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Die Spacer Thickness Reproduction for Central Incisor Crown Fabrication with Combined Computer-aided Design and 3D Printing Technology: An in vitro Study

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Abstract

Statement of problem: The inability to control die spacer thickness has been reported. However, little information is available on the congruency between the computer-aided design parameters for die spacer thickness and the actual printout.

Purpose: The purpose of this study was to evaluate the accuracy and precision of the die spacer thickness achieved by combining computer-aided design and 3-dimensional printing technology.

Material and methods: An ivorine maxillary central incisor was prepared for a ceramic crown. The prepared tooth was duplicated by using polyvinyl siloxane duplicating silicone, and 80 die-stone models were produced from Type IV dental stone. The dies were randomly divided into 5 groups with assigned die spacer thicknesses of 25 μm, 45 μm, 65 μm, 85 μm, and 105 μm (n=16). The printed resin copings, obtained from a printer (ProJet DP 3000; 3D Systems), were cemented onto their respective die-stone models with self-adhesive resin cement and stored at room temperature until sectioning into halves in a buccolingual direction. The internal gap was measured at 5 defined locations per side of the sectioned die. Images of the printed resin coping/die-stone model internal gap dimensions were obtained with an inverted bright field metallurgical microscope at ×100 magnification. The acquired digital image was calibrated, and measurements were made using image analysis software. Mixed models (α=.05) were used to evaluate accuracy. A false discovery rate at 5% was used to adjust for multiple testing. Coefficient of variation was used to determine the precision for each group and was evaluated statistically with the Wald test (α=.05).

Results: The accuracy, expressed in terms of the mean differences between the prescribed die spacer thickness and the measured internal gap (standard deviation), was 50 μm (11) for the 25 μm group simulated die spacer thickness, 30 μm (10) for the 45 μm group, 15 μm (14) for the 65 μm group, 3 μm (23) for the 85 μm group, and -10 μm (32) for the 105 μm group. The precision mean of the measurements, expressed as a coefficient of variation, ranged between 14% and 33% for the 5 groups.

Conclusions: For the accuracy evaluation, statistically significant differences were found for all the groups, except the group of 85 μm. For the precision assessment, the coefficient of variation was above 10% for all groups, showing the printer's inability to reproduce the uniform internal gap within the same group.

Clinical Implications: The incongruence between the computer-aided design program setting and the actual coping printout negatively affect the clinical fit of the definitive restoration.

Clearance is needed between a fixed restoration and the prepared tooth to provide space for the luting agent. Methods such as venting, axial grooves, and provision of axial cement space have been used to reduce the hydraulic pressure between the cement and cast restoration and therefore improve seating, decrease seating time, and allow the escape of excess cement.[1, 2, 3, 4, 5, 6, 7 and 8] The application of paint-on die spacer before waxing is one of the most popular methods for providing this space.[3 and 9] Die spacers have been used in fixed dental prostheses for many years.[3, 10, 11, 12 and 13]

Die spacer has been shown to improve the marginal fit between the restoration and tooth preparation, decreasing the risk of cement dissolution, plaque accumulation, recurrent caries, and periodontal problems.[14] The thickness of this die spacer affects the fracture strength of a ceramic restoration, its retention, and the marginal gap.[1, 2, 15 and 16] According to Tuntiprawon and Wilson,[15] ceramic crowns displayed a greater fracture strength when the mean internal gap at the axial wall was less than 73 μm. A lower failure strength was reported when the mean internal gap was greater than 122 μm without any significant improvement in seating. Conflicting results have been reported on the influence of die spacer thickness on retention. Eames et al[1] reported a 25% increase in retention when comparing 0 μm to 25 μm die spacer thickness. This improved retention was supported by Carter and Wilson,[2] who reported that retention increased from 250 N to 375 N as die spacer thickness changed from 0 to 8 layers. In contrast, Jorgensen and Esbensen[16] reported a moderate association between film thickness and retention, while Vermilyea et al[17] reported a 32% reduction in retention when comparing 0 with 2 layers of Tru-Fit paint on die spacer (George Taub Products and Fusion Co Inc). There is greater consistency when evaluating the cause and effect relationship of die spacer thickness and marginal gap.[2, 3 and 4] The magnitude of the marginal gap observed without the use of die spacer was as high as 649 μm[3]. The marginal gap was significantly improved from 479 μm to 38 μm as the die spacer thickness was increased from 1 to 8 layers.[1, 2 and 3] Marginal gap can also be influenced by the marginal design and total occlusal convergence of the preparation.[18 and 19] McLean and von Fraunhofer[18] showed that the best marginal gap was obtained with chamfer or rounded shoulder marginal design when compared with straight shoulder marginal design. The maximum tolerated marginal gap was 120 μm for ceramic crowns.

Hollenback[20] suggested an ideal die spacer thickness of 25 μm, which corresponds to the film thickness of Type I zinc phosphate cements. However, studies with commercially available paint-on die spacer products have shown inconsistent results.[5, 13, 21 and 22] Computer-aided design (CAD) technology provides the ability to virtually design restorations and program the die spacer thickness. The virtual coping can be produced by milling[23 and 24] or rapid prototyping. Rapid prototyping uses the layer-to-layer fabrication of 3-dimensional physical models directly from CAD data.[25, 26 and 27] Rapid prototyping is further subdivided into stereolithography, selective layer sintering, fused deposition modeling, laminated object manufacturing, and 3D printing technology (3DPT).[28] 3DPT is used for copings, partial fixed dental prostheses, anatomic contour pressable patterns, and partial removable dental prosthesis frameworks, which are formed in either wax or acrylic resin.[29]

Accuracy is defined to assess the degree of closeness of the internal gap measurements to the reference values (programmed die spacer thicknesses). Therefore, the purpose of this study was to evaluate the accuracy and precision of the die spacer thickness achieved by combining CAD and 3DPT to test the accuracy of CAD/3DPT by comparing various measured internal gap thicknesses with the prescribed values of 25 μm, 45 μm, 65 μm, 85 μm, and 105 μm. The accuracy null hypothesis was that no overall difference would be found between the CAD/3DPT achieved internal gap thicknesses and the prescribed die spacer thicknesses. The secondary objective of the research was to measure the printer's ability to reproduce the uniform die spacer thickness for all the specimens within an assigned die spacer thickness group. A statistical analysis was performed to test whether there was difference among the varying die spacer thicknesses and the reproducibility of the printer. The coefficient of variation (CV) was adopted to determine the precision of the measurements. Ten percent of CV has been widely used as cutoff to define high precision.[30, 31 and 32] Therefore, the null hypothesis for precision was that the CV was equal to 10% because a CV less than 10% was considered reasonable.[30, 31 and 32]

Material and Methods

An ivorine maxillary central incisor (T1560; Columbia Dentoform Corp) was prepared to receive a ceramic crown restoration with the following features: a total convergence angle of 12 degrees, an incisal reduction of 2 mm, a uniform axial reduction of 1.5 mm, and a deep chamfer.[28] Before duplication, the prepared tooth was attached to a circular base with 3 rectangular extensions fabricated from a light-polymerized urethane dimethacrylate tray material (Triad; Dentsply Intl). The material increased the diameter of the ivorine tooth shaft to prevent tooth breakage during separation from the silicone mold and to allow sectioning with a low-speed saw (IsoMet speed saw; Buehler Ltd). Polyvinyl siloxane duplicating material (Double Take; Ivoclar Vivodent) was used to make 16 molds of the prepared tooth in a duplicating flask. Type IV dental stone (Resin Rock; Whip Mix Corp) was used to fabricate 80 stone dies from the 16 silicone molds. The stone dies were divided into 5 groups for the 5 die spacer thickness levels: 25 μm, 45 μm, 64 μm, 85 μm, and 105 μm (N=80). A power analysis was completed before the experiment using the mixed models. A statistical analysis was assumed to have been performed for each die spacer thickness level. Given the die spacer thickness level, 5 measurements for each specimen were treated as repeated measurements to account for within individual correlation. The standard deviation of each measurement was assumed to be 15 and the correlation among the 5 measurements from each specimen to be 0.8. A sample size of 80 (5 locations×16 teeth for each die spacer thickness level) was determined to be sufficient to detect a mean difference of 11 between overall mean (mean of the 5 locations) and the mean of the null hypothesis with 80% power and at a 5% significance level.

The stone dies were shipped to a commercial laboratory (Nu-Art Dental Inc) for the fabrication of the resin copings. Each die was scanned (D700 3D scanner; 3Shape) according to the manufacturer's instructions to record the external die form. The 3Shape CAD design system was used to locate the margin and assign the die spacer thickness, which was uniform throughout and terminated 0.5 mm from the finish line and coping thickness of 1.0 mm.[2, 5 and 33] Each resin coping was digitally marked so that it could be paired with its corresponding stone die. The acrylic resin copings were printed (ProJet DP 3000; 3D Systems). The same dental technician at the commercial laboratory completed all of the laboratory processes.

One dispenser increment volume of self-adhesive resin cement (RelyX Unicem 2; 3M ESPE) was used to cement each printed resin coping to its corresponding die. The cement film thickness was determined based on the American Dental Association Specification No. 8 protocol, section 4.3.4.[34] However, the recommended seating force was reduced to replicate the load used in this experiment (49 N). For the test specimen, the coping was seated with a rocking motion until it was completely seated onto the die. The cemented coping-die assembly was placed under an apparatus capable of maintaining a static deadweight load of 49 N (Fig. 1A), and excess cement was removed with a fine microbrush.[35] The mesial, distal, buccal, and lingual surfaces were light polymerized (Demi Plus; Kerr) for 20 seconds each for a total of 80 seconds to ensure complete polymerization. The cemented coping-die assembly was kept under the weighted-base apparatus for 6 minutes. The specimens were stored at room temperature until sectioning.

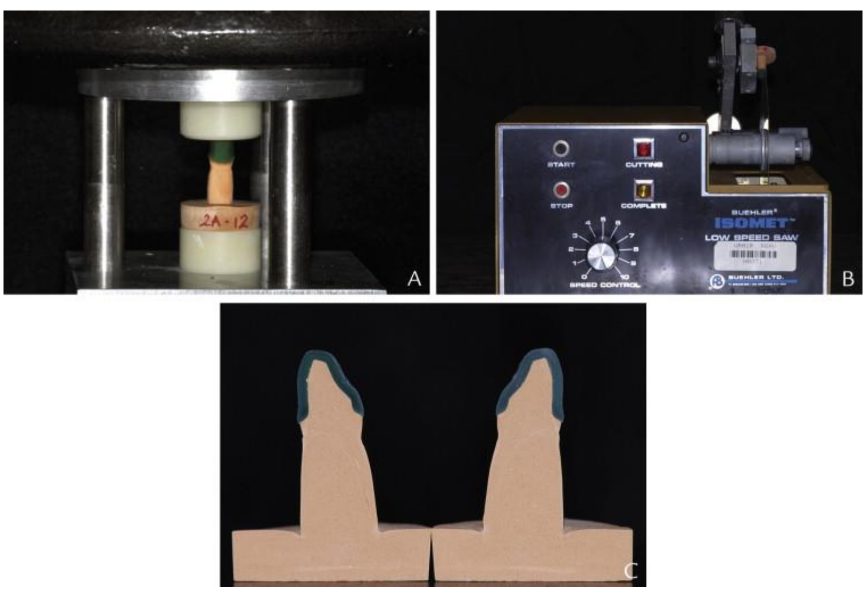

Figure 1. A, Cemented coping-die assembly placed under static load of 49 N. B, Low-speed diamond saw with diamond wafering blade. C, Specimen sectioned into halves.

Each specimen was sectioned in a buccolingual direction by using a low-speed diamond saw (IsoMet speed saw; Buehler Ltd) with a 127×0.4 mm diamond wafering blade under wet conditions (Fig. 1B). This resulted in 2 specimens for evaluation per coping and die stone (Fig. 1C). The sectioned surface was smoothed with wet 1200-grit silicon carbide paper (MicroCut S; Buehler Ltd) for 1 minute under light pressure.

Holmes et al[36] defined the internal gap as the perpendicular measurement from the internal surface of the casting to the axial wall of the preparation; the same measurement at the margin was referred to as the marginal gap. The internal gap between the printed resin coping and stone die for each sectioned specimen was measured at 5 defined locations: (A) facial chamfer, (B) facial midaxial, (C) incisal, (D) lingual midaxial, and (E) lingual chamfer (Fig. 2). Five measurements were made to create an average value at each point, leading to a total of 50 measurements (5×2×5) per die.[37] Overall, 4000 measurements (50 measurements×80 specimens) were obtained for the entire study. The internal gap image was obtained with an inverted bright field metallurgical microscope at ×100 magnification (Metallograph/Microscope; Leco/Olympus). The microscope was linked to a digital image acquisition device and computer software (Spot v4.5 and v5.1; Spot Image) (Fig. 3).

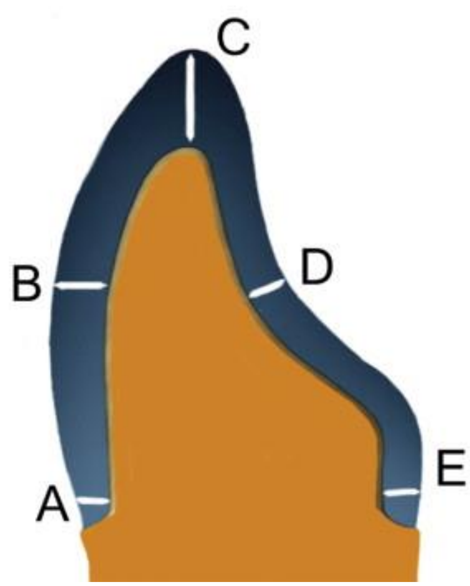

Figure 2. Tooth diagram of measured locations. A, Facial chamfer. B, Midfacial axial wall. C, Incisal. D, Midlingual axial wall. E, Lingual chamfer.

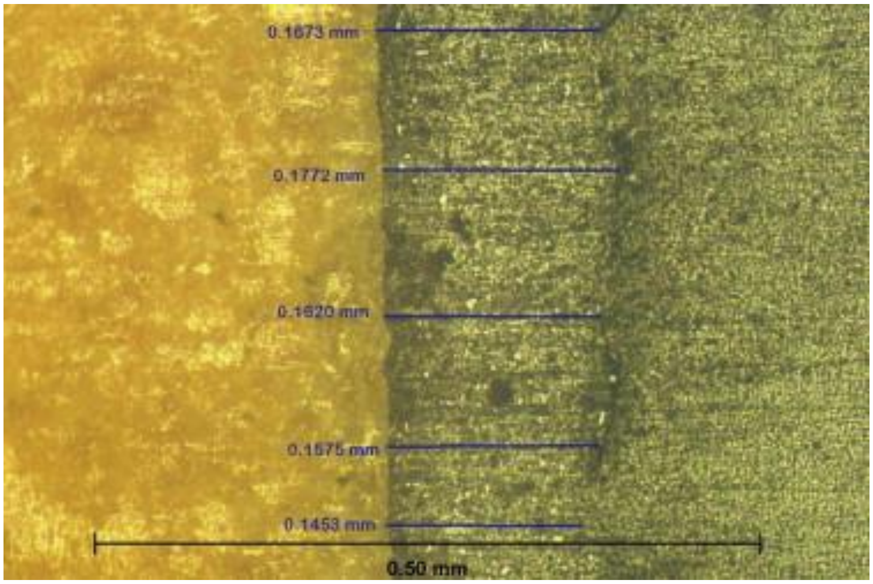

Figure 3. Microscope image at ×100 magnification. Indicated are die stone (I), cement layer (II), and resin coping (III).

Accuracy was evaluated with mixed model statistical analyses with correlated errors (α=.05). Mixed models were performed for each die spacer thickness level. The paired measurements at the 5 locations per specimen were added as random effect, and the 5 measurements per specimen were treated as repeated measurements within the mixed models to account for correlation within the specimens. The mean of the 5 locations was compared with the mean of the null hypothesis. The false discovery rate at 5% was used as a follow-up statistical analysis to adjust for the multiple testing. The coefficient of variation (CV) was adopted to determine the precision of the measurements for each group. This measure was defined as the ratio of the standard deviation to the mean multiplied by 100%. A low CV indicates high precision. Ten percent of CV has been widely used as cutoff to define high precision.[30, 31 and 32] The Wald test was used to evaluate whether the CV is equal to 10% at a statistical significant level of α=.05.[38] All statistical analyses were performed with software (SAS v9.3; SAS Institute Inc).

Results

Table 1 summarizes the mean internal gap measurements for the 5 groups along with their corresponding mean differences. A positive value indicates that the internal gap value was greater than the prescribed die spacer thickness. A negative value indicates that the internal gap value was smaller than the prescribed die spacer thickness. The differences were statistically significant for groups of 25 µm, 45 µm, 65 µm, and 105 µm with adjusted *P* value based on a false discovery rate of <.05. However, the 85 µm group was not statistically significant, with an adjusted *P* value of .329.

Table 1. Statistical analysis of accuracy for 5 groups with mixed models

Group	Mean Measured (µm)	Mean Difference (µm)	SD	*P* (α=.05)	Adjusted *P* Value Based on FDR (.05)
25 µm	75	50	11	<.001	<.001
45 µm	75	30	10	<.001	<.001
65 µm	79	14	14	<.001	<.001
85 µm	88	3	23	.329	.329
105 µm	95	-10	32	.008	.016

FDR, false discovery rate.

Table 2 summarizes the CV values for all 5 groups. The CV expressed in percentages ranged from 14% to 33%. Figure 4 shows the overall mean internal gap (average of the 5 locations) versus the prescribed die spacer thickness, and Figure 5 displays the measured internal gaps for each prescribed die spacer thickness setting for the 5 locations. A marked deviation from the predicted results (red line) is apparent.

Table 2. CV of each group with Wald statistical analysis significance level to compare CV to 10%

Group	CV (%)	*P* Value From Wald Test	Adjusted *P* Value Based on FDR (α=.05)
25 µm	14	<.001	<.001
45 µm	14	<.001	<.001
65 µm	18	<.001	<.001
85 µm	27	<.001	<.001
105 µm	33	<.001	<.001

FDR, false discovery rate; CV, coefficient of variance.

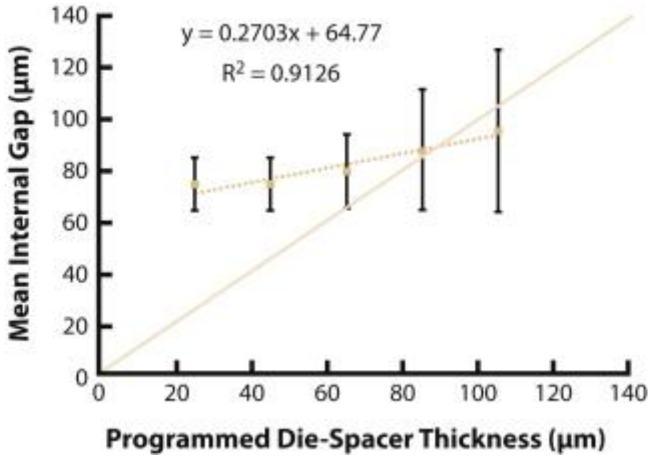

Figure 4. Scatter graph of measured means for each group and standard deviations. Trend line equation and R^2 value. Dotted line represents trend line of measured values. Solid line represents prescribed die spacer thickness.

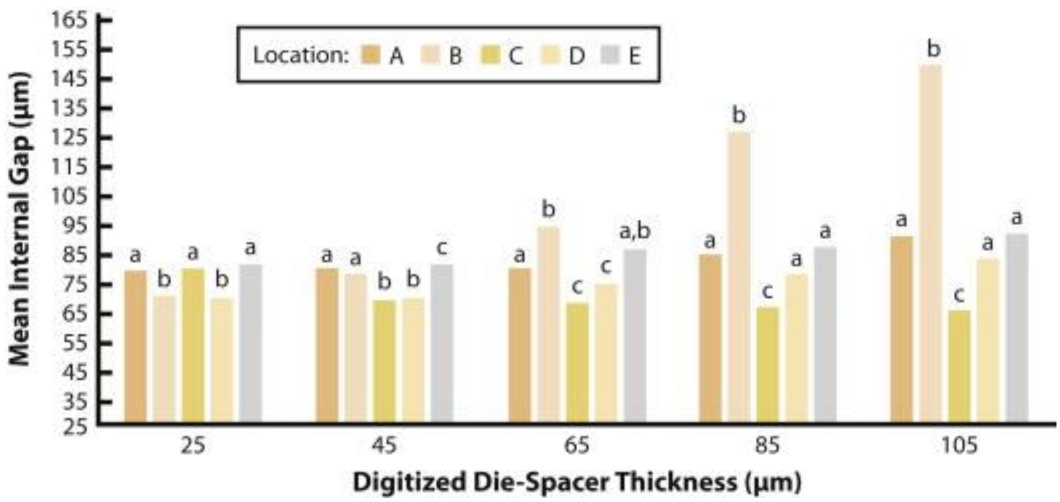

Figure 5. Bar graph indicating accuracy of simulated die spacer thickness of different locations for all 5 groups. Within each group, same letter represents no statistically significant difference (*P*>.05).

Discussion

The primary purpose of this study was to evaluate the accuracy of the CAD/3DPT system. The overall statistical analyses rejected the accuracy null hypothesis of no difference for the groups of 25 µm, 45 µm, 65 µm, and 105 µm that were assessed (Table 1). This study indicated that the prescribed die spacer thickness values differed from the measured internal gaps of the resin copings manufactured by 3DPT for all groups, except for the group of 85 µm. Thus, accuracy was achieved for the combination of CAD/3DPT at 85 µm. However, the

CAD/3DPT system was unable to produce the same die spacer thickness for the groups of 25 μm, 45 μm, 65 μm, and 105 μm.

The average internal gaps obtained from CAD/milling technology have been previously investigated. Kokubo et al[23] investigated the internal gaps of 82 In-Ceram crowns produced by CAD/milling technology where the programmed die spacer thickness was set at 50 μm. The average measured internal gaps obtained ranged from 165.9 to 200.3 μm, which were 3 to 4 times greater than the programmed die spacer thickness. Moldovan et al[24] reported on the internal gap of zirconia copings produced by CAD/Cercon and CAD/Cerec technologies. The programmed die spacer thickness for CAD/Cercon was 10 to 20 μm and CAD/Cerec was -100 μm; the average internal gaps obtained were 100 to 130 μm for CAD/Cercon and 60 to 70 μm for CAD/Cerec. In contrast, Bhaskaran et al[26] reported on the marginal and internal gap of Co-Cr copings cast from 3D printed resin patterns to be 27.22 μm and 36.15 μm. In this study, the mean measured internal gaps of the group of 25 μm was 3 times greater than the programmed die spacer thickness value (25 μm). Clinically, the thicker and nonuniform internal gaps will negatively affect the fracture strength of the ceramic crown. According to Tuntiprawon and Wilson,[15] ceramic crowns displayed a greater fracture strength when the mean internal gap at the axial wall was 73 μm.

From Figure 4, with the trend line equation at a setting where there is no die spacer thickness (0 μm) in the CAD system, the graph indicates that a 65 μm internal gap would still be expected. In addition, the trend line predicts that a measured die space of 25 μm would be achieved with a programmed value of -147 μm. The values of the internal gap observed for all the groups were above the clinically acceptable maximum value suggested by a previous study of 73 μm for a ceramic crown.[15] The mean cement film thickness for RelyX Unicem was confirmed to be 15 μm, which is less than the smallest prescribed die spacer thickness. Because the mean internal gap measured for all groups was greater than 70 μm, the influence of film thickness on incomplete seating for this experiment is unlikely.

The accuracy of the die spacer improved with larger prescribed die spacer thicknesses for locations A, D, and E. However, the mean internal gap at Location B (vertical location on the die) was consistently in the range 28 to 45 μm greater than the expected value (Fig. 5). This phenomenon might have been caused by an increased fit discrepancy between the coping and the die at the vertical location. Because of the straight and vertical shape of Location B, coping deviation during loading would be anticipated, resulting in an increase in the internal gap. The opposite was observed for Location C, where the value of the internal gap decreased as the programed die spacer thickness increased. A greater programed die spacer thickness might have prevented the seating interference at the occlusal-axial line angle, leading to a better seated coping at the incisal portion, Location C.

Precision, expressed as the CV as a percentage, was used to determine the reproducibility of the internal gaps. A large CV value indicates low precision. Overall, the precision for all groups in this study was within the range of 14% to 33%. Because a precision value less than 10% is considered reasonable,[30] the precision of the CAD/3DPT combination used in this study was low (Table 2). Campagni et al[13] reported on the precision of manually applying 2 to 6 layers of Tru-Fit die spacer material in terms of the coefficient of variation expressed as a percentage. The coefficient of variation ranged from 25.6% for 6 layers to 53.2% for 2 layers. Therefore, this CAD/3DPT combination was able to achieve better precision than the manual method.

This research has several limitations with respect to the measurement location, material, and technology used. Errors may have occurred in any step of the process chain, starting from impression making and the generation of die-stone models to the scanning process and printing process. Also, only 50 measurements per specimen were obtained in this study,[37] and the measurements obtained were specific to this software/hardware combination (CAD and 3DPT). The results may not be applicable to other software/hardware combinations. Thus, further studies will be needed to investigate the accuracy and precision of other comparative technologies. In the future, other advanced technologies with improved accuracy will be available for both the scanning and printing systems.

Conclusions

Within the limitation of the study, for the accuracy evaluation, the programmed die spacer thickness reproduction of CAD/3DPT showed statistically significant differences for all the groups except the group of 85 µm. For the precision evaluation, the CV of measurements obtained for all the groups was above 10%, showing the printer's inability to reproduce the uniform internal gap in the same group.

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