillary denture bases on time 0 and over 28 days. Overall the maxillary denture bases showed more consistency in the trueness and stability over time regardless of the post-curing time, compared to the mandibular denture bases that had markedly different dimensional changes with different post-curing times. Over 28 days, the maxillary denture bases had dimensional errors of 113.4 μm, whereas the mandibular bases were 147.6 μm[19]. The results of the current study may be attributed to the fact that the maxillary tray has a palatal portion, the surface points of which are having a cumulative degree of deformation that can cause more contraction to this tray, than the mandibular one which has no buttress warping and distorting the two ends.

On the color-coded map from Geomagic Software for evaluating 3D surface trueness and deviation of the custom trays, a positive deviation (displayed as yellow to red by the extent of deviation) implies that the intaglio surface of the custom tray is located above the surface of the reference virtual tray design, referring to tissue compression or impingement in the mouth. In contrast, a negative deviation (blue) indicates that the intaglio surface of the custom tray is located below the surface of the virtual tray design, referring to space. In this study, the color maps of the Keytray and Raydent trays of the maxillary arch which  have a similar pattern to Shin et al's color map analysis of LCD 3D printed maxillary denture bases, can relate to close-fitting custom trays. Notably, at the maxillary denture bases, the lingual contraction of the palatal region (blue color) and shape deformation around the maxillary tuberosity and hamular notch (yellow to red color) was significant as it can also be seen in the same areas of the trays' color maps[19]. Correspondingly, Hwang et al showed that the 3D printed maxillary denture base, compared with the reference CAD denture base, had a positive deviation (yellow to red) on the posterior ridge crest, palatal rugae, and buccal slope area and a negative deviation (blue) on the labial slope of the anterior ridge and palatal area[25], which comes partially in agreement with the custom trays' deviations. The only difference is that the labial slope of the anterior ridge in our trays presents a  positive deviation and not a negative (blue) (Figure 16). Masri et al gave a more detailed deviation analysis evaluating the exact region-specific mean misfit values (RMSE value) of 3D printed maxillary denture bases and the errors from bigger to smaller were found in the following areas; posterior palatal seal, anterior border seal, the crest of the ridge, palate and maxillary tuberosities.[32] The maxilla of an edentulous patient consists of a flat region in the middle part of the hard palate and inclined slopes towards the residual ridges. Due to the shape of the palatal concavity, shrinkage occurs toward the residual ridge leading to the lifting of the custom tray (blue areas) in the mid-palatal region.[7]

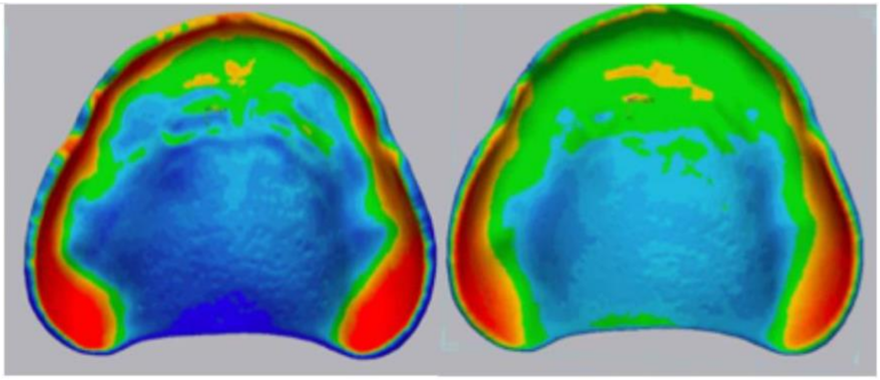


**Figure 16. Color map of 3-D printed maxillary custom trays Raydent and Keytray respectively at t4.**

As far as the mandibular trays' color map is concerned, the current study results are similar to Shin et al, who found distortion of the mandibular bases at the mylohyoid muscle and retromolar pad on the lingual side[19] (Figure 17). Yoon et al investigated the trueness and tissue surface adaptation of CAD-CAM mandibular denture bases manufactured using digital light processing and IPA washable resin. The denture base had a positive deviation (yellow to red) on the posterior ridge crest and a negative deviation (blue) on the labial slope of the anterior ridge, which is the opposite of the custom trays' deviation. The red buccal slope area and the blue area around the retromylohyoid fossa of the mandibular denture base are also shown in this study's mandibular trays' results.[24] The surface deformation patterns of the maxillary and mandibular custom trays can be associated with the nature of the 3D printing technique and materials[25]. The build angle on the printing platform as well as the sagging of the resin under its weight because of the liquid form of the printable material could explain the positive and negative deviation geometry of the intaglio surface of the custom 3D printed trays.

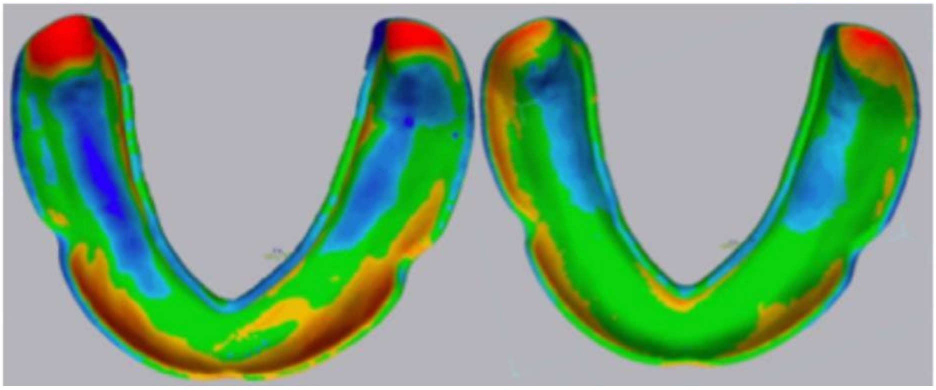


**Figure 17. Color map of 3D printed mandibular custom trays Raydent and Keytray respectively at t4.**

A limitation of this study is that it did not replicate the intraoral conditions, only evaluating the custom trays of standard edentulous arches. Future studies may use edentulous arches with variations of the alveolar ridge should be studied. Moreover, it would be important to investigate the influence of digital trays on the quality of impressions and the adaptability of the final dentures. The intra-observer reliability can also be considered another limitation of the present study, including the use of scan-spray of the imaging agent during the tray scanning process. The uneven spraying during the operation may lead to data error on the tray tissue surface; therefore, different scanning methods and more readily scannable resins should be evaluated in future studies. The outcomes may also differ if the hand wash procedure for the water washable trays was standardized in a way, such as with an ultrasonic device filled with tap water. The limitation of having the virtual design of the custom trays to compare with the 3D printed trays can be eliminated in the future if the handmade custom trays serve as the control group. Lastly, further studies are warranted to assess conditions such as the location of the tray on the build platform, the position of the support structure, and the degree of build angle, all of which might affect the deformity of custom trays made using the LCD technique.

# 5. CONCLUSION

This study investigated the effects of different printing resins with different washing protocols on the dimensional change of 3D printed trays for maxillary and mandibular arches over 21 days.

Within the limitations of this study, the following conclusions can be drawn:

- Maxillary trays showed more distortion than the respective mandibular trays of the same resin over time.
- Mandibular printed trays were more accurate than the respective maxillary trays of the same resin across all time points.
- Keytray printed trays were more accurate than the Raydent trays at all times regardless of the arch (maxillary or mandibular).
- Keytray mandibular trays had the least precise sample at t0 compared to Raydent maxillary ones.
- Dimensional Stability over time:
    a. Keytray mandibular trays remain stable at 21 days.
    b. Keytray maxillary trays remain dimensionally stable until 7 days (t2).
    c. Raydent mandibular and maxillary trays remain without any statistically significant dimensional changes up to 3 days (t1) after printing.

Using these trays after the above-suggested days might require adjustments of the contact points with the mucosal tissues and further extension of the border molding at the custom tray edges on the final impression appointment. Further studies are needed to evaluate the clinical relevance of this postprocessing manufacturing distortion over time.

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