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RESEARCH AND EDUCATION

Effect of printing layer thickness on the trueness and fit of additively manufactured removable dies

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ABSTRACT

Statement of problem. Additive manufacturing is commonly used for the fabrication of definitive casts with removable dies. However, how the trueness and fit of removable dies are affected by printing layer thickness is lacking.

Purpose. The purpose of this in vitro study was to investigate the trueness and fit of additively manufactured removable dies printed in different layer thicknesses.

Material and methods. A mandibular cast with a prepared right first molar tooth was digitized (CEREC Primescan), and its standard tessellation language (STL) file was imported into a software program (DentalCAD 3.0). A removable die (D-STL) and a hollow cast with (M-STL) or without the die (SM-STL) were designed. D-STL and SM-STL were imported into a nesting software program (Composer), and 45 removable dies in 3 layer thicknesses (100 μm, 50 μm, and 50 to 100 μm) (n=15) and 1 cast (100-μm) were additively manufactured. Each removable die (TD-STLs), the cast with each die (TM-STLs), and the cast without the die (TSM-STL) were digitized by using the same scanner. All STL files were imported into a software program (Medit Link v 2.4.4), and TD-STLs were superimposed over D-STL. The root mean square (RMS) method was used to analyze the trueness of the dies at 2 different areas (crown and root portion) and as a complete unit (overall). Overall RMS values of the cast with and without the die were also calculated after superimposing TM-STLs over M-STL. The fit of the dies in the cast was evaluated by using a triple-scan protocol to measure deviations at 5 different points (point M: most mesial point of the margin; point TM: tip of the mesial cusp; point O: deepest point of the occlusal fossa; point TD: tip of the distal cusp; point D: most distal point of the margin) on the crown portion. One-way ANOVA and Tukey honestly significant difference tests were used to evaluate data (α=.05).

Results. The RMS values of removable dies showed significant differences at each area ($P\leq$.002). The 50- to 100-μm group had higher overall RMS values than the 100-μm group (P=.017). The 100-μm group had the highest RMS values for the crown portion ($P\leq$.019), while the 50-μm group had the highest RMS values for the root portion (P<.001). The 50-μm group had the lowest RMS values for the crown portion when the die was in the cast (P<.001). Except for point TM (P=.228), significant differences were observed among the test groups at all points (P<.001). The 50-μm group had the lowest distance deviations at points M, TD, and D ($P\leq$.005), while the 100-μm group had the highest distance deviations at points O and D ($P\leq$.010).

Conclusions. Removable dies fabricated by using a 100-μm or 50- to 100-μm combined layer thickness had trueness that was either similar to or better than that of dies fabricated with a 50-μm layer thickness. When the die was on the cast, the 50-μm layer thickness resulted in the best crown portion trueness. However, because the deviation differences among groups were clinically small, the 100-μm layer thickness can be considered for the efficient fabrication of removable dies when the tested printer and resin are used. (J Prosthet Dent 2022;■:■-■)

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Clinical Implications

Removable dies fabricated by using a 100-μm or 50- to 100-μm combined layer thickness may be suitable alternatives as their trueness is similar to dies in a 50-μm layer thickness. However, the use of a 100-μm layer thickness may enable efficient printing without compromising the trueness of the dies.

Gypsum casts have long been used for the fabrication of dental prostheses.[1] However, shortcomings of conventional impression methods and gypsum casts,[2-4] along with the advancements in computer-aided design and computer-aided manufacturing technologies, have increased the popularity of digital dentistry and casts.[5] Digital scans not only eliminate issues with conventional impressions[1,6,7] and lead to higher patient satisfaction[8] but also facilitate the fabrication of definitive prostheses in a completely digital workflow that does not require a physical cast.[9] However, physical casts with removable dies are still required, particularly when managing complex treatment plans or to improve esthetics.[8-11]

A digital dental cast can be converted into a physical cast by using either subtractive or additive manufacturing.[12,13] Additive manufacturing has the advantage of fabricating complex structures with less waste material.[8,13,14] Among different additive manufacturing technologies,[15] digital light processing is commonly used, as an entire resin layer can be polymerized on the build platform and the manufacturing speed is high.[4] Digital light processing–based 3-dimensional (3D) printers enable more objects to be printed at a time without compromising the printing speed.[16]

Regardless of the manufacturing technique, accurate dental casts are essential to ensure precise prostheses.[1,12] Even though studies have shown that additively manufactured dental casts have an accuracy similar to that of gypsum casts,[4,5,10,17-20] conflicting results have been reported.[4] Therefore, knowledge of the factors that affect the accuracy of additively manufactured casts,[21] including layer thickness, is essential.[22] Layer thickness has an inverse effect on cast accuracy and duration of fabrication; lower layer thickness is required for high accuracy, whereas higher layer thickness shortens the production time.[23] Therefore, the users of printers are limited to long printing durations when a small layer thickness is selected for the critical finish lines of prepared teeth in dental casts. Recently, an additive manufacturing company (ASIGA) introduced the use of 2 different layer thicknesses for the fabrication of dental casts, claiming higher accuracy, where needed, and shorter production time. However, the authors are unaware of a study that investigated the effect of combining different layer thicknesses in a single fabrication process on the accuracy of removable dies. In addition, among the limited number of studies on the accuracy of additively manufactured removable dies,[7,9,10,14,24,25] only 1 focused on the effect of layer thickness on their properties.[25] Therefore, the present study aimed to evaluate the effect of layer thickness on the trueness of removable dies and their fit into an additively manufactured dentate cast. The null hypotheses were that the trueness of additively manufactured removable dies would not be affected by the layer thickness and that the fit of additively manufactured removable dies on a dentate cast would not be affected by the layer thickness.

MATERIAL AND METHODS

A mandibular right first molar tooth in a master dentate typodont model (ANA-4; frasaco GmbH) was prepared for a complete-coverage crown with a 1-mm-wide chamfer finish line.[26] An intraoral scanner (IOS) (CEREC Primescan; Dentsply Sirona) was used to digitize the prepared tooth along with the adjacent molar and premolar teeth. A standard tessellation language (STL) file of this scan was imported into a dental design software program (DentalCAD 3.0 Galway; exocad GmbH). A removable die-sectioned hollow cast was created by using “model creator module” of the software program. For the cast and die style type, “plateless model with cutout dies” was used with the following default presets: horizontal shaft gap: 0.08 mm, vertical shaft gap: 0.08 mm, ditch width: 0.5 mm, ditch height: 2 mm, groove width: 1 mm, groove depth: 1 mm, hollow cast wall thickness: 2.5 mm, bottom sill: 1 mm, cavity fill diameter: 1 mm. After design, the STL files of removable die (D-STL) and hollow cast with (M-STL) or without the die (SM-STL) were exported as STL files.

The D-STL file was transferred into a nesting software program (Composer; ASIGA) and its base was positioned toward the build platform. After generating supports automatically, this configuration was duplicated 10 times for standardization, arranged on the build platform and saved as the master configuration file. The nesting software program used allowed changing the printing layer thickness to the desired object height for those casts fabricated by using the proprietary cast resin of the manufacturer (DentaMODEL; ASIGA). Before importing the master configuration file into a digital light processing–based 3D printer (MAX UV; ASIGA), layer thickness was arranged according to subgroups of 100 μm, 50 μm, and 50 to 100 μm. The number of specimens in each group was based on a priori power analysis[26]; the inclusion of 15 specimens per group was deemed

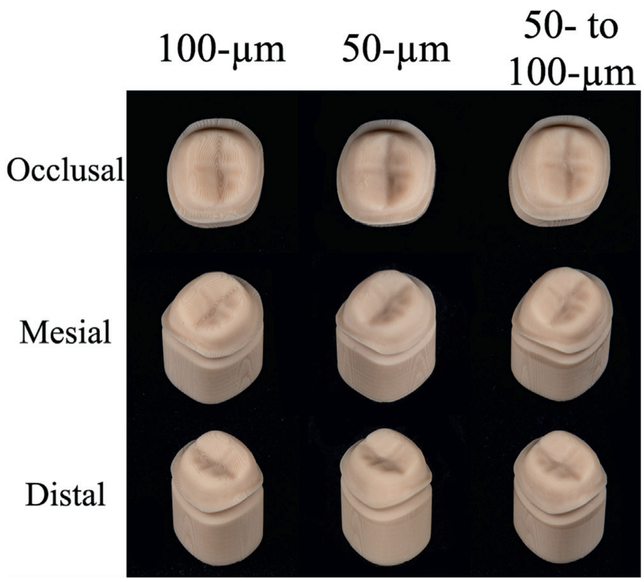

Figure 1. Additively manufactured removable dies.

appropriate (for 95% confidence interval [1-α], 95% power [1-β], and an effect size of f=0.623). Specimens in the 50- to 100-μm group were printed with 100-μm layer thickness until the height of the printed specimen reached 11.6 mm, which corresponded to the edge of concavity beneath the finish line. The remaining coronal 6.99-mm part of the specimens was printed with a 50-μm layer thickness. Specimens of 50-μm and 100-μm groups were printed with a single-layer thickness. After printing, all specimens were placed into an alcohol bath (ProgralPrint Clean; Ivoclar AG) containing 98% isopropyl alcohol and cleaned for 10 minutes (5 minutes in a prewash bath and 5 minutes in a postwash bath). Specimens were left to dry and then postpolymerized by using a xenon polymerization device (OtoFlash G171; NK Optik) under an atmosphere of nitrogen oxide gas (Fig. 1). A dentate cast without the die was fabricated similar to removable dies. The SM-STL was transferred into the nesting software program and printed with 100-μm layer thickness (Fig. 2). The layer thickness for the cast was selected to be 100 μm.[19] Table 1 lists the printing duration and number of layers for each printing process.

The dentate cast was digitized with and without the removable dies, while each removable die was also digitized separately by using the same IOS to generate their respective test-scan STL files (45 TSM-STLs for dentate casts without dies, 45 TM-STLs for dentate casts with removable dies, and 45 TD-STLs for removable dies). To analyze trueness, defined as the deviation of a measurement from the actual dimension of an object,[5] all STL files were imported into a 3D analysis software program (Medit Link v 2.4.4; Medit).[27-29] TD-STL was superimposed over the D-STL after selecting 3 points (1 on the occlusal surface, 1 on the buccal cusp, and 1 on the lingual cusp) on each STL file simultaneously. Color maps that represent 3D deviations were generated with the maximum and minimum critical (nominal) values set at +100 μm and -100 μm, and the tolerance range was set at +10 μm and -10 μm. Overall deviation values were automatically calculated by using the color maps and root mean square (RMS) method, the square root of the mean square of a set of numbers.[5] A high degree of 3D matching of the superimposed data, which indicated high trueness, is obtained when a low RMS is present.[29] STL files were imported again for the evaluation of the crown and root portions of dies. These surfaces were virtually separated, which divided the dies into 2. This superimposition process was repeated for each portion, and RMS values were automatically calculated by the software program (Fig. 3). Overall RMS values of the printed cast without die (Fig. 4) and crown portion of the die when it was inserted into the cast (Fig. 5) were also calculated. Deviation of the cast without the removable die was calculated by isolating second and third molars and premolars after superimposing TM-STLs over M-STL, while deviation of the crown portion was calculated after superimposing TM-STLs over M-STL and isolating the crown part. Even though a single cast was used for all scans, the RMS value of the dentate cast without die was calculated to evaluate the possible effect of the 3D printer and IOS on measured deviations of dentate casts with dies.

After trueness analysis, all test-scan STLs were imported into the 3D analysis software program to analyze the fit of dies by using the triple-scan protocol.[30-36] Briefly, a TM-STL was initially superimposed over the TSM-STL to generate a merged STL, which was followed by the superimposition of corresponding TD-STL over this merged STL. All superimpositions were performed by simultaneously selecting 3 points on each STL file, similar to those performed for trueness analysis. These consecutive superimpositions facilitated 3 different STL files to be merged on the same coordinate system. After superimpositions, a mesiodistally oriented plane that passed through the prepared tooth was generated. Five points (point M: most mesial point of the margin; point TM: tip of mesial the cusp; point O: deepest point of the occlusal fossa; point TD: tip of the distal cusp; point D: most distal point of the margin) were selected both on the TD-STL and on the TM-STL. The distance between each point was recorded either as a positive or negative value depending on the 2-dimensional position of a point on TD-STL according to its corresponding point on TM-STL (positive value indicated that the point on TD-STL was above its corresponding point on TM-STL, whereas negative value indicated otherwise) (Fig. 6). However, absolute values of these linear deviations were used for statistical analysis.

Normality of data was analyzed by using the Shapiro-Wilk test. Due to normal distribution, 1-way ANOVA and the Tukey honestly significant difference

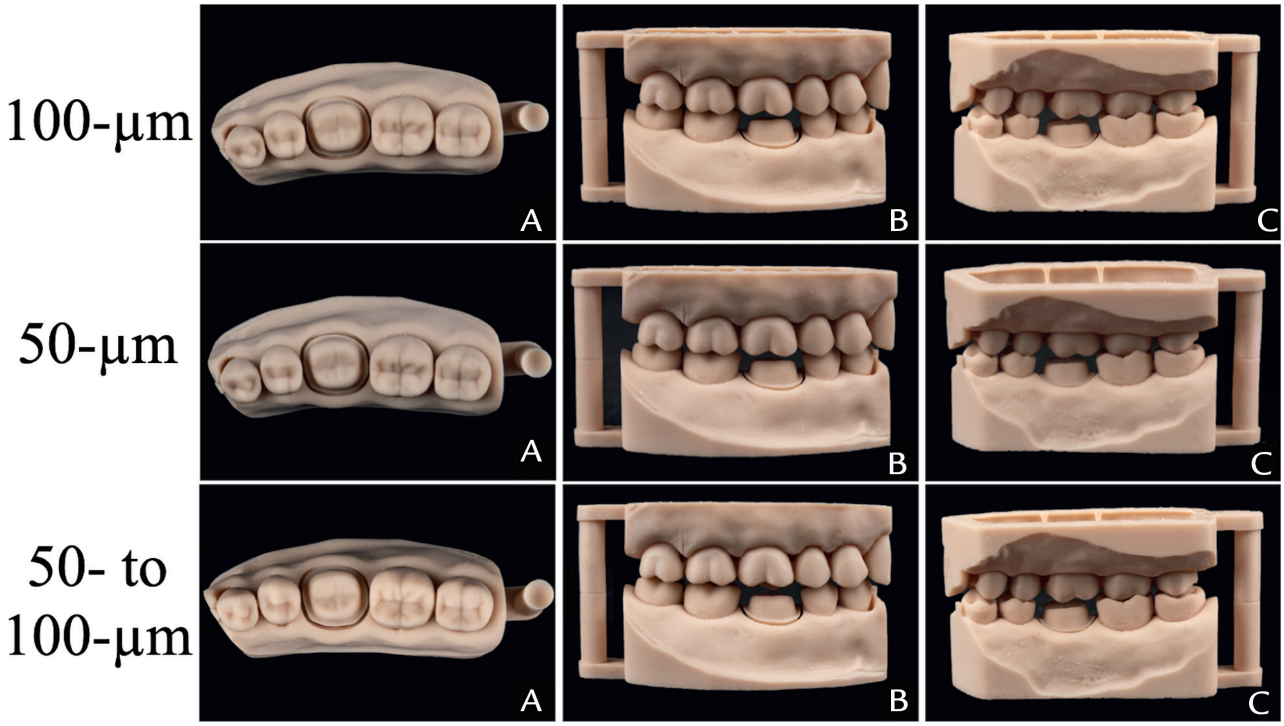

Figure 2. Removable dies on additively manufactured cast. A, Occlusal view. B, Buccal view with cast. C, Lingual view with cast.

tests were used to further analyze RMS and point-based data (α=.05).

RESULTS

Significant differences were observed among the RMS values of different layer thicknesses for each area investigated (*P*≤.002). When overall deviations were considered, the 50- to 100-µm group had higher values than those of the 100-µm group (*P*=.017). For the crown portion, the 100-µm group had the highest deviations (*P*≤.019), and for the root portion, the 50-µm group had the highest deviations (*P*<.001). For the deviation of the crown portion with die in cast, the 50-µm group had the lowest deviations (*P*<.001) (Table 2). The dentate cast without die had an overall RMS value of 39.98 µm.

For the fit of the die in the cast, triple scan data analysis revealed that, except for point TM (*P*=.228), significant differences were observed at all points evaluated (*P*<.001). At points M and TD, the 50-µm group had the lowest deviations (*P*≤.005). At point O, the 100-µm group had the highest deviations (*P*≤.010). At point D, the 100-µm group had the highest and the 50-µm group had the lowest deviation values (*P*≤.001) (Table 3). Figure 7 illustrates the scatter pattern of measured deviations for each thickness-point pair.

DISCUSSION

Overall and portion-based RMS values for dies were different among tested layer thicknesses. The fit of the dies and the RMS values of the portion of the crown when dies were in the cast was also affected by layer thickness. Therefore, the null hypotheses were rejected.

Given the significant differences among die groups when portion-based RMS values were considered, the trueness of an additively manufactured object appears to depend not only on the layer thickness but also on its surface characteristics. This suggestion was consistent with that of You et al,[37] who reported higher trueness at intaglio surfaces when a 100-µm layer thickness was used and higher trueness of denture teeth when 50-µm layer thickness was used while investigating the effect of layer thickness on the evaluation of complete dentures. The authors[37] associated this difference with the relatively simple anatomy of intaglio surfaces, which have a lower potential for error when greater layer thicknesses are used. However, for more complex anatomies such as dental crowns, smaller layer thicknesses seem to be required for more accurate fabrication. Studies on

Table 1. Printing parameters of each group and dentate cast without die

Layer Thickness	Printing Duration	Number of Layers
100 µm	32 min and 46 s	223
50 µm	59 min and 28 s	372
50 to 100 µm	1 h 1 min and 35 s	256
Dentate cast without die (100 µm)	38 min and 56 s	260

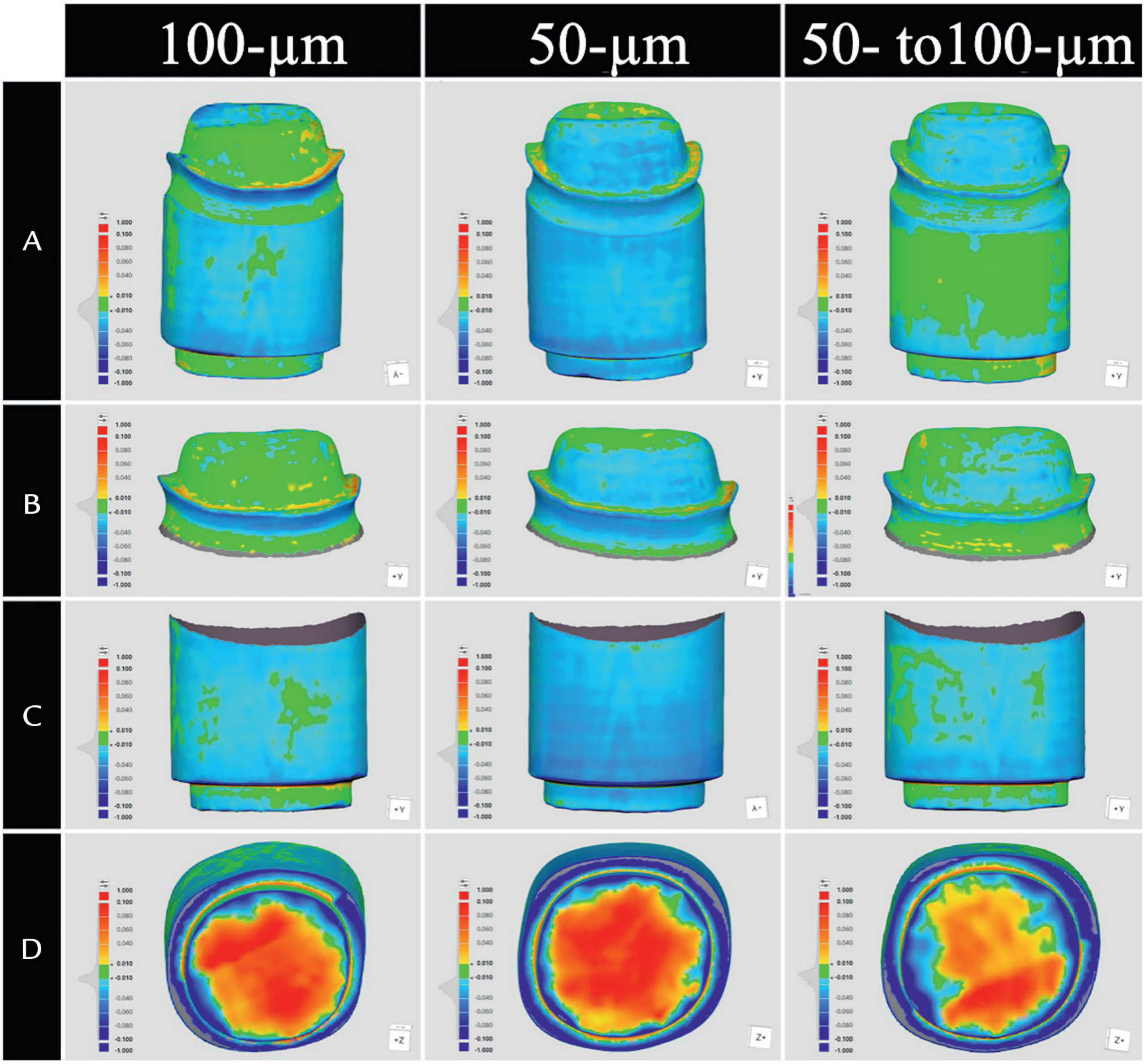

Figure 3. Color maps of dies generated by superimposition process. A, Overall. B, Crown portion. C, Root portion. D, Base of the root portion.

additively manufactured interim crowns and fixed partial dentures confirm these results, as smaller layer thicknesses were reported to result in higher trueness.[26,28] Therefore, it seems logical to modify the settings for the 3D printing of dies and casts and to print the root or cast base portion with a 100-µm layer thickness and the crown portion with a 50-µm layer thickness, corresponding to the 50- to 100-µm group in the present study. When portion-based RMS values were considered, the 50- to 100-µm group had crown portion trueness similar to that of the 50-µm group and root portion trueness similar to that of the 100-µm group. However, the 50- to 100-µm group had lower overall trueness than the 100-µm group and lower crown portion trueness than the 50-µm group when the die was in the cast. A possible explanation for this could be the location of the transition between the 50-µm and 100-µm layer thicknesses of the 50- to 100-µm group. In the present study, dies were designed with a concavity underneath the finish line similar to that of conventional dies. Even though the origin of this concavity facilitated the standardization of transition between different layer thicknesses, a different location of transition such as 1 mm below the challenging occlusal surface may lead to different results. Where the crown portion's trueness when the die was in the cast was concerned, the 50-µm group had the highest trueness. This finding was consistent with that of a previous study,[38] whereas in another study,[39] similar trueness for all evaluated layer thicknesses (25-µm, 50-µm, and 100-µm) were reported. Nevertheless, statistical differences

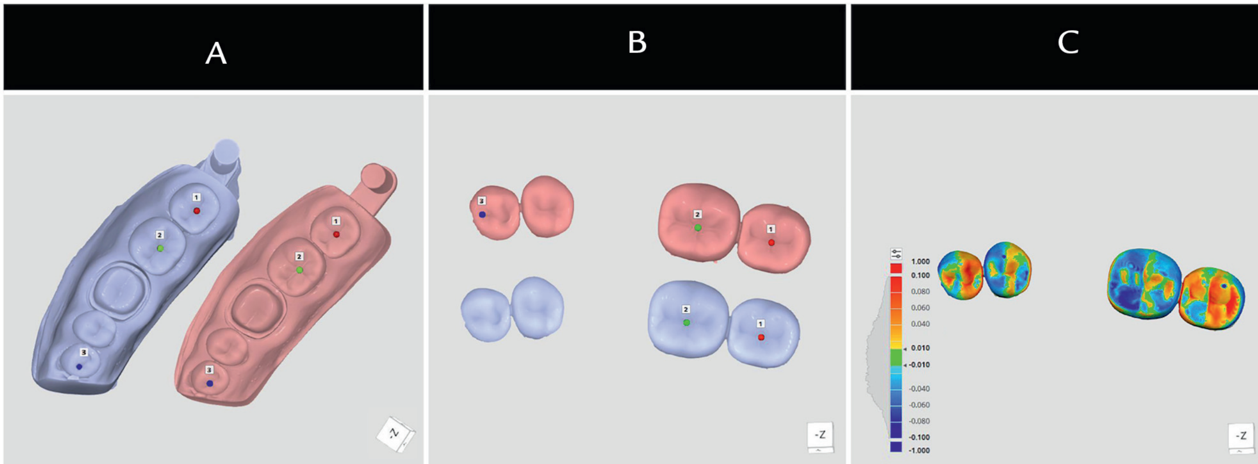

Figure 4. Superimposition process of cast with and without die A, Points selected for superimposition of cast with die. B, Points selected for superimposition of cast without die. C, Color map of cast without die.

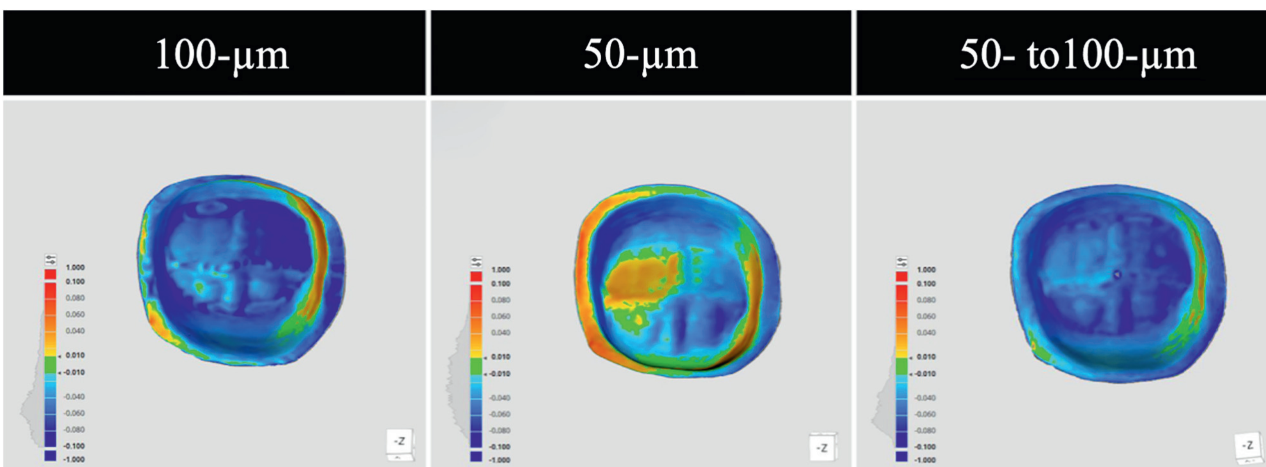

Figure 5. Color maps of crowns with die in cast.

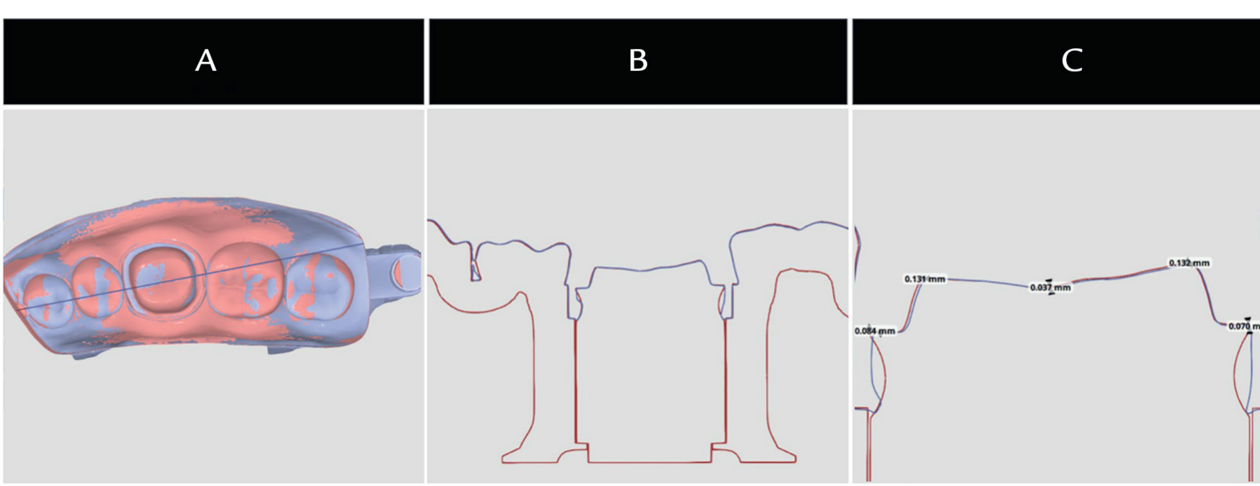

Figure 6. Triple-scan protocol (A, Mesiodistal orientated plane generated after superimpositions. B, Sectional view of the whole cast. C, Points selected to evaluate the fit of dies. *Red* merged STL. *Blue* TD-STL.

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Table 2. Mean ±standard deviation RMS values of each thickness-area pair

Layer Thickness	Overall	Crown	Root	Crown with die in Cast
100 μm	37.87 ±1.15[a]	19.67 ±1.11[b]	48.94 ±1.07[a]	60.12 ±1.13[b]
50 μm	39.52 ±1.1[ab]	17.22 ±1.1[a]	59.35 ±1.07[b]	45.18 ±1.20[a]
50 to 100 μm	43.78 ±1.18[b]	15.93 ±1.19[a]	46.92 ±1.08[a]	58.74 ±1.21[b]

*Different lowercase letters indicate significant differences in columns (*P*<.05).

Table 3. Descriptive statistics of measured deviations for each thickness-point pair (considering horizontal and vertical shaft gap as 0.08 mm)

Layer Thickness	Point M	Point TM	Point O	Point TD	Point D
100 μm	112.93 ±14.95[b]	89.73 ±13.56[a]	181.2 ±25.32[b]	146.4 ±23.68[b]	94.07 ±12.75[c]
50 μm	77.27 ±14.18[a]	103.6 ±31.03[a]	119.73 ±32.15[a]	97.27 ±26.24[a]	48.4 ±13.06[a]
50 to 100 μm	110.13 ±11.68[b]	99.67 ±18.85[a]	143.8 ±40.11[a]	132.2 ±34.68[b]	73.13 ±16.5[b]

*Different lowercase letters indicate significant differences in columns (*P*<.05).

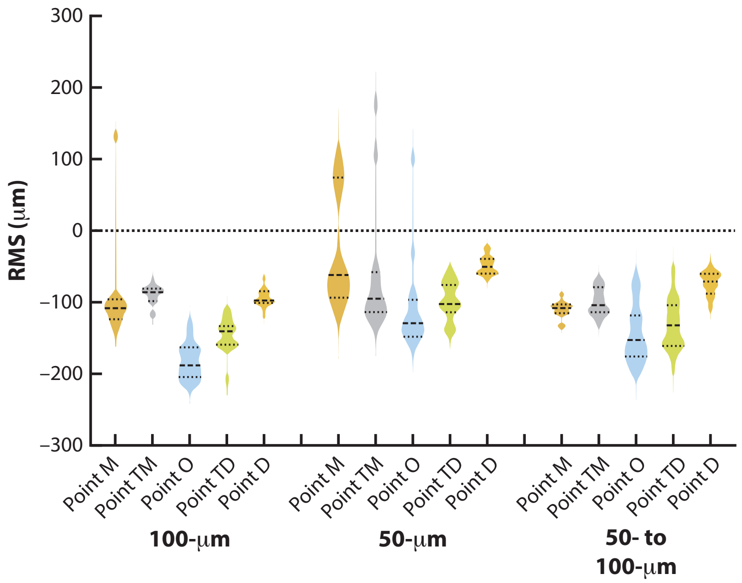

Figure 7. Violin graph of raw RMS data of each thickness-point pair.

found in the present study may not have considerable clinical importance given the small deviation values and differences among groups. Similarly, Sabbah et al[25] concluded that even though significant differences were observed, layer thickness alone (25-μm, 50-μm, and 100-μm) had no influence on the precision of additively manufactured dies. The deviation values of dies in the cast in the present study can be even smaller when the trueness of the cast without die is considered. The mean RMS value for this cast was 39.98 μm. This value is within previously reported acceptability values for printed casts.[19] The mean RMS values when the die was in the cast were 60.12 μm, 45.18 μm, and 58.74 μm for 100-μm, 50-μm, and 50- to 100-μm groups, respectively. The 39.98-μm deviation may be considered the fabrication error, which is potentially sourced by scanning and printing of the cast irrespective of the presence of a die. Therefore, the fitting trueness of the die could probably be determined by subtracting this value from the mean RMS value when the die was on the cast: 20.14 μm for the 100-μm group, 6.20 μm for the 50-μm group, and 22.52 μm for the 50- to 100-μm group. These subtracted values can be considered clinically small for the effect of the die's position in the cast on the interproximal and occlusal contacts of the definitive prosthesis, particularly for the 50-μm group. Nevertheless, the RMS values of die on the cast should be considered clinically. When the dies were visually assessed, even though the 100-μm group had apparent waviness on the crown portion of the dies, the outline of the margins was similar and the most outer border of the finish lines was similarly detectable among test groups. Therefore, marginal adaptation of definitive crowns fabricated on dies fabricated by using tested layer thicknesses appears to be similar.

The fit of the dies into the cast might also have affected the trueness of the crown portion. As the fit of a die mainly depends on the root portion, the best fit would have been expected from the group that had the highest root portion trueness. However, in the present study the group that had the lowest root portion trueness (50-μm group) had the better fit. This could be associated with the distribution of measured deviations as the 50-μm group had both negative and positive deviations, while the other groups mostly had negative deviations. In the 50- to 100-μm and 100-μm groups, the dies were apically positioned and, accordingly, the crowns fabricated on these dies may result in discussion. The deviation values obtained from the triple scan protocol should be interpreted carefully. All dies were fabricated with standardized horizontal and vertical shaft gap values (0.08 mm), which are set parameters in printer software programs. These values enable a certain amount of distance for the die to be placed in the cast without excessive friction. Thus, 80 μm of the measured point deviations were potentially because of the settings in the software program, and the actual deviations and the differences among test groups should be considered clinically small. For the correct positioning of the dies, a vertical stop at the bottom was designed. Given that this stop had a smaller diameter than the remaining rest of the root portion and rather had a more detailed structure, the authors believe that the effect of smaller layer thicknesses on more complex structures might have contributed to these results.

The IOS used in the present study has been reported to have accuracy similar to that of laboratory scanners[40,41] and can scan the entire die in a single scan. However, laboratory scanners require the scanning of different surfaces of dies, which should then be digitally stitched. This stitching may lead to accumulated errors. The RMS method and the 3D analysis software program used in the present study have been reported to be reliable.[27,29] In addition, the triple-scan protocol has been commonly used to evaluate the fit of prosthetic structures.[30-36] The 3D printer used in the present study enabled printing objects in varying layer thicknesses within the same print job. Nevertheless, the results of the present study cannot be generalized because only 1 3D printer was used. All dies and the cast were printed according to the manufacturer's recommendations. However, similar to layer thickness, other controllable parameters such as printing orientation may also affect tested parameters. The highest mean difference in RMS values of all groups was approximately 15 μm, clinically small. Therefore, the results of the present study should be considered as preliminary, and while the clinical acceptability of measured die deviations should be tested with studies on the comparison of conventionally manufactured removable dies, the effect of measured positional die deviations on the proximal and occlusal contacts of definitive prostheses fabricated when casts with different layer thicknesses are used should be investigated in future in vitro and in vivo studies.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. Combining different layer thicknesses (50 to 100 μm) enabled an overall die, crown portion, and root portion trueness similar to or better than the 50-μm layer thickness group. The layer thickness of 100 μm resulted in overall die and root portion trueness similar to or better than 50 μm.
2. Even though the 50-μm layer thickness group resulted in the best trueness for the die on the cast, the differences among groups can be considered clinically small.
3. Layer thicknesses of 100 μm or 50 to 100 μm may be selected for the efficient printing of dies for subsequent crown fabrication when tested printer and resin are used.

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