INFLUENCE OF DIFFERENT POSTPROCESSING RINSING AGENTS ON THE MANUFACTURING ACCURACY OF DENTAL MODELS PRINTED BY LCD RESIN 3D PRINTER

A Thesis

by

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ABSTRACT

State of Problem. The COVID-19 pandemic disrupted the supply chain, causing shortages of isopropyl alcohol (IPA), the gold standard wash solvent in resin 3D printing. Alternative rinsing agents have been suggested by the 3D printing community; however, there is limited data evaluating the efficacy of these alternative solvents.

Purpose. This study evaluates the influence of IPA alternative rinsing solvents on the manufacturing accuracy of dental models printed with LCD resin 3D printer.

Materials and Methods. A Frasaco maxillary typodont was scanned in a laboratory scanner to create a master file. 46 models were printed in an LCD 3D printer. One master model was fabricated (IPA). Three separate groups (n = 15) of alternative solvents were fabricated and rinsed Mean Green, Yellow Magic 7, and propylene glycol. Specimens were scanned and exported into a 3D comparison software to measure deviations from the master model. Statistical analysis was performed using Kruskal-Wallis with Bonferroni corrections (α= 0.05).

Results. Mean error across the propylene glycol group ranged from 0.0009mm^2 to 0.0137mm^2 (median= 0.0045, IQR= 0.0029). The Yellow Magic 7 group had the second highest average error, ranging from 0.0056mm^2 to 0.0100mm^2 (median= 0.0081, IQR=0.0020), and the Mean Green group had highest average error ranging from 0.0015mm^2 to 0.0141mm^2 (median= 0.0111, IQR= 0.0034). Group comparisons using non-parametric comparisons showed statistically significant differences between the propylene glycol group and the Yellow Magic 7 group (P<.001, P=.001) and the PG group and the Mean Green group (P=0.005, P=0.016). However, there was no statistically significant difference between the Yellow Magic 7 and Mean Green groups (P=0.366).

Conclusions. The propylene glycol group had the lowest mean error thus producing the most accurate dental models in comparison to the Mean Green and the Yellow Magic 7 groups. The obtained results suggest future studies should compare IPA and propylene glycol to see if there is a significant difference.

Clinical implications. All groups were within the clinically acceptable range of discrepancy.

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

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NOMENCLATURE

3D	3-dimensional
AM	Additive manufacturing
RP	Rapid prototyping
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
MG	Mean Green
YM	Yellow Magic 7
PG	Propylene glycol

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1. INTRODUCTION

3-dimensional (3D) printing, also known as additive manufacturing (AM) or rapid prototyping (RP), has become popular in dentistry in recent years due to its cost effectiveness and convenience. Advantages of 3D printing include fast speed, high precision, customization, less waste compared to milling (subtractive manufacturing), and economical benefits. Dental applications of 3D printing include diagnostic models, surgical guides or drilling guides for implants, custom trays, provisional restorations, and complete dentures[1-5]. The most common and popular 3D printers used in dentistry are photopolymer or resin 3D printers such as stereolithography (SLA) and digital light processing (DLP) printers. Liquid crystal display (LCD) 3D printers have also gained traction in dentistry in a techie niche for do-it-yourself user types that are looking for more economical options compared to SLA or DLP printers. However, there is limited published data on accuracy of LCD printers and their applications in dentistry.

Resin 3D printers used in dentistry, SLA, DLP, and LCD printers, all share similar main concepts and parts — photopolymer resins in a resin vat or tank, light source, and a build platform. In all of these technologies, the build platform moves in a z-axis direction (down) into the resin vat immersing into the resin vat and photo-sensitive resin is cured under light layer by layer until the final model is formed.[1-6] What differs among the three different 3D printing technologies is the light source used to cure or solidify the resin. In SLA, the light source is a ultraviolet (UV) laser. The laser beam traces the path and cures resin along its pathway, not the entire layer at once, which makes SLA printing generally slower than DLP and LCD technologies. DLP uses a projector to reflect light onto photo-sensitive resin by using thousands of tiny mirrors called the digital micromirror device (DMD), and curing an entire layer at once. The projectors in the DLP system use pixels which determines the printer's resolution and the

pixels become voxels as each layer cures. LCD printing is similar to DLP technology but uses LCD panels to expose via light emitting diode (LED) light to cure resin and also cures the entire layer at one time. The LCD screen only reveals the current layer for curing, covering the rest of the image. LCD technology also uses pixels as its smallest resolution. SLA and LCD printers are accurate and precise. With the DLP technology, prints can get distorted due to the use of projected lens. Additionally, the resolution of DLP printers is not as high as the SLA or LCD technologies. DLP printers are also expensive. Table 1 summarizes and compares photopolymer 3D printer technologies, SLA, DLP, and LCD.

Table 1. SLA, DLP, LCD technology comparison

	Stereolithography (SLA)	**Digital light processing (DLP)**	**Liquid crystal display (LCD)**
Light source	UV light	Projector lens	LED light
Resolution	Laser beam	Pixel	Pixel
Printing speed	Slow	Fastest	Fast
Resolution	High	Not as high	High
Accuracy	Accurate	Not as accurate	Accurate
Cost	Expensive	Most expensive	Inexpensive

There are distinct steps in photopolymer 3D printing: acquisition of digital scan or conventional model, translation of this data into a standard tessellation language (STL) file, preprocessing which involves preparing the file for printing — slicing and adding supports, 3D printing, and postprocessing which involves rinsing and curing (Table 2).

Table 2. Photopolymer 3D printing process

Photopolymer 3D Printing Process	
1 Data acquisition	Intraoral scan Conventional model (laboratory scan) CBCT
2 Computer-aided design (CAD)	Conversion of data into STL file format
3 Preprocessing	Slicing Layer thickness Build orientation and angle Supports
4 Computer-aided manufacturing (CAM)	3D printing
5 Postprocessing	Part removal from printing bed Rinsing Curing (photopolymerization) Removal of support structures

Each step can influence the accuracy of 3D printed models. 3D printing factors that can affect manufacturing accuracy include printer technology, printer, accuracy of STL file, printing parameters such as layer thickness and build angle, and postprocessing such as rinsing.

Layer thickness of 100 microns is adequate for most diagnostic models[2], but 50 microns can be selected for a smoother finish. For dental prosthesis, 25-50 microns is clinically acceptable.[2] As the layer thickness decreases, the print accuracy increases, but the print time also

increases. A decrease in layer thickness also resulted in an increased strength of 3D printed objects.[2]

Build angle also affects the accuracy of 3D printed models. Formlabs suggests printing directly on the build platform at 0 degree for fastest printing time and angling models between 65 and 75 degrees for the most accurate print jobs. For maximum output, Formlabs recommends printing at almost 90 degrees to fit the most models on the build platform. Other studies have shown 45 to 60 degrees was the most accurate.[2, 8, 10, 20] Kim et al. found that the build angle of 75 degrees had the lowest mean discrepancy.[11] The disadvantage of angling models for 3D printing is the need for support structures, which may end up on crucial sections of dental models such as occlusal surfaces.

The last step of 3D printing, or post-processing printed parts, is critical to the 3D printing workflow. Rinsing and curing finishes 3D printed objects by removing any uncured resin (monomer - liquid state of resin) and fully photopolymerizing the part for an accurate, smooth, and functional part.[18, 19] >90% isopropyl alcohol (IPA) is the gold standard for rinsing resin 3D printed objects.[7] The purpose of rinsing during postprocessing is to remove any residual uncured resin (monomer) on printed models. Improper rinsing protocol can result in sticky and unaesthetic models. There are other issues such as artifacts, surface powdering, and pooling thus resulting in inaccurate models.[14] There are many ways to wash or rinse printed models including hand washing and using ultrasonic bath; however, there is no consensus on time or methods.

The Coronavirus disease (COVID-19) pandemic has disrupted the supply chain making it extremely difficult to obtain IPA, leaving 3D print enthusiasts to come up with new alternatives. In addition to the IPA shortage problem, there are restrictions of IPA use in some areas due to flammability concerns.[11] Formlabs, one of the leading manufacturers of SLA 3D printers, was

already recommending tripropylene glycol monomethyl ether, or TPM, to non-biocompatible resins as an alternative to IPA to its users prior to the COVID-19 pandemic.[11] Formlabs listed more options on their website during COVID-19 as their customers sent in suggestions as TPM is expensive and only comes in large containers for industrial use. Other alternatives to IPA and TPM include Poly-Flush SLA 3D Printing Cleaning Solvent, Yellow Magic, Mean Green, propylene carbonate, and dipropylene glycol monomethyl ether (DPM).[11] Other sources from the 3D printing community have also suggested substituting IPA with Simple Green, propylene glycol, acetone, Mr. Clean, ethanol, rubbing alcohol (70% isopropyl alcohol), denatured alcohol, and mineral spirits[14].To the author's knowledge, there is no published data on the efficacy of alternative solvents and whether or not the alternative solvents influence the manufacturing accuracy of printed dental models.

Advancements in digital dentistry have allowed dentists to simplify workflows and decrease overhead due to less conventional material use. An increase in intraoral scanner use means that 3D printers are necessary to make physical study models. Most workflows allow dentists to design final prosthesis even without a physical model; however, a hybrid approach where both conventional and digital methods are integrated in treatment is still popular as each technique has advantages and disadvantages. Having physical 3D printed models allows for fabricating provisional restorations or putty matrix or essix retainer in a conventional way.[1-4]

3D printed models must have similar dimensional accuracy and stability as conventional stone models in order to be acceptable in clinical applications such as mockup and fabrication of provisional restorations or essix retainers. Whether in 3D printing or fabricating provisional restorations, accuracy is crucial and dentists and dental technicians should do their best to avoid errors in each step. An error can be introduced to each step that together can lead to clinically

unacceptable results. Therefore, it is important to have a workflow that minimizes errors in each step and one in which that uses the best material and technique available for each step.

The combination of the importance and influence of rinsing agent in 3D printing and shortages of IPA, the author wanted to know if other alternative solvents are as effective in washing 3D printed models as IPA, the gold standard. Therefore, the aim of this study was to evaluate the influence of IPA alternative rinsing solvents on the manufacturing accuracy of dental models printed with LCD resin 3D printer. The null hypothesis is that there are no significant differences in dimensional accuracy among the 3D printed models rinsed with alternative rinsing solvents, Mean Green, Yellow Magic 7, and propylene glycol. The clinical hypothesis is that there is a difference in accuracy between 3D printed models rinsed with alternative rinsing solvents.

2. MATERIALS AND METHODS

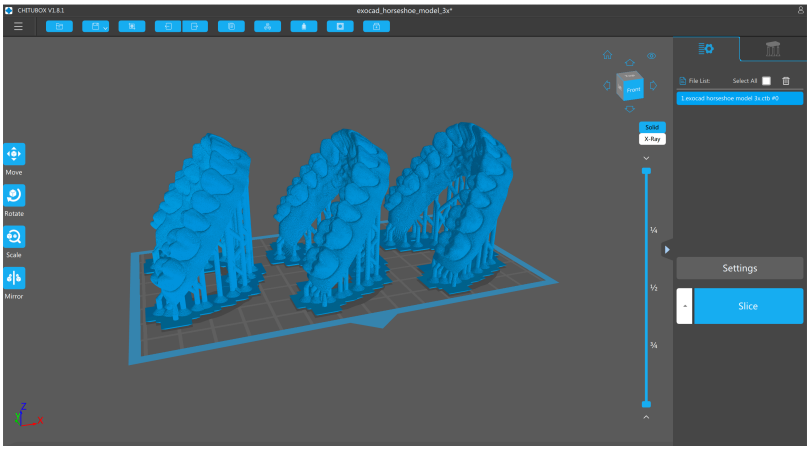
2.1 Specimen preparation

A Frasaco maxillary typodont was scanned in a dental laboratory scanner (D900; 3Shape). A standard tessellation language (STL) file of the typodont was generated and exported. A plane cut function on Meshmixer (Autodesk) software was used to cut excess base and vestibule of the digitized typodont and was exported as an STL file. This STL file was then imported into a CAD software (Exocad; exocad GmbH) to generate a hollow model using their Model Former module. This new version of the STL file was imported into Meshmixer once again to visually inspect and identify any scanning errors and to shrink the typodont to x = 55mm (original x value = 70mm). This final version of the digitized typodont, or master STL file, was exported.

2.2 Print file preparation

A slicing software (Chitubox v1.8.1) was used to prepare the Chitubox file (.ctb) for using an LCD 3D printer (Sonic Mini 4K; Phrozen).The master STL file was imported into Chitubox and duplicated twice to fit three models at 70 degrees on the printing bed. Phrozen Sonic Mini 4K and Aqua-Ivory 4K resin were selected in settings and print precision was set at 50 microns. Heavy supports were added making sure no supports were on the cameo surface of the typodont (Figure 1). The models were sliced and a CTB file was generated and saved to a flash drive.

Figure 1. Chitubox slicing software



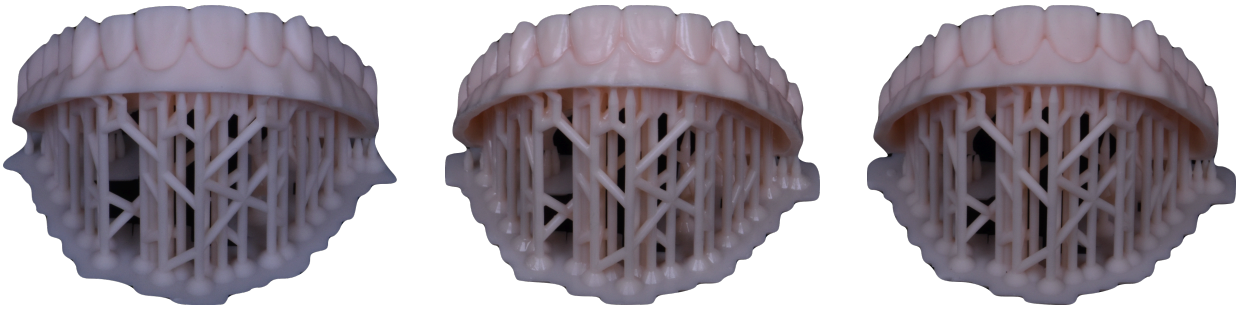
2.3 Experimental group fabrication

The CTB files were loaded directly to the LCD 3D printer external USB port to the Sonic Mini 4K. Each print job consisted of three identical dental models printed 15 times, for a total of 45 samples.

2.4 Post-processing

Three different washing agents were used: Group 1 Mean Green MG (Rust-Oleum); Group 2 Yellow Magic 7 YM (Bradley Systems); and Group 3 Propylene Glycol PG (SK picglobal). Each group had 15 samples. After each print job, a hand washing protocol by Phrozen was followed. Three printed models were washed in the first bath for 60 seconds and then washed in the second bath for 60 seconds. The models were gently moved around in the first bath and shaken vigorously in the second bath side to side. For each print job of three, a new batch of wash solvent was used. After the second bath, all models were washed in room temperature tap water for 20 seconds each. All models were air dried on a drying rack for an hour and cured in a curing unit (Wash & Cure 2.0; Anycubic) for 20 minutes. After the models were cured, they were stored in a dark box until they were scanned.

Figure 2. Printed dental models



2.5 Master model fabrication

A single model was printed for the master control file. The model was washed using the same wash protocol as working groups. The master model was washed in the first bath with 99% isopropyl alcohol (Solimo; Amazon) for 60 seconds and then washed vigorously in the second bath with IPA for 60 seconds. Then the model was air dried on a drying rack for an hour and cured in a curing unit (Wash & Cure 2.0; Anycubic) for 20 minutes. After the model was cured, it was stored in a dark box until it was scanned in a scanner.

2.6 Scanning printed models

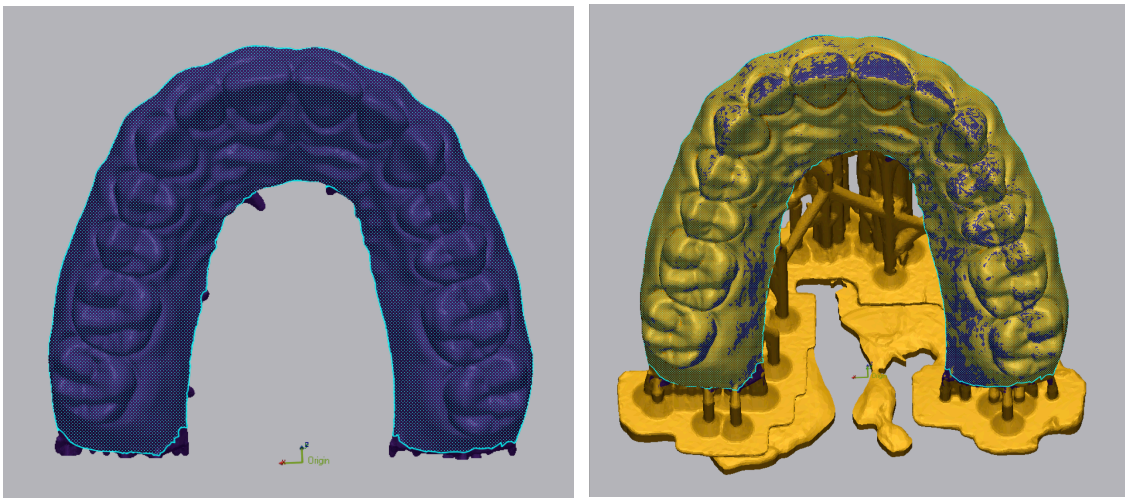
The single master model and 45 samples were scanned in a dental laboratory scanner (D700; 3Shape). Each scan was exported as an STL file for 3D comparison to the master IPA model.

2.7 3D comparison

3D comparison of the master model and each working group was performed on a 3D quality inspection software (Geomagic Control X; Artec 3D). The master IPA file was imported into Geomagic and one file from the working groups was imported at a time. A region over occlusal surfaces was selected (Figure 3a) to reduce noise and select the exact region for each 3D

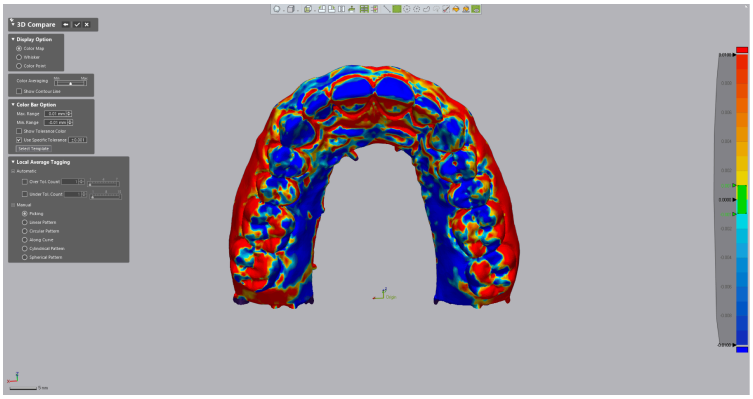
comparison. The models were aligned using the Alignment and Best Fit Matching tools, Initial alignment and Best fit alignment (Figure 3b).

Figure 3. Geomagic Control X model alignment. A. Region selected for 3D comparison. B. Initial alignment to master IPA file.



The 3D Compare function was used to calculate the differences (Figure 4). A report was generated with metrics. The output files were compiled into Excel spreadsheets reporting all report variables.

Figure 4. Geomagic Control X 3D Compare



2.8 Study variables

All measurements of volume differences between the master file and sample files were reported in millimeters (Table 3). The 3D comparisons report average shape distances across all surfaces of the two scanned objects, resulting in averaged deviations from the master file.

Table 3. Study variables output for each sample comparison

Output Variable	Description
Min	Minimum total volume error between sample scan and master scan
Max	Maximum total volume error between sample scan and master scan
Avg	Average of all surface scan volume errors between the sample scan and master scan
RMS	Root mean square of all surface scan volume errors between the sample scan and master scan
Std. Dev.	Standard deviation of all surface scan volume errors between the sample scan and master scan
Var.	Variance of all surface scan volume errors between the sample scan and master scan
+ Avg	Average of all positive surface scan volume errors (additive errors) between the sample scan and the master scan
- Avg	Average of all negative surface scan volume errors (deficiency errors) between the sample scan and the master scan

2.9 Statistical analysis

All data were checked for normality using Kolmogorov-Smirnov and Shapiro-Wilk tests for skewness and kurtosis. Due to non-normal distribution and sample size, non-parametric statistical tests were utilized for all statistical tests, with mean, standard deviation, median, and interquartile range (IQR) reported for all study variables. Kruskal-Wallis tests were used to

compare the differences between the master IPA model and the three working groups, MG, YM, PG ($\alpha = 0.05$), with Bonferroni corrections for multiple comparisons. All statistics were performed in statistical software SPSS (v28.0, IBM).

3. RESULTS

Overall estimate errors were non-normally distributed across the entire sample (n=45), and the smaller sample size of the individual groups (n=15 each) necessitated the use of non-parametric statistics for analysis. Mean error across the propylene glycol group (n=15) ranged from 0.0009mm^2 to 0.0137mm^2 (median= 0.0045, IQR= 0.0029). The Yellow Magic 7 group (n=15) had the second highest average error, ranging from 0.0056mm^2 to 0.0100mm^2 (median= 0.0081, IQR=0.0020), and the Mean Green group (n=15) had highest average error ranging from 0.0015mm^2 to 0.0141mm^2 (median= 0.0111, IQR= 0.0034; Table 4). The distributions and ranges of mean errors are shown in Figure 5.

Table 4. Summary statistics for all specimens and the three different rinsing solutions.

	Mean Green	**Yellow Magic 7**	**Propylene Glycol**
1	0.0015	0.0100	0.0009
2	0.0087	0.0075	0.0027
3	0.0053	0.0063	0.0051
4	0.0121	0.0070	0.0025
5	0.0072	0.0099	0.0045
6	0.0040	0.0056	0.0043
7	0.0112	0.0084	0.0032
8	0.0085	0.0077	0.0043
9	0.0112	0.0103	0.0137
10	0.0111	0.0071	0.0052
11	0.0141	0.0090	0.0058
12	0.0111	0.0088	0.0059
13	0.0087	0.0079	0.0081
14	0.0113	0.0095	0.0075
15	0.0139	0.0081	0.0025
Summary Statistics			
Mean	0.0093	0.0082	0.0051
St. Dev	0.0036	0.0014	0.0031
Median	0.0111	0.0081	0.0045
IQR	0.0034	0.0020	0.0029
1st Quart	0.0079	0.0073	0.0030
3rd Quart	0.0113	0.0093	0.0059

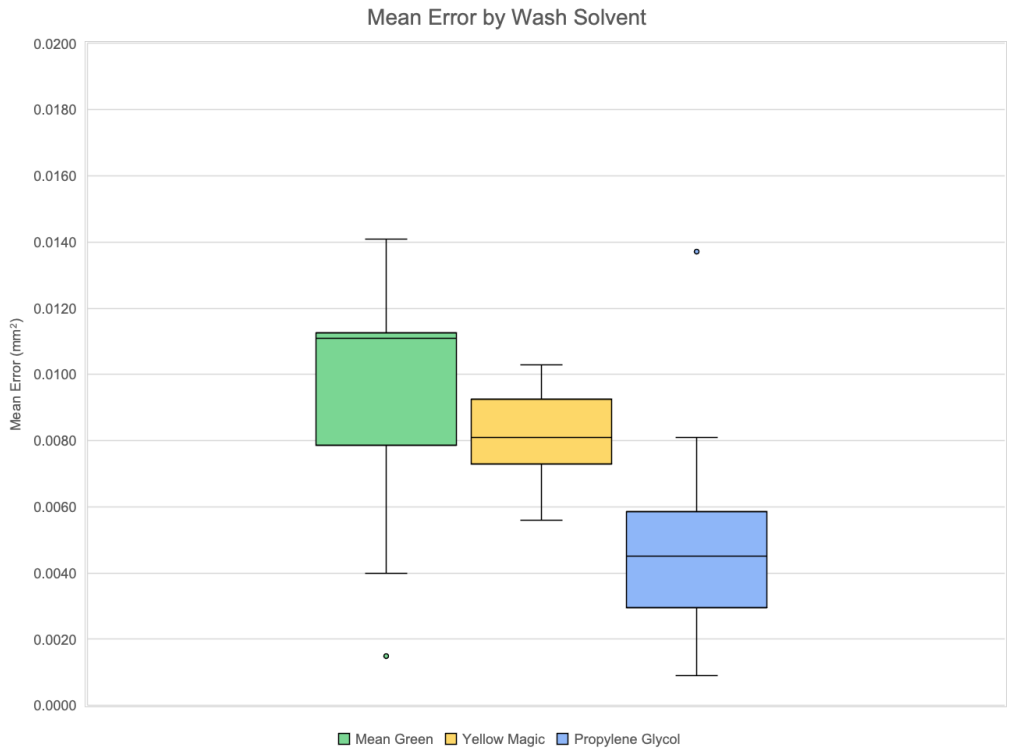


Figure 5. Median, quartiles, and IQR of mean error for all prints (n=45) and respective rinsing agents. Statistically significant differences (adjusted) were found between Mean Green and Propylene Glycol (*P*=.001) and Yellow Magic 7 and Propylene Glycol (*P*=.016).

Group comparisons using non-parametric comparisons (Kruskal-Wallis tests) showed statistically significant differences between the propylene glycol (PG) group and the Yellow Magic 7 group (*P*<.001, *P*=.001 with Bonferroni correction) and the PG group and the Mean Green group (*P*=.005, *P*=.016 with Bonferroni corrections). However, there was no statistically significant difference between the Yellow Magic 7 and Mean Green groups (*P*=.366; Table 5, Figure 5).

Table 5. Comparisons using Kruskal Wallace non-parametric comparison for multiple samples.

Comparison Samples	Test Statistic	Significance	Adjusted Significance*
Mean Green – Yellow Magic 7	2.781	0.005	*0.016*
Mean Green – Propylene Glycol	3.685	<0.001	*0.001*
Propylene Glycol – Yellow Magic 7	0.536	0.366	1.000

*Significance adjusted by Bonferroni correction for multiple tests

4. DISCUSSION

In the present study, the efficiency of rinsing agents was evaluated by comparing dentate models washed with three different alternative solvents: Mean Green, Yellow Magic 7, and propylene glycol. Propylene glycol group had the lowest mean error of 0.0045mm^2. Mean Green had the highest mean error of 0.0111mm^2. Yellow Magic 7 was in the middle with 0.0081mm^2. The results showed a significant difference between propylene glycol and Mean Green and a significant difference between propylene glycol and Yellow Magic 7. There was no significant difference between Mean Green and Yellow Magic 7; thus rejecting the null hypothesis.

Many printing parameters can influence 3D printing accuracy. Each step of the 3D printing process can have an additive error, resulting in clinically unacceptable models. Therefore, other printing parameters were set as the most ideal and kept constant. Build angle was set at 70 degrees, which is in the range of build angles that produce the most accurate prints.[7, 10] Layer thickness of 50 microns was selected to produce highly precise and detailed dentate models. Additionally, a single printer and a single bottle of resin were used to minimize variables.

Mean error across all three groups (n=45) ranged from 0.0009mm^2 to 0.0141mm^2. Clinically acceptable discrepancy is 0.2 to 0.5mm according to Brown et al.[16] In another study by Mostafavi et al.[17], clinically acceptable range of additively manufactured casts were 0.1 to 0.3mm. Park at al. states 0.3mm is an acceptable discrepancy for diagnostic casts; therefore, 3D printing can meet this requirement.[20] Mostafavi et al. tested the difference between IPA and TPM as well as different wash times in manufacturing accuracy of 3D printed models. They found that discrepancies among different postprocessing groups ranged from 10 to 220 microns (0.01 to

0.22mm). In the current study, the discrepancy ranges of 0.0009mm^2 to 0.0141mm^2, or approximately 0.9 to 14 microns, were found, which are within clinical acceptability.

In Mostafavi's study, TPM resulted in more true and precise models compared to IPA.[17] Conversely, Hwangbo et al.[18] found there was no significant difference between IPA and TPM in manufacturing accuracy. Additionally, cell viability, cytotoxicity, flexural strength, and mechanical properties were tested in this study. Hwangbo et al. found the cell viability and the cytotoxicity decreased as the washing time increased, indicating an improved biocompatibility. As the washing time increased, there were no reductions in the flexural strength or changes in surface defects, while the flexural modulus decreased. Neither IPA not TPM caused significant defects in mechanical properties, and the biocompatibility increased with the washing time for both solvents.[18] Chen et al. measured cytotoxicity of temp resin and found that without postpolymerization, the material had cytotoxic potential. When parts were cured for 15 minutes in FormCure unit, all groups reached 100% in cell viability meaning there was very low risk of cytotoxic potential.[6] Therefore, curing is also an important part of postprocessing process in addition to rinsing.

Formlabs recommends replacing IPA when its resin concentration reaches around 10–12%. 3D printed parts may start to feel tacky when the IPA's resin concentration reaches 5–10%. Depending on the sequence, part size, and volume of the wash bucket, up to 200 parts can be washed before the IPA needs to be replaced. To prolong the lifetime of the solvent before replacement, a separate rinse in a small volume of solvent can be performed before inserting printed parts into the main wash container or ultrasonic.[21]

The ingredients of Mean Green are water, 2-(2-butoxyethoxy)ethanol, C9-C11 alcohols ethoxylated, sodium edetate, silicate salts, and sodium hydroxide. Ethanol acts as a solvent and

alcohol ethoxylates act as a surfactant. The ingredients of Yellow Magic 7 are water, secondary alcohol ethoxylate, propoxypropanol, potassium, hydroxide 45%, sodium xylene sulfonate, sodium gluconate, disodium laryl phenyl ether disulfonate, sodium hydroxide, Q-17-2, lauramine oxide, butoxyethanol, and dye (yellow). Like Mean Green, Yellow Magic 7 also contains alcohol ethoxylate, which acts as a surfactant. Yellow Magic 7 is a water-based ink cleaner used in human and pet food packaging and its manufacturer, Bradley Systems, claims it is safe. The website states Yellow Magic 7 can clean water-based and UV-based inks. Another main component of Yellow Magic 7 is propoxypropanol, which is an alcohol. Lastly, propylene glycol, also known as 1,2-propanediol, is a synthetic liquid that absorbs water in medications, cosmetics, and food products. Propylene glycol is FDA-approved to be used as food additive. Propylene glycol is a diol, which means it has two alcohol functional groups instead of just one. Other diols can be tested in future studies to see if there is a difference between diol groups and conventional alcohol groups. Other organic solvents such as ketone family should be tested as only alcohol-based solvents were tested in the current study. Acetone, commonly used as nail polish remover, could be used, which is inexpensive and readily available.[9]

Limitations of the current study were small sample size, a lack of ultrasonic bath, and use of a single LCD printer and one type of resin. Intra-observer reliability is also something that could have skewed data as every sample was hand washed by the author at different times of the day. The reason for not using an ultrasonic bath was only IPA is recommended by the manufacturer. The use of these alternative solvents has not been FDA-approved. When using these alternative rinsing agents, the standard infection control should be maintained when fabricating dental models for patient use.

Future studies could test larger sample sizes to increase power and include different printer technologies such as DLP, SLA, and LCD. Multiple resin types can also be evaluated as well as water-washable resin, which is pretty new in the market. In the current study, only dentate model was used; other applications can be tested in the future such as edentulous models, surgical guides, and provisional restorations. Dentate arches have distinct anatomical differences compared to edentulous arches such as grooves and fossa and gingival sulcus that can pool uncured resin in these concave areas. For edentulous arches, rinsing solvent may not be as crucial.

Since all other printing parameters were kept constant in the current study, future studies could test different build angles and layer thicknesses as well as different storage times to evaluate dimensional accuracy over time. Outcomes other than accuracy can also be tested such as flexural strength. In the present study, propylene glycol performed the best with the lowest mean error. Propylene glycol is approved by the FDA for human consumption as it is found in food and cosmetic products. Future studies could test if there is a difference between IPA and propylene glycol as propylene glycol is FDA-approved and relatively easy to obtain.

There is no clear consensus on postprocessing rinsing protocol in regards to solvent, time, and in which method i.e. hand wash vs. ultrasonic to rinse 3D printed parts. Further studies and development of protocol are needed on this important step of 3D printing process.

5. CONCLUSIONS

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

- Propylene glycol was the most effective in removing residual resin on 3D printed models.
- Mean Green cleaner was the least effective in removing residual resin on 3D printed models.
- Propylene glycol had the lowest average errors and Mean Green had the highest average errors.
- There was no statistical difference between Mean Green and Yellow Magic 7 cleaners.

REFERENCES

1. Dawood A, Marti Marti B, Sauret-Jackson V, et al: 3D printing in dentistry. *Br Dent J.* 2015;219:521-9

2. Tian Y, Chen C, Xu X, Wang J, Hou X, Li K, Lu X, Shi H, Lee ES, Jiang HB. A review of 3D printing in dentistry: Technologies, affecting factors, and applications. *Scanning*. 2021 Jul 17;2021

3. Schweiger J, Edelhoff D, Güth JF. 3D printing in digital prosthetic dentistry: an overview of recent developments in additive manufacturing. *Journal of Clinical Medicine*. 2021 Jan;10(9):2010

4. Lin L, Fang Y, Liao Y, Chen G, Gao C, Zhu P. 3D printing and digital processing techniques in dentistry: a review of literature. *Advanced Engineering Materials*. 2019 Jun;21(6):1801013

5. Abduo J, Lyons K, Bennamoun M. Trends in computer-aided manufacturing in prosthodontics: a review of the available streams. *Int J Dent.* 2014; 2014: 78948

6. Chen H, Cheng DH, Huang SC, Lin YM. Comparison of flexural properties and cytotoxicity of interim materials printed from mono-LCD and DLP 3D printers. *J Prosthet Dent*. 2021 Nov 1;126(5):703-8

7. Application Guide: 3D Printing Diagnostic Models With Formlabs SLA 3D Printers. Formlabs. Accessed March 4, 2022. https://dental.formlabs.com/indications/diagnostic-models/guide/

8. Alharbi N, Osman RB, Wismeijer D. Factors Influencing the Dimensional Accuracy of 3D-Printed Full-Coverage Dental Restorations Using Stereolithography Technology. *Int J Prosthodont*. 2016 Sep 1;29(5):503-10

9. Firestone JA, Gospe Jr SM. Organic solvents. *In Clinical Neurotoxicology* 2009 Jan 1 (pp. 401-414). WB Saunders

10. 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 Mar 1;30(2)

11. Kim T, Lee S, Kim GB, Hong D, Kwon J, Park JW, Kim N. Accuracy of a simplified 3D-printed implant surgical guide. *J Prosthet Dent*. 2020 Aug 1;124(2):195-201

12. Alternate Wash Solutions for SLA Parts. Accessed February 20, 2022. https://formlabs.com/blog/alternate-wash-solutions/

13. Maker Tales. IPA Alternatives For Resin Print Cleaning | EU. 2021. Accessed January 20, 2022. https://www.youtube.com/watch?v=FCXL9du58L0

14. Dwamena M. How to clean resin 3D prints without isopropyl alcohol [Internet]. 3D Printerly. 2020. Accessed March 5, 2022. https://3dprinterly.com/how-to-clean-resin-3d-prints-without-isopropyl-alcohol/

15. SLA vs DLP vs LCD 3D printing: Which is best? 3DSourced. 2020. Accessed March 5, 2022. https://www.3dsourced.com/3d-printing-technologies/sla-vs-dlp-3d-printing/

16. Lalwani C. LCD vs. DLP vs. SLA: Which 3D Printer is Best For You. Phrozen Technology. 2020. Accessed March 24, 2022 https://phrozen3d.com/blogs/guides/sla-vs-dlp-vs-lcd-which-resin-3d-printer-is-the-best-for-you

17. Brown GB, Currier GF, Kadioglu O, Kierl JP. Accuracy of 3-dimensional printed dental models reconstructed from digital intraoral impressions. *Am J Orthod Dentofacial Orthop*. 2018 Nov 1;154(5):733-9

18. Mostafavi D, Methani MM, Piedra-Cascón W, Zandinejad A, Revilla-León M. Influence of the Rinsing Postprocessing Procedures on the Manufacturing Accuracy of Vat-Polymerized Dental Model Material. *J Prosthodont*. 2021 Aug;30(7):610-6

19. Hwangbo NK, Nam NE, Choi JH, Kim JE. Effects of the Washing Time and Washing Solution on the Biocompatibility and Mechanical Properties of 3D Printed Dental Resin Materials. *Polymers*. 2021 Jan;13(24):4410

20. Park ME, Shin SY. Three-dimensional comparative study on the accuracy and reproducibility of dental casts fabricated by 3D printers. *J Prosthodont*. 2018 May 1;119(5):861-e1

21. Measuring the resin concentration of IPA. Formlabs.com. Accessed March 1, 2022. Available from: https://support.formlabs.com/s/article/Measuring-IPAs-Resin-Concentration?language=en_US

22. Zhang ZC, Li PL, Chu FT, Shen G. Influence of the three-dimensional printing technique and printing layer thickness on model accuracy. *J Orofac Orthop*. 2019 Jul;80(4):194-204