# Positional Trueness with Different Titanium Base Bonding Techniques for Single Implant Crowns: In Vitro Evaluation of Model-Free Workflow Versus Additively Manufactured Models

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***Objectives:*** To compare the positional trueness of implant-crown bonding to titanium bases (Ti-bases) using different bonding protocols. ***Materials and Methods:*** A nonprecious alloy model with a single implant at the mandibular right first molar site was digitized, then a single implant crown was designed. The crown was milled, adhesively cemented on a Ti-base, and screw-retained on the implant in the master model to obtain a reference scan. Forty PMMA implant crowns were subtractively manufactured and allocated to one of four study groups (n = 10 crowns per group) based on the bonding protocol on Ti-bases: Group 1 = model-free bonding; Group 2 = bonding on the master model (control); Group 3 = bonding on a model from an industrial-grade 3D printer (Prodways); Group 4 = bonding on a model from a conventional 3D printer (Asiga). To assess the positional trueness of crowns, the scans of crowns when on the model were superimposed over the reference scan. Median distance and angular deviations were analyzed using Kruskal-Wallis and Mann-Whitney tests ($\alpha$ = .05). Mesial and distal contacts of crowns were assessed by two independent clinicians. ***Results:*** The control group (Group 2) resulted in the smallest distance deviations (0.30 ± 0.03 mm) compared to model-free (0.35 ± 0.02 mm; *P* = .002; Group 1) and conventional 3D printer (0.37 ± 0.01 mm; *P* = .001; Group 4) workflows. Buccolingual (*P* = .002) and mesiodistal (*P* = .01) angular deviations were higher in the conventional 3D printer group than in the control group (*P* = .002). Proximal contact assessments did not show any differences among groups. ***Conclusions:*** While bonding crowns to Ti-bases on a master model created with an industrial-grade 3D printer resulted in the highest positional trueness, model-free workflows had a similar positional trueness to those manufactured with a conventional 3D printer. *Int J Prosthodont 2024;37(suppl):s265–s273. doi: 10.11607/ijp.8896*

The use of digital workflows in implant prosthetic patient care is steadily increasing.[1–4] CAD/CAM technologies based on digital intraoral impressions using intraoral scanners have proven to be particularly effective in implant dentistry.[5] The digital process for the fabrication of tooth- or implant-supported single crowns appears to be similar or even superior in precision to the conventional method of taking an impression with a precision material and then fabricating the prosthesis on a plaster model.[6,7] This digital workflow has further advantages, such as increased

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patient comfort and reduced costs due to time savings in the dental laboratory.[8–10]

The fabrication of implant-supported single crowns, irrespective of the impression type, mostly takes place utilizing CAD/CAM technology. Several studies have compared conventional and optical impression techniques for single tooth–- or implant-supported restorations and found that digital impressions showed similar accuracy and working time compared to conventional impression-taking.[2,5–7,9] Manufacturing an implant restoration using a laboratory milling unit is based either on an intraoral scan or a digitized plaster model. Both approaches have been demonstrated as valid and reliable options.[11,12] Nonetheless, differences in the fitting time of conventionally and digitally fabricated implant single crowns have been reported.[9] An explanation for this issue may be inaccuracies in model fabrication. Additively manufactured models are subject to significant variations in their accuracy, which depend on several factors, such as the material used, the 3D printer, or even the model's storage conditions after fabrication.[13–16] Another influencing factor is the precision in positioning the implant analog in resin models, as discussed by Mata-Mata et al.[17] Therefore, the suitability of additively manufactured models as a control for adjusting proximal and occlusal contacts or bonding implant crowns seems questionable.[13–16] A critical factor that can significantly influence the trueness of the final crown is one of the few remaining manual steps in the digital workflow: the bonding of the crown to a titanium base (Ti-base). Many dental technicians prefer to perform the bonding on a haptic model, usually produced additively in the digital workflow using 3D printing. This model allows the crown's position to be evaluated during bonding. However, as reported above, the accuracy of additively manufactured models and the positioning of the implant analogs is questionable. One potential solution to this issue is bonding the crowns to the Ti-bases without using a model. The absence of a haptic model prevents a detailed quality evaluation by the dental technician. Nevertheless, it reduces costs, increases time efficiency, and decreases the waste that 3D printing involves.[18–20] The present study aimed to evaluate the positional trueness of implant crowns bonded to Ti-bases model-free vs that of implant crowns bonded to Ti-bases on additively manufactured models. To the present authors' knowledge, no study has done this comparison before. The following hypotheses were proposed for the present study: *(1)* The positional trueness of implant crowns bonded to Ti-bases without a model on additively manufactured models vs the master model would not differ (H01); and *(2)* the proximal contacts of implant crowns bonded to Ti-bases without a model would not differ from those bonded to Ti-bases on additively manufactured models or the master model (H02).

## MATERIALS AND METHODS

### Fabrication of the Master Model

The study outline is presented in Fig 1.

An overview of the model situation of a missing mandibular right first molar (position 46; FDI numbering system) to be replaced with an implant-supported single crown served as the initial situation for the present study. The metal master model was digitized using a laboratory scanner (S600 ARTI, Zirkonzahn) with 10-µm accuracy. Scan powder (Zirko Scanspray, Zirkonzahn) on the master model was used to avoid mismatch or stitching errors caused by scattered light from the shiny metallic surface. The implant in position 46 (Tissue Level 4.1-mm RN, Straumann) was scanned using the corresponding scan body (CARES Mono Scanbody, Straumann). The implant had an internal butt connection with an engaging Ti-base. The implant neck was positioned 0.5 mm submucosally with a palatal inspection window to visually control the seating of the implant components on the implant. The digitized situation based on the typodont model data with the above-described situation (STL file) was then converted into a haptic model (Fig 2) out of a nonprecious metal alloy using a high-precision industrial milling unit (DC7, Dental Concept System). This haptic master model was the reference for subsequent experiments.

### Data Acquisition and Crown Manufacturing

Based on the scan with the scan body, an implant-supported provisional crown was digitally designed (CAD) and then computer-controlled milled (CAM) from a polymethyl methacrylate (PMMA) resin block (Temp Premium, Zirkonzahn) by using a laboratory milling unit (M1, Zirkonzahn). On the reference model, the crown was bonded to a Ti-base (Variobase, Straumann). Subsequently, mesial and distal proximal contacts were evaluated using dental floss, and the crown margin fit on the Ti-base using magnifying glasses with ×3.5 magnification. If one of the proximal contacts was too light, tight, or absent, the digital crown design was adjusted until the appropriate design was found. After five board-certified prosthodontists (S.A.A.) agreed on the tightness of the proximal contacts, the resulting design was used as the master design. Then, 40 crowns were fabricated according to the master design using a CAM milling unit (Milling Unit M1, Zirkonzahn). After every 10 crowns, the milling burs were replaced with new ones.

These 40 PMMA implant crowns were then allocated to one of four study groups (n = 10 crowns per group) based on the bonding protocol on Ti-bases: Group 1 = model-free bonding; Group 2 = bonding on the master model (control); Group 3 = bonding on a model from an industrial-grade 3D printer (Prodways); Group 4 = bonding on a model from a conventional 3D printer (Asiga).

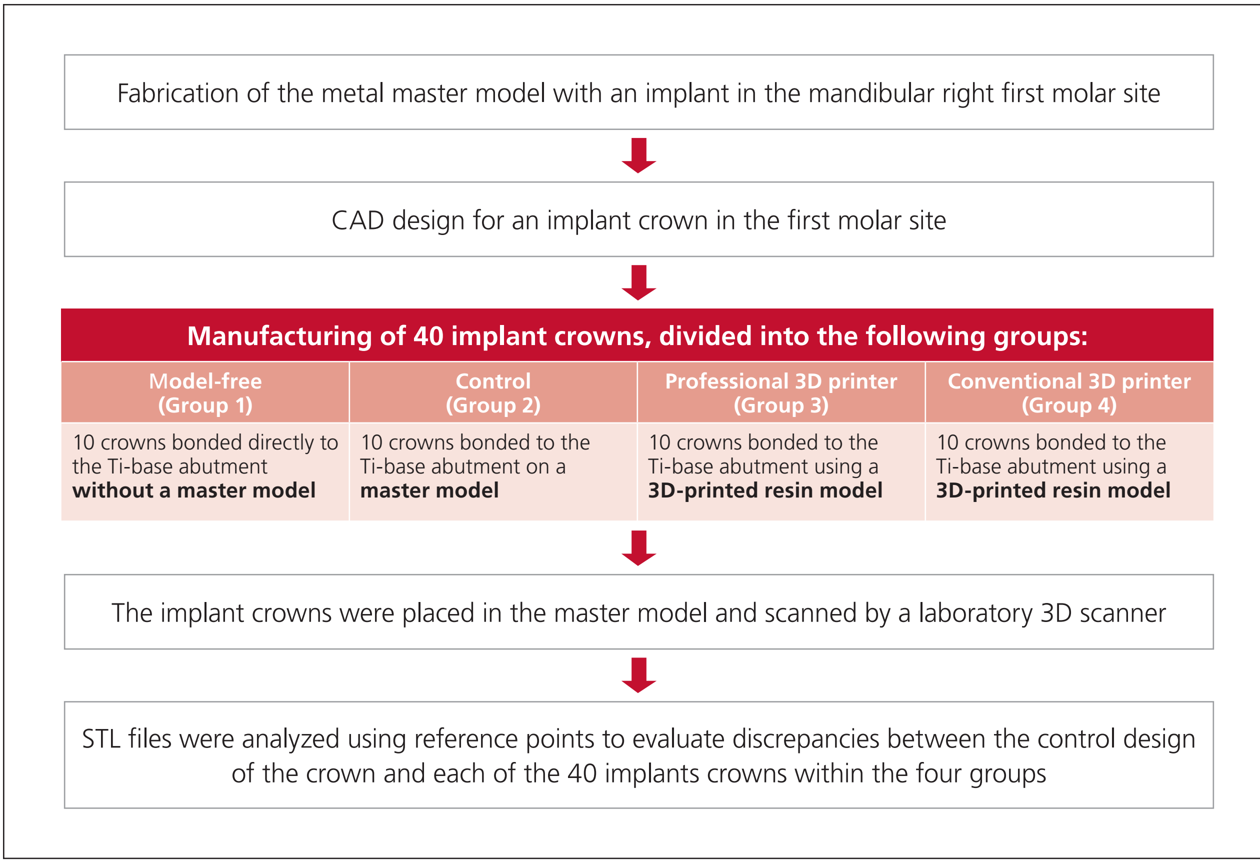


**Fig 1** Outline of the study design.

### Bonding Model Manufacturing

Twenty resin bonding models, each with an RN manipulation implant (Tissue Level 4.1-mm RN, Straumann) in position 46, were produced; 10 were produced with an industrial-grade 3D printer (ProMaker L5000, Prodways Machines) used primarily in large CAD/CAM centers (Group 3), and the other 10 were produced with a mid-priced 3D printer commonly used in dental laboratories (MAX UV, 385 nm, Asiga; Group 4). The postprocessing protocols of both manufacturers were followed. Both printers used the compatible premium resin available at the start of the trials to produce digital models.

**Fig 2** Outline of the study design. Metal master model of the situation based on an STL-file.

### Sample Preparation

In each group, 10 crowns were bonded to the Ti-bases (Variobase for Crown, Straumann). In Group 1, the provisional crowns were directly bonded to the Ti-bases in a model-free workflow using reference points and anti-rotational carvings on the milled crown and the Ti-base. In Groups 3 and 4, the provisional crowns were bonded to the Ti-bases on models manufactured by the industrial-grade 3D printer (Group 3) or the conventional laboratory 3D printer (Group 4). In the control group (Group 2), the bonding was carried out directly on the nonprecious alloy model. Before bonding the provisional crowns on Ti-bases, the Ti-bases were tightened on the implants with 35-Ncm torque using a mechanical torque limiting device. All crowns were bonded to the Ti-bases by the same master dental technician using the same bonding system (Multilink Hybrid Abutment, Ivoclar Vivadent). Then, all bonded implant crowns were tightened onto the implant in a nonprecious metal alloy model, one at a time, in a torque-controlled manner,

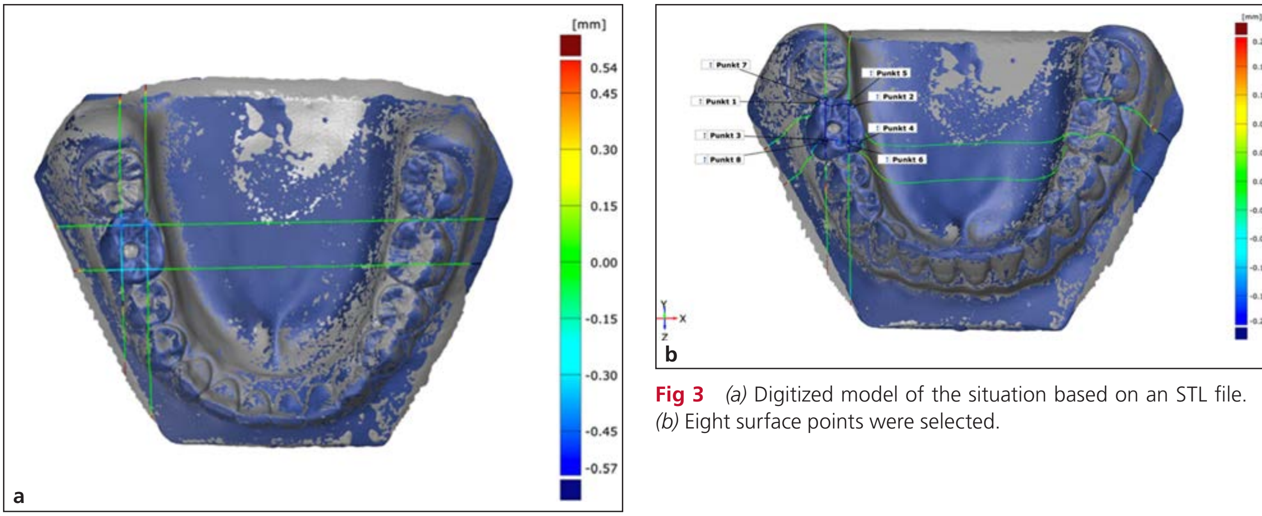


**Fig 3** *(a)* Digitized model of the situation based on an STL file. *(b)* Eight surface points were selected.

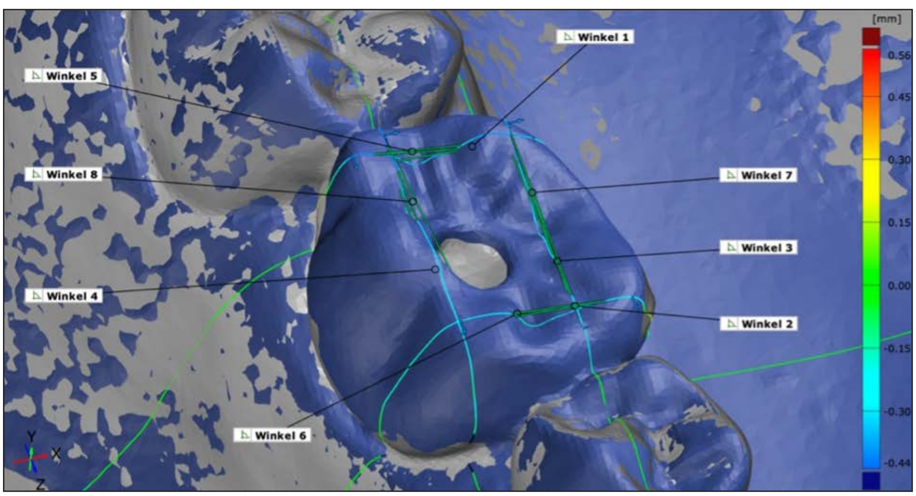


**Fig 4** Eight selected angles in the buccolingual and mesiodistal directions.

then digitized with a laboratory scanner (S600 ARTI) using contrast powder (Zirko Scanspray) to optimize the surface scams.[21] To determine the positional trueness, all digital models of each test group (n = 40) were superimposed onto the digital reference model, using the pre-alignment tool from the software (GOM Inspect, Metiris), followed by a local best-fit algorithm. For the best-fit alignment, surface data of the provisional crown were excluded (Fig 3).

On the reference model, eight surface points were determined (four on the x-plane, four on the z-plane) on the provisional crown's occlusal surface, and the coordinate data were saved, ensuring the use of identical points for future comparisons. The mean root mean square deviation between the reference and the test models was calculated based on the deviations at the eight defined surface points. In addition, the deviations of the buccolingual and mesiodistal angles were measured between the test and reference model in the x- and z-planes using lines between the chosen reference points (Fig 4).

Subsequently, all crowns were coded with a number for blinded evaluation of the proximal contacts. The quality of the proximal contact was evaluated by two board-certified prosthodontists, who were blinded to the crowns' study group allocation. First, the crown fabricated for the digital reference model was screwed on with a torque of 35 Ncm. Subsequently, the proximal contacts were evaluated with dental floss (Pro-Expert, Oral-B) with a width of 0.3 to 0.5 mm, providing guidelines for the subsequent examinations. Then, each crown was tightened onto the implant in the reference model with the same torque, and the proximal contacts were evaluated with the dental floss. The examiners evaluated the proximal contacts using a five-point numerical rating scale: –2 = proximal contact not present; –1 = proximal contact present but too light; 0 = proximal contact corresponds to that of the reference; +1 = proximal contact present but tight; +2 = proximal contact too tight and the dental floss tears. Both examiners evaluated the quality of the mesial and distal proximal contacts of the implant crowns separately.

**Table 1** Descriptive Values of 3D Deviations by Model Type

| Group | Median | Minimum | Maximum | Mean | SD |
|---|---|---|---|---|---|
| Model-free | 0.36 mm | 0.31 mm | 0.38 mm | 0.35 mm | 0.02 mm |
| Conventional 3D printer | 0.37 mm | 0.34 mm | 0.38 mm | 0.37 mm | 0.01 mm |
| Industrial 3D printer | 0.33 mm | 0.29 mm | 0.40 mm | 0.33 mm | 0.04 mm |
| Control | 0.30 mm | 0.26 mm | 0.34 mm | 0.30 mm | 0.03 mm |

For the primary outcome (trueness), a sample size calculation was conducted based on a previous study that analyzed the accuracy of 3D-printed single implant crown master casts.[14] For the model-free workflow, the median deviations were estimated (100 ± 33 µm). There was no closed power function for the tests, so the power was approximated using 2,000 simulations. Finally, the power analysis was performed using four scenarios to account for possible distribution assumptions: *(1)* the data follow a normal distribution, and the variance homogeneity between the groups is given; *(2)* the data follow a Student *t* distribution, and the variance homogeneity between the groups is given; *(3)* assumption: the data follow a normal distribution, and the variance homogeneity between the groups is not given; and *(4)* assumption: the data follow a Student *t* distribution, and the variance homogeneity between the groups is not given. Ten specimens per group resulted in a power of 99.9% to detect differences among the groups for all scenarios, with an alpha set to .05.

### Statistical Analysis

All analyses were performed with R statistics software (version 4.1.0). Descriptive data were summarized using median, minimum, maximum, mean and SD values and by showing boxplots and tables.

Kruskal-Wallis tests were performed to determine whether deviation outcomes and contact scores in the four experimental groups differ significantly on an overall scale. If Kruskal-Wallis test was significant, pairwise comparisons were made post hoc using Mann-Whitney test.

$P < .05$ was considered statistically significant. *P* values of all post hoc tests were corrected using the Holm method. Post hoc *P* values presented in text, tables, and figures are all after correction. Further, for the contact point analysis, exact 95% CIs for the median score were groupwise and clinician-wise calculated (binomial method) to assess whether scores significantly differ from 0. The reliability between the two clinicians was assessed using weighted kappa values.

## RESULTS

### Trueness

The smallest distance deviations were found in Group 2, while deviations were highest in Group 4 (Table 1). Significant differences were found in the global comparison of all study groups ($P = .0002$). Pairwise post hoc tests revealed significant differences between Group 1 and Group 3 ($P = .002$) and between Group 2 and Group 4 ($P = .001$), with the former showing smaller deviations. Other comparisons did not show significant differences (Fig 5).

Global testing of angular deviations showed significant differences for buccolingual deviations ($P = .005$, Fig 6) and mesiodistal deviations (P = .001, Fig 7). Post hoc tests revealed higher buccolingual angular deviations in crowns bonded to Ti-bases in Group 4 (2.58 ± 0.22 degrees) compared to Group 2 (1.99 ± 0.39 degrees; $P = .002$). Mesiodistal angular deviations were significantly higher in Group 1 (2.62 ± 0.26 degrees; $P = .01$) and Group 4 (2.66 ± 0.28 degree; $P = .01$) compared to Group 2 (2.03 ± 0.29 degrees). Other comparisons did not show significant differences.

### Mesial and Distal Contact Scores

For the mesial contact scores, median values were 0 in all groups (Table 2). The kappa score was 0.92, indicating an excellent interrater agreement. No significant difference among all four groups (global test) were found for the first ($P = .13$) and for the second ($P = .16$) clinician. Thus, no post hoc tests were performed.

Regarding the distal contact scores (Table 2), the clinicians' ratings resulted in identical median scores for all groups, with the lowest rating seen in Group 3 (median: –1.5) and the best rating for Group 1 (median: 0). None of the median scores were significantly different from 0 (all $P > .05$). Reliability between the two clinicians resulted in a kappa of 0.67, indicating a good agreement. The global test revealed no significant differences between all four groups for the second clinician ($P = .08$), but a significant difference in the global test was found for the first clinician's ratings ($P = .04$). However, post hoc tests failed to detect significant differences between model types.

## DISCUSSION

The present study evaluated positional trueness of single implant crowns bonded to Ti-bases using model-free and model-based workflows. The first null hypothesis (H01) was rejected due to significant differences in 3D

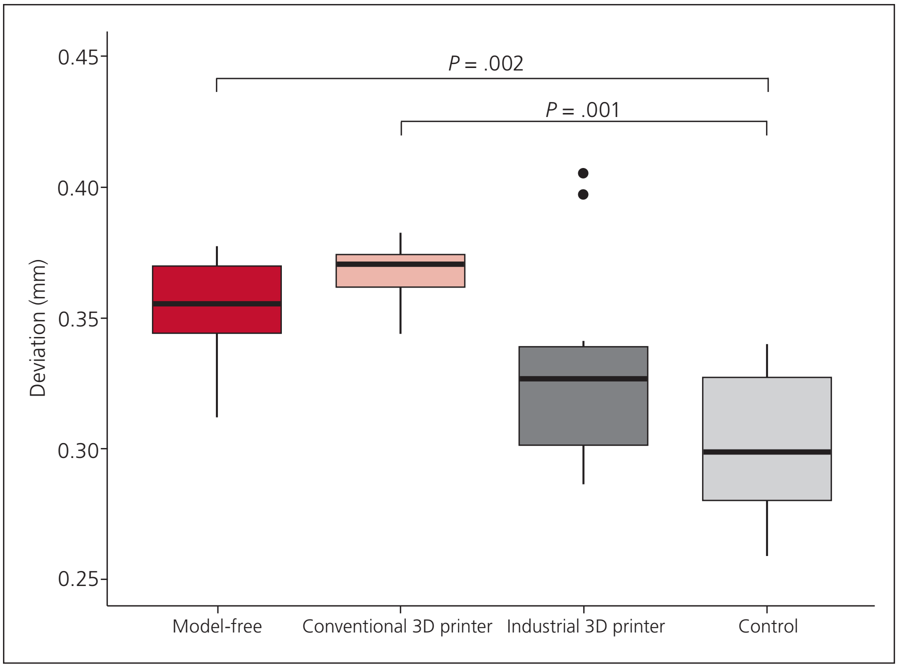


**Fig 5** Boxplot of mean deviations by workflow type. Post hoc–corrected *P* values (Mann-Whitney test) are shown for groups with significantly different outcomes.

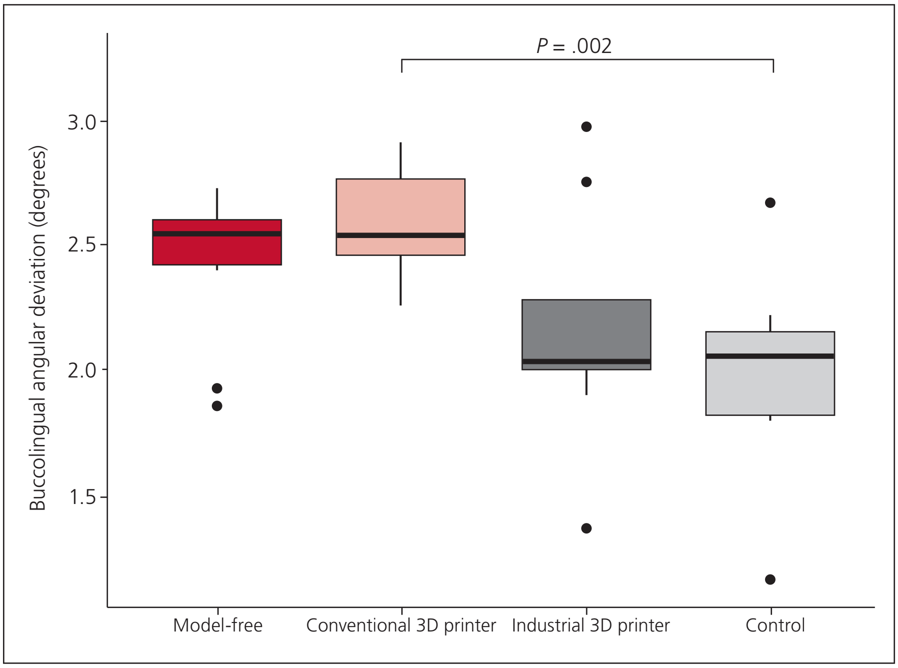


**Fig 6** Boxplot of buccolingual angular deviations by workflow type. Post hoc–corrected *P* values (Mann-Whitney test) are shown for groups with significantly different outcomes.

point and angular deviations between the study groups. No statistically significant differences were found in the proximal contact scores of implant crowns in the different groups, and therefore, the second null-hypothesis (H02) was accepted.

Significant statistical differences were observed between the model-free and the industrial 3D printer (Groups 1 and 3, respectively) and between the conventional 3D printer and control groups (Groups 4 and 2, respectively). The positional trueness evaluation showed that an industrial-grade 3D printer improved the trueness by 0.06 mm. Nevertheless, most dental labs working with 3D models are manufacturing their models using a conventional 3D printer instead of an industrial grade one because of the industrial 3D printers' high costs. For this reason, the comparison between the model-free and conventional 3D printer groups were of particular interest in the present study. The comparison of the

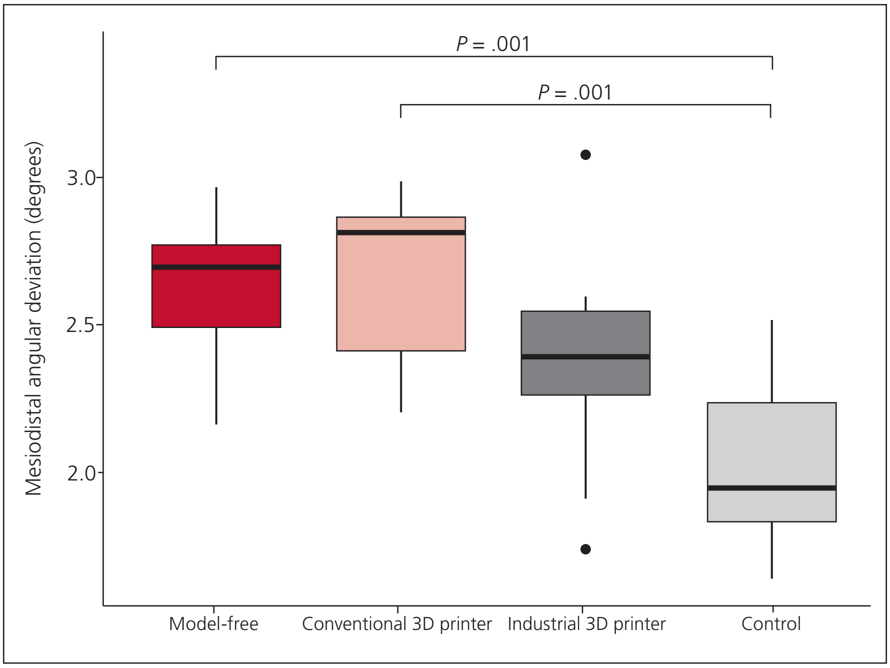


**Fig 7** Boxplot of mesiodistal angular deviations by workflow type. Post hoc–corrected *P* values (Mann-Whitney test) are shown for groups with significantly different outcomes.

**Table 2** Median Mesial and Distal Contact Scores per Clinician

| | Mesial contact score | | Distal contact score | |
|---|---|---|---|---|
| Model | Clinician 1 | Clinician 2 | Clinician 1 | Clinician 2 |
| Model-free | 0 (0 to 0) | 0 (0 to 0) | 0 (–1 to 0) | 0 (–1 to 0) |
| Conventional 3D printer | 0 (0 to 1) | 0 (0 to 1) | –1 (–1 to 0) | –1 (–1 to 0) |
| Industrial 3D printer | 0 (–1 to 0) | 0 (–1 to 0) | –1.5 (–2 to 0) | –1.5 (–2 to 0) |
| Control | 0 (–1 to 1) | 0 (–1 to 0) | –1 (–1 to 0) | –1 (–1 to 0) |

The examiners evaluated the proximal contacts using a five-point numerical rating scale: –2 = proximal contact not present; –1 = proximal contact present but too light; 0 = proximal contact corresponds to that of the reference; +1 = proximal contact present but tight; +2 = proximal contact too tight and the dental floss tears.
Data are presented as median (range). Median values did not significantly differ, indicating a good agreement and reliability between both calibrated clinicians.

trueness between model-free bonded implant crowns vs bonding using a resin model printed by a conventional 3D printer was not statistically significant. These findings suggest that resin models fabricated with a conventional 3D printer do not provide a more accurate workflow for bonding implant crowns to Ti-bases.

As mentioned above, an improved trueness (0.06 mm) was seen when using an industrial-grade 3D printer compared to the model-free method. Here, the present authors leave it to the readers' opinion to judge how relevant 0.06 mm is in clinical practice. Normally, when delivering an implant crown, minor intraoral adjustments are often needed (eg, due to the periodontal mobility of the teeth adjacent to an implant crown).[22] Further, additively manufactured resin models are subject to variations in trueness, affecting the single implant crown's fit on the control model.[13–16] Despite the statistical significance and all of the factors affecting the trueness of implant restorations, it could be stated that all methods (model-free, conventional, or industrial printer) may be used to fabricate implant crowns with positional trueness.

Several authors have assessed the accuracy of restorations fabricated using a digital workflow.[6,7,23] For instance, some studies have compared the internal and marginal fit of crowns manufactured using a conventional and digital workflow, and Benic et al reported a 30- to 40-μm deviation in tooth-retained crowns.[23] The theory for the cause of minor misfits is a slight deviation in the implant analog position within the resin model.[24] Rödiger et al compared the marginal fit of tooth-retained zirconia crowns, comparing a conventional vs digital impressions in a clinical setting. No statistically significant differences between groups were found, and it was concluded that both impression techniques offered marginal and internal precision.[7] Nejatidanesh et al used a similar study design in implant crowns and reported clinically acceptable marginal and internal fit of the materials (zirconia, lithium disilicate and metal-ceramic) and reported better fit with CAD/CAM restorations as compared to the conventional workflow.[6] Regarding model fabrication, Rungrojwittayakul et al evaluated the liquid interface production and digital light processing and found a small difference in accuracy between two resin model manufacturing processes, but no loss in precision was reported.[13]

Regarding the angular deviations, both the model-free and conventional 3D printer groups in the present study had higher values than the industrial 3D printer and control groups. Interestingly, when comparing the buccolingual angles, the model-free and conventional 3D printer groups had similar values, but the mesiodistal angles were evaluated, the control group stands out with the slightest deviation. This may be explained by the fact that crowns bonded to Ti-bases using the control model have a higher positional trueness. Mata-Mata et al confirmed that the position of the analog in the model is another factor affecting the trueness of a final implant restoration.[17]

In the present study, the quality of the two groups using 3D-printed models was measured by assessing the proximal contacts of the implant crowns. There were no effects on the clinically measured proximal contacts regardless of the bonding protocol. The implant crowns bonded on an industrial 3D printer's model showed slightly better distal proximal contact scores. The data indicates that the difference in the precision of both resin-model manufacturing processes can influence the quality of the proximal contact due to small differences in the implant analog position inside the resin models as well as slight differences in the printing quality of the mesial surface of the distal tooth 47. Nevertheless, no comparison between the groups was statistically significant; both groups with 3D-printed resin models performed similarly. These results are in line with a study by Rungrojwittayakul et al, which found high model-fabrication precision in the manufacturing process of the resin model, as mentioned earlier.[13] A study by Pan et al also evaluated the quality of crown production by observing the quality of proximal contacts, and it was found that adjustments were required by crowns manufactured using a conventional and fully digital workflow.[20] Considering the lighter distal, proximal contacts, a probable cause could be the error summation due to more stages throughout the production workflow, and also deviations in precision during manufacturing, to which additively fabricated models subject.[13–16] In addition to the manufacturing of the resin models, the additional implant crown adjustments (eg, polishing or removing minor excess material) may be possible sources for mistakes. The results of the two examiners in the present study were in good agreement, showing that the quality of proximal contacts was consistent.

The data collection using GOM Inspect software and the definition of measurement points, planes, and angles was as accurate as the data set allowed. This software has already been used in several studies as a precise measuring tool and is characterized by its reliability and reproducibility of data.[25] Another important methodologic aspect of the present study is the deviations during the milling, which may produce inaccuracies in crown manufacturing. To counteract this issue, the milling burs were changed every 10 crowns. The use of a nonprecious alloy model may be questioned, but these model types were recommended for master models in in vitro studies due to their wear resistance based on the material hardness.[26]

The results of the present study showed that implant crowns bonded to a Ti-base without a model were as accurate as when models from a conventional 3D printer were used, questioning the need to create a model for manufacturing single posterior implant crowns. Although the positional trueness of model-free bonded implant crowns is satisfactory, there was a statistically significant difference when compared to the control group and to the industrial 3D printer group. The findings of this study are interesting, but they should be treated with caution, as there are limitations to consider; for example, just one implant system and one material were evaluated, and an occlusal contact assessment was not implemented in the study design. Further implant systems—including different implant-abutment connections, dental materials manufactured with different methods, and other bonding techniques—should also be investigated. Finally, the findings of this in vitro study should be confirmed with clinical studies that assess the precision, reproducibility, and accuracy of the digital model-free workflow.

## CONCLUSIONS

Considering the limitations of the present in vitro study, single implant crowns bonded to Ti-bases without a model had positional trueness similar to those bonded to Ti-bases on a model manufactured with a conventional 3D printer. For bonding a single implant crown to a Ti-base, models from a conventional 3D printer may be omitted, reducing costs, time, and waste in the dental laboratory.

## ACKNOWLEDGMENTS

The authors declare no conflicts of interest.

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