Accuracy of LCD Printed Hollow Models with Differences in Thickness and the Presence of Grid

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Abstract

Printing dental models with hollow design can reduce resin usage, but the accuracy must be considered. The purpose of this study was to evaluate the accuracy of hollow models manufactured by a liquid crystal display (LCD) printer with differences in thickness and the presence of a grid.

The 10 different designs of hollow models consisted of hollow with grid (group G) and hollow without grid (group H), and each group was divided by thickness (1.0, 1.5, 2.0, 2.5, and 3.0 mm). Including solid design as control, all models were printed by LCD printer. Trueness and precision were evaluated. The root-mean-square error (RMSE) and average were used in statistical analysis. The interaction of two factors was investigated by two-way ANOVA. One-way ANOVA with Dunnett T3 was used to compare deviation among the groups (α=0.05).

The results showed that thickness affected both trueness and precision, but the presence of grid affected only trueness of models. The trueness of hollow with grid or non-grid hollow with thickness of 3 mm design were significantly higher than other models and comparable to solid ($p<0.05$). The precision of hollow models with thickness of 3 mm was significantly higher than others and comparable to solid ($p<0.05$).

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Introduction

Currently, the fabrication of dental models or dental restorations has been developed from the conventional technique to the digital workflow. From digital files, three-dimensional (3D) printing can be used to create dental models or restorations. On occasion dental models are necessary for diagnosis or appliance manufacturing in laboratories, particularly in the orthodontic and prosthodontic fields[1, 2].

There are various techniques of 3D printing. Recently, LCD printing has been applied in the field of dentistry. This technology has been developed from the digital light processing (DLP) technique. It applies LCD as an imaging system. After an electric field is applied to the liquid crystals, its molecules rearrange and block light passing through. Transmitted light from the LCD becomes the light source to polymerize photosensitive liquid resin in the building platform. This technique is claimed to be a fast and precise form of printing[3]. However, LCD printed models still require post-curing which may affect the accuracy of models.

Numerous recent studies evaluated the accuracy of 3D printed models. They reported that several factors influenced accuracy. These included manufacturing techniques[2, 4-6], polymerization shrinkage[3, 7], dimensional change from post processing[8], and internal structure and base design of models[5, 9, 10]. The errors from printing may cause a wrong diagnosis, inaccurate appliances, or improper fitting of restorations, therefore the accuracy of a printed model must be considered. The International Organization for Standardization (ISO5725-1:1994) identifies that accuracy is combined with two parts. First, trueness is defined as

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a closeness of agreement between test results and the true or accepted reference value. The latter is precision, defined as a closeness between test results[11].

The main disadvantage of 3D printed models is the high cost of materials[12]. This steers many laboratories to modify printed models as palate-free, horseshoe-shape or hollow design in order to save resin usage[9, 10, 13]. However, printed models must be accurate enough for dental applications. Studies further reported that the accuracy of hollow models was not different from solid models[9, 13, 14], however there is no protocol or recommendation for designing models hollow. The purpose of this study was to evaluate the accuracy of hollow models with differences in thickness and the presence of a grid. The null hypotheses were 1) thickness and the presence of grid in hollow design did not affect trueness and precision of models and, 2) there was not significant differences in trueness and precision of printed hollow models with different designs in thickness and the presence of a grid.

Materials and methods

Fabrication of printed models.

The maxillary full-dentate stone model was used as a reference. The stone model was scanned by a desktop scanner (DS300, Shining 3D, China). The obtained STL file was sent to the modelling software (Materialise Magics version 22, Materialise HQ, Belgium) to modify the horseshoe-shape model by aligning the occlusal plane parallel with the horizontal plane and remove the palate below the cervical margin about 2-3 mm, thus, simulating the laboratories design. This digital model was exported as reference data and prepared for printing as a solid model (group S).

To create hollow models, the reference data was modified by a model hollowing function in 3shape appliance Designer 2015 software (3shape, Denmark). Each subgroup in the hollow with grid group (group G), was set as surface thickness 1.0, 1.5, 2.0, 2.5, 3.0 mm with grid size 10 mm, and each subgroup in the hollow without grid group (group H), was set as the same thickness with grid size 80 mm. These 10 different designs of hollow models: 10G 10H 15G 15H 20G 20H 25G 25H 30G 30H, represented in different thickness and grid, were exported as STL files.

Before printing, a supporting structure was added to each model by Auto-add support order in 3D printing preparation software (Chitubox, CBD-tech, China). All 10 hollow models, and the solid models, were printed by LCD printer (Phrozen Sonic 4K, Phrozen, Taiwan) using a photosensitive liquid resin (Phrozen ABS-like gray resin, Phrozen, Taiwan). The printing resolution was set at 1080x1920 µm for XY resolution and at 50 µm for Z resolution. Models were printed in the amount of 10 models for each design (n=10). After printing and removing printed models from the building platform they were washed with a 90% concentration of isopropyl alcohol, this was done twice, and then a further washing by an ultrasonic machine (Form wash, Formlabs Inc., USA) for two minutes. Following the manufacturer's recommendations, ultraviolet (UV) post-curing was done at 40°C temperature for 5 minutes to complete polymerization (Form cure, Formlabs Inc., USA). Lastly, all printed models were left in room temperature for about 1 hour and all supporting structures were removed from the models.

Accuracy testing by using a surface matching software.

All printed models were scanned by a desktop scanner (DS300, Shining 3D, China) and the scan data were sent to surface matching software (Geomagic Control X 2017, 3D Systems, USA) for accuracy testing. For trueness analysis, the superimposition between the reference model and the printed model was conducted by an initial alignment and best-fit alignment function, and then a 3D comparison was conducted to create color maps which were set as a critical value of ±0.5 mm (500 µm), and a specific range of ±0.05 mm (50 µm). The RMSE and the average offset values were evaluated. The RMSE performs the amount of deviation between two superimposed models and was calculated by using the formula below[(15)]. To evaluate precision, all printed models were superimposed within groups by the same process. Figure 1, 2 illustrates the experiment process in this study.

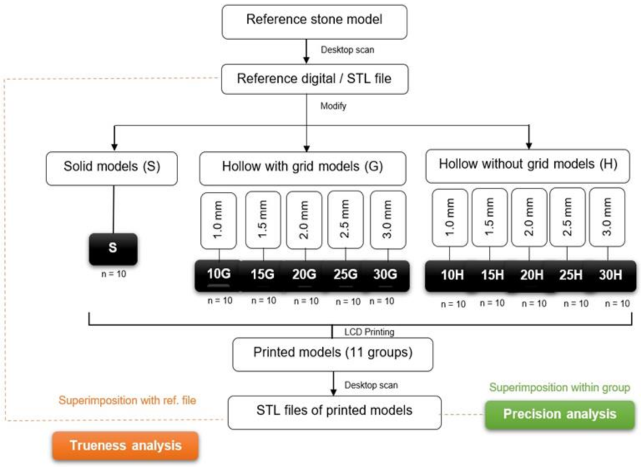

Figure 1. A flowchart of the working process in this study.

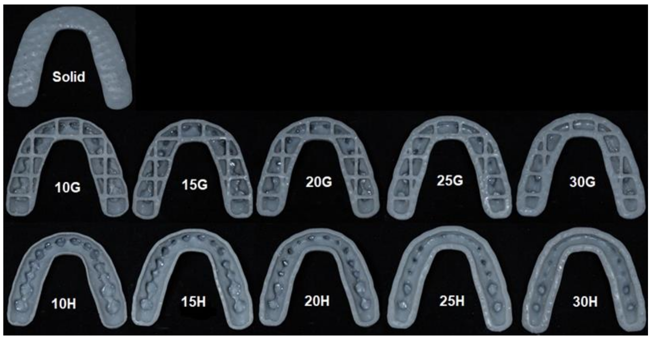

Figure 2. 11 groups of LCD printed models in this study.

$$RMS=\frac{1}{\sqrt{n}}\sqrt{\sum_{i=1}^{n}(x_{1,i}-x_{2,i})^2}$$

Where, $x_{1,i}$ is measuring point i on the reference model, $x_{2,i}$ is the measuring point i on the test model and n is the total number of measuring points.

Statistical analysis

The numerical data were analyzed by statistical software (IBM Statistics SPSS 24, IBM, USA), and the normal distribution of data was tested. Two-way ANOVA was performed to identify the influence of two factors (thickness and the presence of grid) on trueness and precision. One-way ANOVA was used to compare intergroup differences, and *Dunnett's T3 test was used for multiple comparison* (α = 0.05).

Results

In trueness analysis, the results of the two-way ANOVA reported that the accuracy of models significantly depended on thickness ($F = 63.792$, $p = 0.000$) and the presence of grids ($F = 447.932$, $p = 0.000$). In addition, the interaction between both factors was found ($F = 55.181$, $p = 0.000$).

Model	Resin volume (ml / 1 model)	Trueness				Precision	
		Mean RMSE (µm)		SD (µm)	Average (µm)	Mean RMSE (µm)	SD (µm)
S	9.02	122.28		14.97	-26.76	29.10	5.56
10G	3.69	120.04		17.42	-26.52	54.20	7.31
15G	5.01	110.94		21.99	-26.56	42.30	13.15
20G	6.10	105.33		17.12	-21.65	37.19	11.84
25G	6.98	108.17		25.35	-23.66	34.41	7.47
30G	7.64	110.12		6.43	-29.85	28.79	5.07
10H	3.41	419.93		55.78	+28.03	54.32	11.89
15H	4.76	330.25		65.60	+25.91	41.43	7.42
20H	5.87	213.79		43.36	+7.19	37.51	6.81
25H	6.78	190.14		23.64	-4.09	35.31	9.65
30H	7.47	125.05		10.10	-18.69	29.67	4.71

Table 1. The descriptive results in trueness and precision analysis.

The descriptive results, shown in table 1, reported that the minimum deviation was found in model 20G (105.33 ± 17.12 µm). The overall RMSE of group G (110.92 ± 17.66 µm) was lower than group H (255.83 ± 39.70 µm). The results of the one-way ANOVA, shown in figure 3, presented that the accuracy was not significantly different among the solid, 10G, 15G, 20G, 25G, 30G, and 30H models. In addition, the average deviations of these models showed negative values. This was contrary to, 10H 15H 20H and 25H models which showed significantly lower accuracy than the other models mentioned above. The average deviations of these models were positive (except model 25H). Compared within group H, the mean RMSE of the models decreased when thickness increased. The maximum deviation was found in model 10H (419.93 ± 55.78 µm).

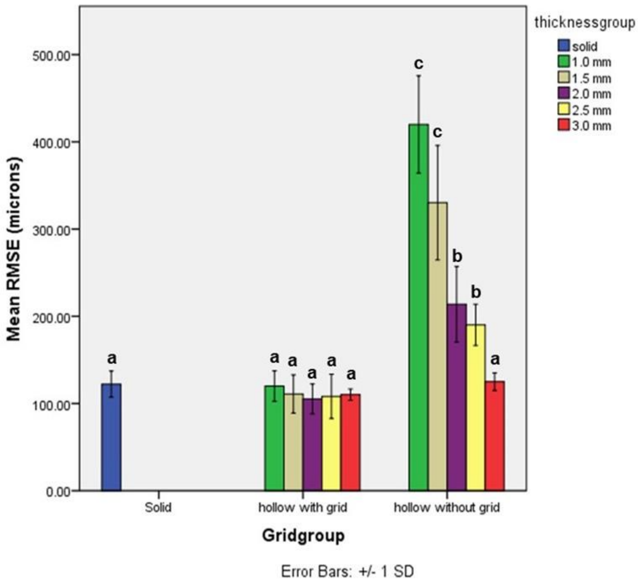

Figure 3. Result of one-way ANOVA showed the comparison among solid, hollow with grid and hollow without grid model groups by graph. The different letters represented significant differences on deviation from trueness analysis.

The 3D color maps, shown in figure 4, were used to evaluate the characteristics of deviation. In group G, the slight contraction and expansion were scattered around the arch. This pattern was relatively similar among each model in group G. In contrast to group H, where the color maps showed the expansion in the buccal direction around the posterior area of the arch. The additional expansion was found in thin models, especially in model 10H.

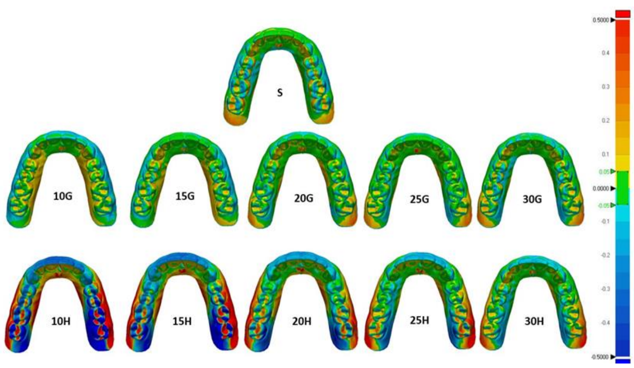

Figure 4. Color map of superimposed printed model with reference model. Green area showed deviation within ±50 µm. Yellow to red area showed expansion on printed model more than 50 µm compared to reference model. Light blue to dark blue area showed contraction on printed model more than 50 µm compared to reference model.

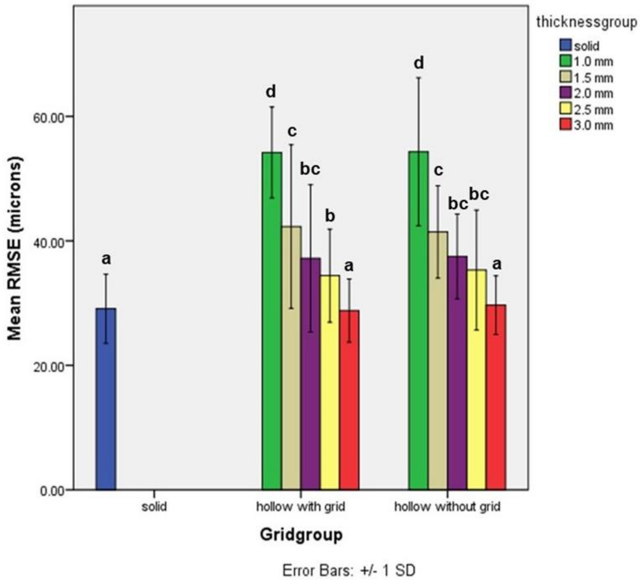

Figure 5. Result of one-way ANOVA showed the comparison among solid, hollow with grid and hollow without grid model groups by graph. The different letters represented significant differences on deviation from precision analysis.

In precision analysis, the descriptive results reported that the minimum deviation was found in model 30G (28.79 ± 5.07 µm) and the maximum deviation was found in model 10H (54.32 ± 11.89 µm). The results of the two-way ANOVA reported that thickness affected the precision of the models (F = 99.082, p = 0.000), whereas the presence of grids did not affect (F = 0.101, p = 0.75). The interaction between the two factors was not found (F = 0.146, p = 0.97). The results of one-way ANOVA shown in figure 5, presented that the solid, 30G and 30H models were not significantly different in precision and had better precision significantly than other models, additionally, the ecision of the models tended to increase when thickness increased.

Discussion

There have not been any studies that have evaluated the accuracy of an LCD printer. From Park et al., models printed by a DLP printer showed shrinkage compared to the reference model7. According to this study, most models (except models 10H 15H and 20H) showed slight contraction, that was indicated from negative average values. Shrinkage and expansion area shown in color map represented the distortion of 3D printed models.

Shape distortion of models results from volume change in polymerization and post-curing process,[8] and thus influences the accuracy of models.

For numerical assessment, the mean RMSE and average of deviation was used. The RMSE is accurate and reliable to represent the amount of deviation of 3D models. Although the average could not represent the true amount of deviation because the deviation had both a positive and negative, it may be used to inform the direction of deviation[15].

The production of models with hollow design can reduce the resin usage but shape distortion still occurs. According to recent studies, internal structures of hollow models affected the accuracy of DLP models[10] and increased thickness of printed samples could increase overall stiffness and reduce the amount of distortion[8]. They found that U-shaped hollow models with 1.5 mm and 4 mm thickness had lower accuracy than solid model[10], this was similar to this study where model 15H had lower accuracy than the solid model. From the results, thickness and the presence of grids related to trueness of models. Moreover, hollow with grid models (every model in group G) were not significantly different from the solid model. It could be implied that the presence of grids increased the stiffness of the model and reduced the distortion of printing. Whereas in the hollow without grid models, only model 30H was not different from the solid, and all other models showed more deviation. It was implied that thickness in the hollow without grid design models had to be enough to prevent distortion in printing, at least 3 mm from this study.

There were few previous studies about the accuracy of hollow models. Rungrojwittayakul et al. reported that there was no significant difference in accuracy between solid models and hollow models with a thickness of 2 mm, but their hollow design included cross-arch bars[9]. Printing models designed with a cross-arch stabilization structure, like palate or transverse bar, could give higher accuracy than printing in horseshoe-shape design. The cross-arch structures played an important role in preventing the distortion of models, even in the solid or hollow models[5, 10]. In horseshoe-shape design without cross-arch structures, only the supporting structure of printing could resist the distortion[10]. Some studies found that the accuracy of printed models which included cross-arch structure was higher than horseshoe-shape models[5, 10]. However, in this study we printed models only in horseshoe design due to simulating laboratory works and we could not compare with previous studies because of the differences in design, type of printers, type of resin and experiment methods.

From our study, the models in group H performed more deviation, especially in thin-hollowed models. In contrast, models in group G slight distortion and rather was found to be stable results. This finding reflected that the presence of grid in hollow design could improve the accuracy of printing. The pattern of deviation found in this study opposed to recent studies. Shin et al. reported that the characteristic of deviation in U-shape models showed contraction in lingual direction at the posterior region[10], however they used a DLP printer and photopolymer resin which were different from this study. The one important factor that impacted the distortion of models was UV post-processing. Wu et al. found that the DLP printed strips would bend directly toward UV light, called UV-induced bending and the degree of contraction related to thickness of strip[8]. Nevertheless, there was no recent study that investigated the pattern of deviation in printed dental models or arch shape.

In current systematic reviews, they assessed the precision of DLP printing in full-arch dental models and found the deviation was 53.8 – 76 μm[13]. However, this research found the deviation range was lower than that study (the mean RMSE was 28.79 – 54.32 μm in precision analysis), this finding supported that advanced LCD printing technology resulted in high precision. The precision of solid, 30H, and 30G models was highest in this study. The similarity of these models was the internal structure of teeth portion, which was fully filled in the solid model, and almost fully filled in models 30G and 30H. Thin models showed inferior repeatability of printing compared to thick models. It could be considered that the internal structure of thin models which had more hollowed area may cause the increased shrinkage. A recent study found that the internal structure of hollow models affected both trueness and precision and the hexagon internal structure was higher precision than hollow structure[10]. The appropriate porosity in internal structure could result in accurate printing[16]. Though the presence of a grid did not affect the precision in this study, it affected trueness.

The accuracy of printed models should be considered strongly, dependent upon their clinical application. The prosthodontic work requires a higher accuracy of models than the orthodontic work. The digital model distortion of less than 200 µm can be used in a clinical setting[17]. For fixed and implant prostheses fabrication, the deviation of more than 100 µm is not acceptable because of the concern of a misfit of these restorations[9, 18]. For orthodontic purposes, including diagnostic models and Invisalign production, the acceptable measurement error is up to 300 µm[4, 19]. From this study, models 10H and 15H were not accurate enough for dental application. However other models could be applied for orthodontic uses, but not acceptable for prostheses production, or other applications requiring high accuracy. In hollow models, 30G and 30H models showed best precision and trueness, and could reduce resin volume by 15.30% and 17.18% respectively. However, in dental fields where models are often printed in small quantities, consideration of trueness may be more necessary than precision. Accordingly, hollow with grid design is a good alternative to save material and remain accurate for orthodontic applications. This design is able to reduce resin usage by 15.30 - 59.09%. On the other hand, printing hollow models without grids requires a minimum thickness of 3 mm to be accurately close to a solid model.

For further studies, other internal structure designs, or other factors about hollow design should be investigated to find out the best methods that can produce hollow models in high accuracy. Moreover, the protocol or recommendations for variables and methods for accuracy testing must be determined because it is necessary when undertaking a comparison to other studies. The factors about type of resin, type of printer and print settings are the limitations of this study.

Conclusions

Hollow models with thickness of 3 mm showed highest accuracy. The lowest accuracy was found in non-grid hollow models with thickness of 1 mm. The more thickness could result better accuracy (both trueness and precision) of models. The presence of grid did not affect the precision of models.

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All authors have made substantive contribution to this study and/or manuscript, and all have reviewed the final paper prior to its submission.

Declaration of Interest

The authors report no conflict of interest.

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