Accuracy of Dental Restorations Fabricated Using Milling vs 3D-Printed Molds: A Pilot Study

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Purpose: To compare the accuracy of 12 different dental restorations fabricated with milling or 3D-printed molds and robotically controlled casting. ***Materials and Methods:*** Twelve dental restorations (11 inlays and onlays and 1 crown) were made per restoration type, one per each of the 12 different teeth models (total of 24 restorations). On each tooth preparation, two restorations were manufactured using different CAD/CAM techniques: *(1)* milling and *(2)* robotically controlled casting and 3D-printed molds. In addition, two-layer restorations were manufactured with 3D-printed molds. The marginal and internal gaps were evaluated at 120 points per restoration based on micro-CT 3D imaging. Internal gaps were evaluated using a replica technique with silicone. ***Results:*** Median values (interquartile ranges) for marginal gaps, middle internal gaps, and central internal gaps were significantly lower for 3D-printed mold restorations (44.3 [65.4] μm, 95.4 [96.2] μm, and 104.6 [78.1] μm) compared to milled restorations (58.4 [93] μm, 145.9 [85.8] μm, and 138.6 [65.7] μm). Internal gaps in the 3D-printed mold group were 6% to 51% smaller than in the milled group. ***Conclusions:*** The accuracy of restorations fabricated with 3D-printed molds may be preferable compared to milled restorations, except in the case of crown restoration. However, additional studies with a larger number of samples and different types of restorations are needed to confirm the results. *Int J Prosthodont 2024;37(suppl):s79–s88. doi: 10.11607/ijp.8236*

In developed countries, direct composite resin fillings are the most frequently used material in dental posterior lesions.[1] Composite resins consist of fillers (eg, bisphenol-A-glycidyl dimethacrylate) and other dimethacrylate monomers, which are converted into solid polymers during operation by additional polymerization.[2] These composite resins provide better esthetics than metal alloys, are easily repairable, and can be bonded to tooth tissues.[3] Polymerization shrinkage remains a major disadvantage of composite resin fillings, which causes stress to the filling material and to the bonded defect walls and may lead to marginal leakage, discoloration, and sensitivity.[4–6] Volumetric shrinkage values between 1.08% and 4.68% are reported.[7–9] The main reasons for their failures in posterior regions are fractures and caries.[10,11] For more

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complex indirect restorations, ceramic or metal-ceramic materials are often indicated. Compared to direct fillings, indirect restorations involve more invasive tooth preparation and higher material costs.[12] Providing good esthetics, durability, and competitive cost-benefit ratios are the future challenges for the development of dental restoration materials.

Today, minimally invasive treatment options combined with adhesive techniques provide a solution for conventional prosthodontic treatment methods using metal-free materials.[13] Additive manufacturing, also called 3D-printing technology could be a solution for cost-effectively manufacturing precisely fitting dental restorations. For this technology, successive layers of material are deposited under computer control to create an object layer by layer, based on a computer-aided design (CAD).[14,15] The 3D printing process is either direct or indirect. Direct 3D printing means printing the object, while in indirect 3D printing, a mold is fabricated using the printer and the object is prepared using the mold.[16] Few studies have been published concerning 3D printing in the field of dental restorations manufacturing; lithium disilicate crowns are printed under laboratory conditions,[17] marginal accuracy of 3D-printed ceramic onlays is clinically acceptable,[18] but the fit of inlays produced from 3D-printed wax patterns is inferior compared to milling.[19] In contrast to subtractive CAD/CAM technology, the 3D printing process offers many benefits: Accuracy is not limited to the milling unit's machining tools, material loss is low, and complex structures can be produced from a variety of materials.[20] Based on the present literature, direct 3D printing is still challenging, partly due to the material demands.[21] Therefore, indirect 3D printing may be a viable option by fabricating dental restorations with molds corresponding the restoration and robotically controlled casting. With this technique, systematic errors in the restoration manufacturing process (such as polymerization shrinkage) can be compensated during the CAD process. Furthermore, this technique allows clinicians to optimize the roughness of the restoration's bonding surface and the use existing photocurable, chemically curable, or dual-curable restorative materials for indirect restorations. Generally, automated 3D-printed mold–fabricated restorations also provide good reproducibility, minimizing human errors, and the technique reduces dentists' challenging workload in large defects. Furthermore, 3D-printing technology might offer a solution for manufacturing bioinspired dental materials and restorations, which are challenging for conventional and subtractive techniques.[22]

Good accuracy improves the prognosis of an indirect restoration.[23] The *accuracy* of the restoration is defined as marginal and internal gaps between the restoration and tooth, with a smaller gap indicating higher accuracy. *Internal gap* describes the perpendicular distance from the restoration's internal surface to the axial tooth wall. The identical measurement at the restoration margin is the *marginal gap*.[24] Most investigators use McLean and von Fraunhofer's proposed values to determine a clinically acceptable marginal gap (≤ 120 mm).[25] Optimal gap values range between 25 and 40 mm, based on ISO standards and the Council on Dental Materials and Devices.[26–29]

The aim of the present study was to *(1)* evaluate the accuracy of 11 composite resin inlay and onlay restorations and a crown manufactured by a newly developed manufacturing technique with 3D-printed molds and robotically controlled casting and *(2)* compare their accuracy to milled restorations manufactured with a commercially available milling system, based on an in vitro experiment. The working hypothesis was that the accuracy of dental restorations fabricated with 3D-printed molds are at least as good as the accuracy of milled restorations.

MATERIALS AND METHODS

Twelve different inlay and onlay defects with different shapes and one crown were prepared on 12 model teeth (Frasaco). Restorations (Fig 1) were manufactured for each tooth using milling or 3D-printed molds and robotically controlled casting[30] (n = 12 per restoration type; n = 1 per restoration type and specific tooth defect).

Digital impressions were performed according to the manufacturer's guidelines of the defect and the adjacent and opposing dentition. Based on the hardware display screen, all details of the defects were clearly captured. The digital impressions for the milled restorations were captured with an intraoral scanner (Emerald, Planmeca), the CAD process was carried out using design software (PlanCAD Easy, Planmeca), and restorations were milled using an in-lab milling unit (Planmill40, Planmeca) and hybrid ceramic blocks (Enamic, Vita). The digital impressions for the 3D-printed mold restorations were captured with a different intraoral scanner (Trios 4 Wireless, version 20.3.1, 3Shape) and designed in Trios Design Studio (3Shape). Restoration files were saved in STL file format, a standardized file format for 3D printing. The files were imported to a newly developed custom-design software (Mould Designer, 3DToothFill, Rayo 3D Biotech) where a mold was designed corresponding to the restoration. Figure 2 illustrates the software's different restoration preparation steps. The mold included two to three fine holes to prevent air pockets in the casting stage. Uniform (isotropic) 3% shrinkage compensation was considered in the mold design based on a separate set of dental fillings prepared for different defects. This shrinkage compensation provided a generally optimal fit in agreement with the typical shrinkage of polymer composite filling materials.[7–9]

A customized 3D printer (Inkspire with Z-Suite software version 2.15.1, Zortrax) was used to print out the

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Restoration no.	Type	Approximate width/ height/depth (mm)	Restoration form
1	Four-surface onlay	7/6.6/2.5	
2	MOD (mesio-occluso-distal)	3.5/8.5/2.8	
3	Three-surface onlay	3.8/8.2/2.5	
4	Approximal surface inlay	5.5/7.8/2.5	
5	Approximal surface inlay	4/7.1/1.6	
6	Approximal surface onlay	6.4/8.4/3	
7	Three-surface inlay	5.1/10/3.5	
8	Crown	1.2/1/1.2	
9	Three-surface onlay	7.7/9.8/3.7	
10	Approximal surface inlay	4.3/8.8/2.2	
11	Three-surface inkay	4.5/8.6/4.2	
12	Two-surface inlay	3.7/6/3	

Fig 1 The shape and approximate dimensions of the restorations made with milling and 3D-printed molds.

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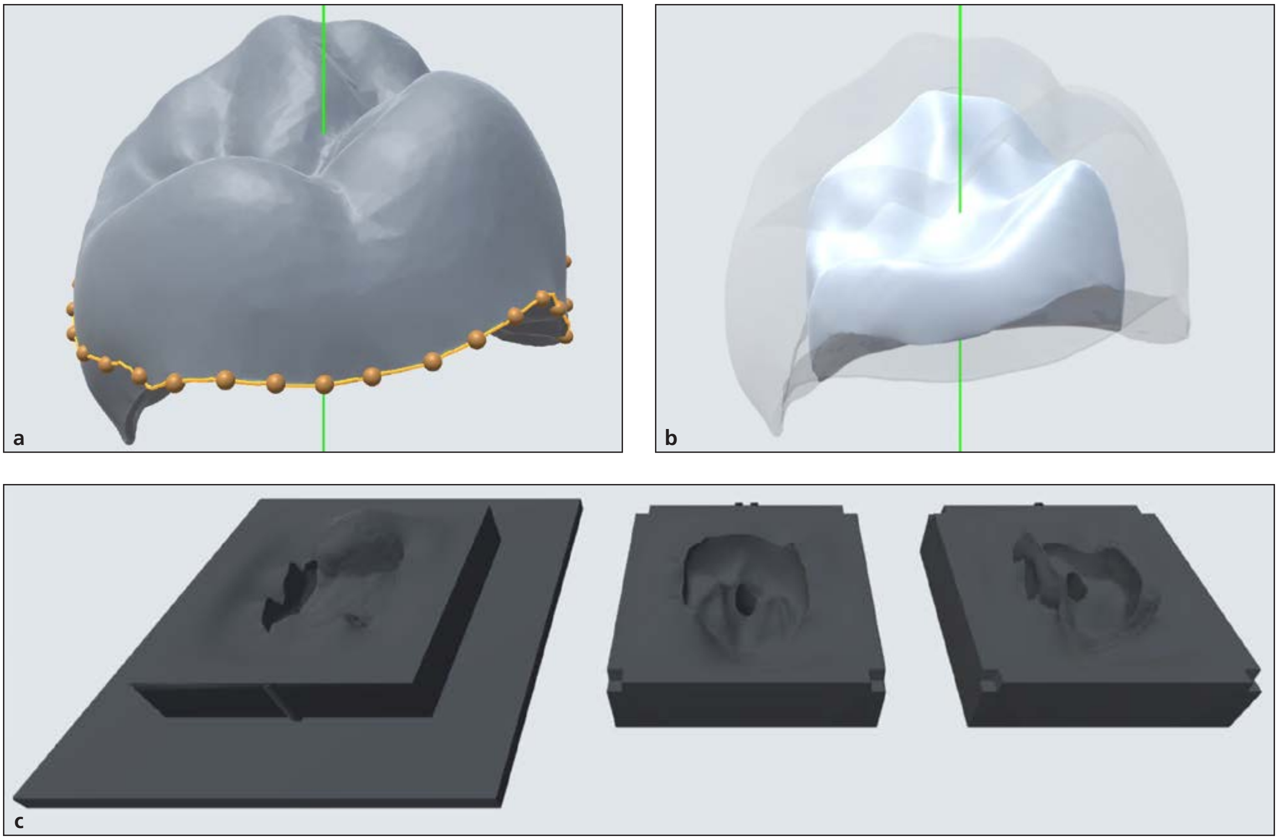

Fig 2 The different steps performed to manufacture the two-layer restorations (restoration 1). *(a)* The restoration's prominence line is determined in a specific software, allowing a mold split to be designed along that line. *(b)* The core and surface layer of the restoration is determined. *(c)* A mold is designed, including a bottom part *(left)*, one cap for core casting *(middle)*, and another cap for surface layer casting *(right)*.

molds for one- or two-layer restorations using water-washable biocompatible resin (Raydent SG, Ray). Print parameters were selected based on separate tests for print surface quality and dimensional accuracy. For printing, the layer thickness was 0.05 mm, and the flat face of the mold was against the build plate. The layer exposure time was about 5 seconds, and the printing typically lasted about 15 minutes. The mold inner surface was handled with separating liquid (Very Special Separator, DVA) and dried to prevent the restoration material from adhering to the mold. Next, a dental robot (3DToothFill) manufactured the restoration by well-controlled casting of filling material (G-aenial Universal Injectable, GC) layers into the mold as per the original design specifications. The injection pressure was comparable to normal hand application with a syringe. Two-layer restorations were prepared for tooth model restorations 1 and 5 using flowable composite (everX Flow, GC) as a core material. After filling the mold with the core material and preliminary curing, a larger cover was replaced on the mold and filled with G-aenial Universal Injectable. After curing for 10 to 15 seconds, a fully light cured restoration with a hardness comparable to manufacturer specifications was ready for accuracy testing. Curing was confirmed by hardness measurement.

The accuracy of the restorations was evaluated and compared based on radiographic microtomography (micro-CT scans; n = 12 per group; 1 per restoration). The samples were scanned in plastic tubes (Fig 3) with a desktop micro-CT scanner (Skyscan 1172, Bruker). The scanning was performed with 100 kVp and 10 W and an image pixel size of 7 µm. An Al+Cu filter, equivalent approximately to 2 mm of Al, was used to remove low energy x-rays. The rotation step was 0.40 degrees, frame averaging 4, 180 degrees of rotation, and 20% of beam hardening was used. Three contact points were checked with 3D inspection software (DataViewer, Bruker) to ensure the correct position of the restoration. For the 3D-analysis of the gap between tooth and restoration, the micro-CT data was processed as follows: *(1)* median filtering with a round 3D filter, *(2)* binarization, and *(3)* removal of random speckles. The 3D analysis of the gap distribution and volume was calculated with CT-Analyzer software (version 1.18, Bruker). The marginal

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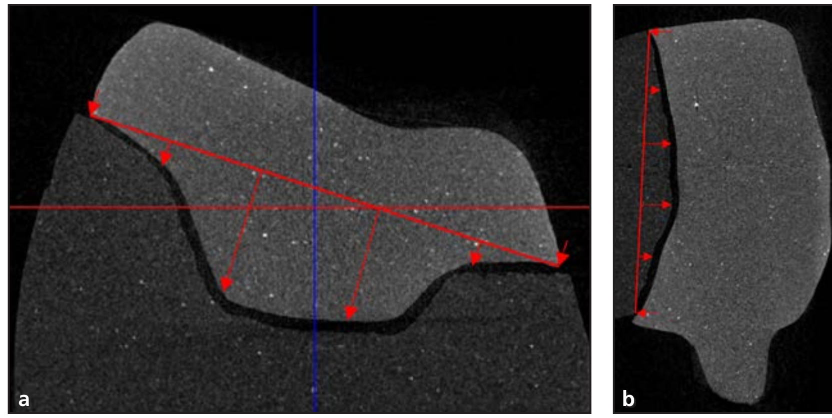
Fig 3 Each restoration was fixed on the tooth by wrapping a thin strip of adhesive tape around the pair. The samples were then placed in a plastic tube, and a light cushion was applied on top to prevent movement during the imaging. No cement layer was present; there was only an air layer between the tooth and restoration.



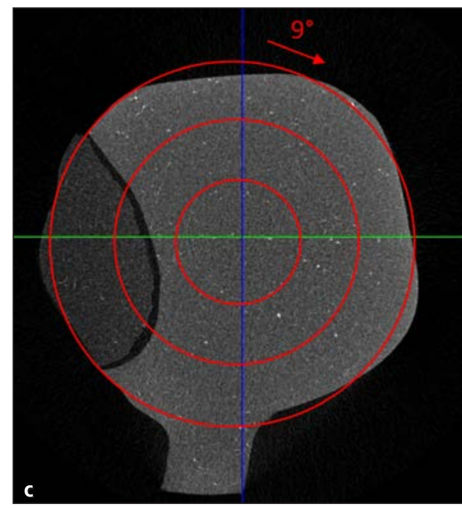


Fig 4 The marginal gaps of the restorations were determined at 40 points around the entire outer edge of the restoration. Internal gaps of the restorations were measured in the same sections as marginal gaps by dividing mesiodistal and buccolingual sections into six parts. *(a and b)* The exact measurement point was determined by taking a perpendicular distance from the dividing line to the edge of the restoration and the tooth. *(c)* Middle and central circles indicate the series of measurement points. After each measurement, the image was rotated 9 degrees through the transaxial (x–y) plane.

gaps of the restorations were measured in 20 uniformly spaced sections, in an angle around a single axis. The first measuring point was set in the middle of the outer edge of the restoration when the image was oriented mesiodistally. After each measurement, the section was rotated 9 degrees through the transaxial (x–y) plane, and the marginal gap was measured at both marginal edges with the criteria set by Holmes et al.[24] Internal gaps of the restorations were measured from the same sections as marginal gaps by dividing mesiodistal and buccolingual sections into six parts. The exact measurement point was determined by taking a perpendicular distance from the dividing line to the edge of the restoration and the tooth. Middle and central gaps were measured from 40 points. In total, each filling had 120 measurement points (Fig 4).

The internal gaps of the restorations were also evaluated with a replica technique. The defects were filled with a light-body low-viscosity A-silicone (Affinis, Coltène), and the restorations were pressed onto their corresponding preparation using finger pressure on the restoration's occlusal surface until it met the tooth, and the restorations were held in place with maximum finger pressure for 2 minutes, which is the total working time for the impression material. Excess impression material was removed from the outer lines using a disposable scalpel (no. 15 blade, B. Braun). The restoration and the impression material were carefully removed and weighed with an analytical balance (XSE, Mettler Toledo; 0.01-mg precision scale). Each measurement was repeated four times.

Statistical Methods

Kolmogorov-Smirnov test was used to examine the normal distribution of micro-CT measurements. Median values and interquartile ranges (IQRs) were calculated at each measuring point. The statistical differences between the micro-CT measurements of milled and 3D-printed mold restorations were analyzed using Mann-Whitney *U* test. $P < .05$ was considered statistically significant. Statistical analyses were performed using SPSS (version 27.0.1.0, IBM). The differences between the measurements of the milled and 3D-printed mold techniques were analyzed using *t* test.

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Table 1 Marginal and Internal Gap Measurements Based on Micro-CT Scans

	Restoration no.					
	1	2	3	4	5	6
Marginal gap, μm						
Milled	51.1 (58.3)	113.1 (164.0)	80.2 (131.3)	36.5 (72.9)	72.9 (74.7)	109.4 (49.3)
3D-printed	50.0 (50.0)	64.1 (179.8)	34.8 (46.9)	27.8 (71.2)	34.7 (74.6)	63.9 (63.9)
P	.810	.048*	.041*	.908	.001*	< .001*
Middle internal gap, μm						
Milled	138.6 (43.8)	222.5 (120.4)	164.2 (62.0)	153.2 (109.4)	58.4 (21.8)	167.8 (111.2)
3D-printed	84.4 (37.5)	99.7 (94.4)	128.5 (93.7)	41.7 (62.5)	100.7 (142.4)	111.9 (133.9)
P	< .001*	< .001*	.001*	< .001*	.014	.022*
Central internal gap, μm						
Milled	138.6 (21.9)	222.5 (58.3)	145.9 (36.5)	116.7 (34.7)	65.7 (21.8)	189.7 (34.6)
3D-printed	87.5 (23.5)	99.7 (33.8)	135.5 (27.8)	55.6 (39.9)	69.5 (121.5)	175.8 (37.9)
P	< .001*	< .001*	.052	< .001*	.321	.162
	Restoration no.					
	7	8	9	10	11	12
Marginal gap, μm						
Milled	43.8 (43.7)	116.7 (297.3)	43.8 (29.2)	54.8 (94.8)	36.5 (36.5)	83.9 (107.6)
3D-printed	29.9 (44.8)	55.6 (79.8)	59.9 (87.9)	54.2 (86.3)	37.3 (57.9)	46.9 (50.0)
P	.589	.001*	.241	.550	.110	.007*
Middle internal gap, μm						
Milled	142.3 (56.6)	193.4 (107.6)	167.8 (36.5)	116.7 (69.3)	127.7 (49.3)	142.3 (87.5)
3D-printed	89.6 (50.5)	138.9 (100.7)	131.8 (79.9)	91.5 (50.8)	89.6 (43.0)	62.5 (106.3)
P	< .001*	< .001*	< .001*	.099	< .001*	< .001*
Central internal gap, μm						
Milled	142.3 (34.7)	218.8 (160.5)	142.3 (21.9)	87.5 (36.5)	109.4 (34.7)	167.8 (36.5)
3D-printed	74.7 (37.4)	239.6 (241.3)	119.6 (69.9)	121.9 (25.4)	74.7 (37.4)	112.5 (193.8)
P	< .001*	.126	.031*	< .001*	< .001*	.014*

Data are presented as median (IQR).
*Statistically significant difference ($P < .05$).

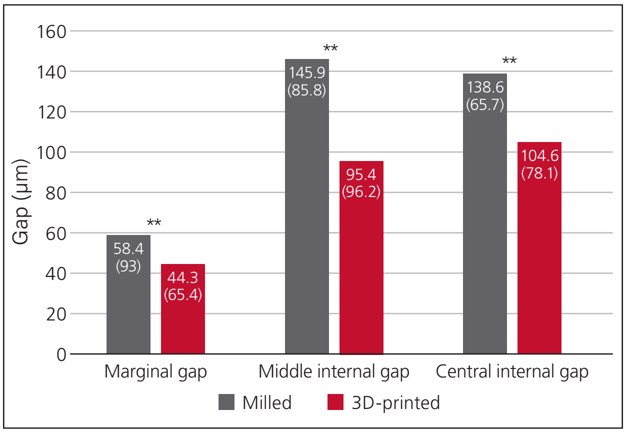

Fig 5 Median values (IQRs) for marginal gaps, middle internal gaps, and central internal gaps of all measurement points for all restorations in both groups. **Statistically significant difference ($P < .05$).

RESULTS

The median marginal and internal gap values obtained from the micro-CT measurements are presented in Table 1. Median values (IQRs) for marginal gaps, middle internal gaps, and central internal gaps were significantly lower for 3D-printed mold restorations (44.3 [65.4] μm, 95.4 [96.2] μm, and 104.6 [78.1] μm, respectively) compared to milled restorations (58.4 [93] μm, 145.9 [85.8] μm, and 138.6 [65.7] μm, respectively) (Fig 5). The 3D group had statistically significantly lower marginal gap values in restorations 2, 3, 5, 6, 8, and 12; significantly lower middle internal gap values in restorations 1, 2, 3, 4, 6, 7, 8, 9, 11, and 12; and significantly lower central internal gap values in restorations 1, 2, 4, 7, 9, 10, 11, and 12. Based on the replica technique measurements, internal gaps were 6% to 51% lower for the 3D-printed restorations in all defect forms (Table 2).

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Table 2 Comparison of Replica Weighted Means Between the Restorations and Abutment Teeth

Restoration no.	Milled		3D-printed			Two-layer 3D-printed		
	Mean	SD	Mean	SD	*P*	Mean**	SD**	*P***
1	902	9.0	639	57.5	.002*	641	70.51	.05
2	1,515	30.3	744	14.9	< .001*			
3	1,535	46.	893	187.5	.005*			
4	1,187	47.5	798	95.8	.001*			
5	1,234	61.7	994	89.5	.006*	1,125	90	.099
6	2,310	138.6	1,561	171.7	< .001*			
7	1,749	122.4	1,206	72.4	< .001*			
8	2,593	207.4	2,186	21.9	.029*			
9	2,174	195.7	1,700	153	.010*			
10	1,433	143.3	1,067	74.7	.080			
11	1,188	130.7	1,120	11.2	.375			
12	1,012	121.4	852	8.52	.008*			

Silicone masses are the original data multiplied by 100,000 (ie, 902 = 0.00902 g).
*Statistically significant difference ($P < .05$).
**Two-layer 3D-printed restorations were compared to milled ones.

DISCUSSION

The present study found that the marginal and internal fit of restorations fabricated with 3D-printed molds was better than those of milled restorations, as the gap values were significantly lower for 3D-printed mold restorations when all measuring points were considered. Based on the replica technique, the 3D-printed mold restorations had an average of 27% smaller internal gaps than milled restorations.

Minimal marginal and internal gaps are important for clinicians; inadequate marginal accuracy of the prosthetic restoration can lead to gingival inflammation, increased probing depths, bone resorption, and cement dissolution.[31,32] Other complications related to indirect composite restorations are secondary caries and pulp inflammation.[33] Further, failure loads of ceramic CAD/CAM crowns decrease when resin cement thickness increases.[23] In the present study, the marginal and internal gaps of the milled restorations were larger than that of 3D-printed mold restorations. Multiform onlay restorations 1, 2, 3, 6, 7, 9, 11 in the 3D-printed mold group contained complex shapes and long margins, which may be challenging for milling technology, resulting in a larger gap. In turn, the fit of the milled restorations showed better values for the two surface inlay defects (5 and 10) that were not as complex in shape as the others. Further, the milling technique resulted in a better fit for crown preparation compared to the 3D-printed mold technique. However, it should be noted that the study set included only one crown preparation per restoration type. In addition, the mold design parameters and printing settings were not fully optimized (eg, related to shrinkage compensation), which could be an anisotropic factor influencing the isotropic factors herein. Optimal nonisotropic shrinkage compensation may provide significant improvements in the accuracy of this 3D-printed mold technique. Thus, no further conclusion on the applicability of the technique for preparation of crowns can be made based on the present pilot study.

The present results are supported by earlier studies. In a systematic review, marginal and internal fit of milled inlays and onlays ranged from 36 to 223 mm and from 23 to 407 mm, respectively.[34] Based on micro-CT measurements, other studies found that marginal and internal gaps of milled onlays ranged from 35 to 128 mm and from 53 to 407 mm, respectively.[35,36] These results are partly above the clinically acceptable limit. In turn, clinically acceptable cement space is reported for milled ceramic mesial-occlusal-distal inlays, but the fit in other forms of defects remains uncertain.[37] May et al[23] suggested that CAD/CAM system manufacturers may optimize their milling systems to produce satisfying marginal values, as the outer edge of the restoration can be easily examined but the internal fit may differ from it. This might explain the relatively good marginal fit for milled restorations in the present and previous studies, though the internal fit was not optimal. In the literature, marginal and internal fit for 3D-printed interim crowns ranged between 27 and 143 mm and 24 and 217 mm, "respectively.[38–43] Mean cement film thicknesses of 320 mm and 620 mm were reported for 3D-printed provisional resin veneers and crowns, respectively.[44] For additively manufactured inlay and onlay wax patterns, mean marginal and internal gaps of 39.7 to 86.5 mm and 82.9 to 91.9 mm were reported, respectively.[19,45] Further,

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mean marginal gaps ranged from 63.1 to 129 mm for direct 3D-printed resin inlays.[46] For direct 3D-printed resin or metal crowns, marginal and internal gaps were between 71 and 111 mm and 101 and 253 mm, respectively.[47,48] Compared to previous studies, the results of the present study seem promising.

In the present study, the accuracy of the restorations manufactured using 3D-printed molds showed better fit than milled ones. This may indicate that 3D-printed mold restorations could provide a solution for less invasive defect preparation in the fabrication of indirect dental restorations, as the printing accuracy is not dependent on milling burs. Among the clinical advantages, it is worth noting that 3D printing can minimize material waste compared to conventional milling techniques. The 3D-printed molds enable the use of commercially available composite resins to manufacture multi-surface indirect restorations, which might be more cost-effective than traditional techniques. With this technique, the core of the mold can be roughened to improve bonding to the restorations. In addition, two-layer restorations can be manufactured with the presented 3D-printing mold technique, which makes it possible to mimic dentin and enamel layers, as seen in restorations 1 and 5. This is challenging with current manufacturing methods. Furthermore, with the 3D-printing mold technique, polymerization shrinkage can be considered during the CAD process, and shrinkage compensation of about 2% to 3% seems to be optimal. While the hardware required for 3D-printed mold restorations may incur initial investment costs, the anticipated technical advantages hold significant promise. Controlled mold design with an automated casting procedure leads to good reproducibility in restoration manufacturing.

The present study used Frasaco model teeth, which do not accurately mimic oral conditions. Thus, it is necessary to perform this kind of comparison study with human teeth, too. A micro-CT device was selected for marginal and internal fit measurements because it provides a nondestructive method for analyzing gap space in any direction or position.[49] The technique has been successfully used in earlier studies[35,36,49–51] and recommended for marginal fit analysis.[52] A resolution of about 7 µm was chosen, allowing quantitative comparisons of fit in different locations. For marginal and internal gap measurements, 120 measuring points were chosen per restoration, as at least 50 measurement points are recommended for reliable results.[53] There are some uncertainties related to the technique; micro-CT sectional images are inaccurate if two materials have similar densities,[35] and there may have been bias if the orientation of the tooth was not perpendicular. Further, the micro-CT analysis does not always determine the shortest distance between surfaces at a certain point but rather the distance in a certain direction. For example, in restorations 2 and 8, there is a significant variation in the values (ie, the orientation of the gap). In those restorations, some of the measuring points were in the middle of the gap, between the defect wall and the restoration, which explains the high IQR values. The actual distance is less than the specified "oblique" value. Cementation is reported to increase marginal discrepancy.[54] Therefore, not including cement may lead to an underestimation of the true gaps in a clinical application. However, the same measurements were used for both groups so that the results could be compared reliably. Gap measurements with luting cement could be carried out in future studies.

The micro-CT data was not normally distributed, so IQRs and Mann-Whitney *U* test were used instead of SDs and *t* test for the replica technique measurements. The current study incorporates crown preparation, given that achieving a smooth margin in crowns is conveniently achievable using a milling system. The intention was to examine the impact of 3D mold printing on the accuracy outcomes of currently used indirect restoration preparations. This is the rationale behind selecting crown restoration, as well as more intricately contoured inlay and onlay restorations, as illustrative examples. Because this is a pilot study, only one restoration per tooth model per group was manufactured. Two two-layer restorations were incorporated to showcase the potential of 3D-printed mold restorations. The number of the studied restorations was relatively low, which is why additional studies using larger sample sets and different forms of defects are needed to confirm the findings. In a pilot study, it is commonly advised to produce a minimum of five samples per experimental group. Technical developments are also needed to improve the usability of the 3D-printing mold technique. Further studies are also needed to determine the optimal shrinkage compensation and to optimize the surface roughness for bond strength.

Another limitation of the study was that different digital imaging, design software, and restoration materials were used for the groups, which may have affected the results. As for the imaging and design, Planmeca (Emerald and PlanCAD) did not support the mold technique, but Trios (Trios 4 and Design Studio) did, which is why Trios was selected for the 3D mold and robotics. The Planmeca system was used for the milled restorations because it includes a milling unit from the same manufacturer, enabling a seamless working protocol. Trios does not include a milling unit. Additionally, studies have shown differences in terms of precision and trueness between various intraoral scanners.[55,56] This factor should be considered when comparing results between milling and additive manufacturing. The filling material for the 3D-printing mold technique was selected based on the commercially available material, which can be layered, thus simulating the natural structure of the tooth.

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However, for the milled technique, only homogeneous blocks can be used.

Subsequent studies should utilize an intraoral scanner proficient in STL data extraction with an associated milling unit, which will facilitate the establishment of a uniform baseline dataset across subtractive and additive manufacturing methods. Moreover, it is advisable that future research provide a comprehensive synthesis and detailed documentation of the preparation design to enhance methodologic transparency. Further, micro-CT data continues to be a modern reference for assessing the accuracy of dental restorations. The use of micro-CT software enables the seamless alignment of a scanned object with the associated CAD file used in its design.

CONCLUSIONS

Except for the crown preparation, the accuracy of 3D-printed mold restorations was more favorable than that of the milled restorations. Due to the limited sample size, any strong conclusions cannot be drawn. Thus, additional investigations are needed to confirm these findings using a larger set of specimens and different types of restorations.

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REFERENCES

1. Heintze SD, Rousson V. Clinical effectiveness of direct class II restorations—A meta-analysis. J Adhes Dent 2012;14:407–431.
2. Pitel ML. Low-shrink composite resins: A review of their history, strategies for managing shrinkage, and clinical significance. Compend Contin Educ Dent 2013;34:578–590.
3. Kruzic JJ, Arseculаratne JA, Tanaka CB, Hoffman MJ. Recent advances in understanding the fatigue and wear behavior of dental composites and ceramics. J Mech Behav Biomed Mater 2018;88:504–533.
4. Mantri SP, Mantri SS. Management of shrinkage stresses in direct restorative light-cured composites: A review. J Esthet Restor Dent 2013;25:305–313.
5. Kaisarly D, Gezawi ME. Polymerization shrinkage assessment of dental resin composites: A literature review. Odontology 2016;104:257–270.
6. Darvell BW. Resin restorative materials. In: Overend L (ed). Materials Science for Dentistry, ed 10. Woodhead Publishing, 2018;145.
7. Kim RJ, Kim YJ, Choi NS, Lee IB. Polymerization shrinkage, modulus, and shrinkage stress related to tooth-restoration interfacial debonding in bulk-fill composites. J Dent 2015;43:430–439.
8. Al Sunbul H, Silikas N, Watts DC. Polymerization shrinkage kinetics and shrinkage-stress in dental resin-composites. Dent Mater 2016;32:998–1006.
9. Tauböck TT, Jäger F, Attin T. Polymerization shrinkage and shrinkage force kinetics of high- and low-viscosity dimethacrylate- and ormocer-based bulk-fill resin composites. Odontology 2019;107:103–110.
10. Opdam NJ, van de Sande FH, Bronkhorst E, et al. Longevity of posterior composite restorations: A systematic review and meta-analysis. J Dent Res 2014;93:943–949.
11. Astvaldsdottir A, Dagerhamn J, van Dijken JW, et al. Longevity of posterior resin composite restorations in adults—A systematic review. J Dent 2015;43:934–954.
12. Morimoto S, Rebello de Sampaio FB, Braga MM, Sesma N, Özcan, M. survival rate of resin and ceramic inlays, onlays, and overlays: A systematic review and meta-analysis. J Dent Res 2016;95:985–994.
13. Edelhoff D, Liebermann A, Beuer F, Stimmelmayr M, Güth JF. Minimally invasive treatment options in fixed prosthodontics. Quintessence Int 2016;47:207–216.
14. Alharbi N, Osman R, Wismeijer D. Effects of build direction on the mechanical properties of 3D printed complete coverage interim dental restorations. J Prosthet Dent 2016;115:760–767.
15. Alharbi N, Wismeijer D, Osman RB. Additive manufacturing techniques in prosthodontics: Where do we currently stand? A critical review. Int J Prosthodont 2017;30:474–484.
16. Park JH, Jung JW, Kang HW, Cho DW. Indirect three-dimensional printing of synthetic polymer scaffold based on thermal molding process. Biofabrication 2014;6:025003.
17. Baumgartner S, Gmeiner R, Schönherr JA, Stampfl J. Stereolithography-based additive manufacturing of lithium disilicate glass ceramic for dental applications. Mater Sci Eng C Mater Biol Appl 2020;116:111180.
18. Alenezi A, Yehya M. Evaluating the accuracy of dental restorations manufactured by two CAD/CAM Milling systems and their prototypes fabricated by 3d printing methods: An in vitro study. Int J Prosthodont 2023;36:293–300.
19. Homsy FR, Ozcan M, Khoury M, Majzoub ZAK. Marginal and internal fit of pressed lithium disilicate inlays fabricated with milling, 3D printing, and conventional technologies. J Prosthet Dent 2018;119:783–790.
20. Dawood A, Marti Marti B, Sauret-Jackson V, Darwood A. 3D printing in dentistry. Br Dent J 2015;219:521–529.
21. Della Bona A, Cantelli V, Britto VT, Collares KF, Stansbury JW. 3D printing restorative materials using a stereolithographic technique: A systematic review. Dent Mater. 2021;37:336–350.
22. Saratti CM, Rocca GT, Krejci I. The potential of three-dimensional printing technologies to unlock the development of new 'bio-inspired' dental materials: An overview and research roadmap. J Prosthodont Res 2019;63:131–139.
23. May LG, Kelly JR, Bottino MA, Hill T. Effects of cement thickness and bonding on the failure loads of CAD/CAM ceramic crowns: Multi-physics FEA modeling and monotonic testing. Dent Mater 2012;28:e99–109.
24. Holmes JR, Bayne SC, Holland GA, Sulik WD. Considerations in measurement of marginal fit. J Prosthet Dent 1989;62:405–408.
25. McLean JW, von Fraunhofer JA. The estimation of cement film thickness by an in vivo technique. Br Dent J 1971;131:107–111.
26. Alfaro DP, Ruse ND, Carvalho RM, Wyatt CC. Assessment of the Internal Fit of Lithium Disilicate Crowns Using Micro-CT. J Prosthodont 2015;24:381–386.
27. ISO: ISO 4049 Dentistry–polymer-based filling, restorative and luting materials. 2009.
28. ISO: ISO 9917-1:2007 Dentistry — Water-based cements — Part 1: Powder/liquid acid-base cements. 2007.
29. Council adopts American Dental Association Specification No. 8 (dental zinc phosphate cement) and 11 (agar impression material). Council on Dental Materials and Devices. J Am Dent Assoc 1967;74:1565–1573.
30. Tarvonen PL, Sipilä K, Tarvonen K, Lappalainen R. Simplified Chairside Restorations: Scan and Fill with Rayo 3DToothFill. Oral Health 2020; July 24. Available from: www.oralhealthgroup.com/features/simplified-chairside-restorations-scan-and-fill-with-rayo 3dtoothfill/
31. Jacobs MS, Windeler AS. An investigation of dental luting cement solubility as a function of the marginal gap. J Prosthet Dent 1991;65:436–442.
32. Knoernschild KL, Campbell SD. Periodontal tissue responses after insertion of artificial crowns and fixed partial dentures. J Prosthet Dent 2000;84:492–498.
33. D'Arcangelo C, Zarow M, De Angelis F, et al. Five-year retrospective clinical study of indirect composite restorations luted with a light-cured composite in posterior teeth. Clin Oral Investig 2014;18:615–624.
34. Goujat A, Abouelleil H, Colon P, et al. Marginal and internal fit of CAD-CAM inlay/onlay restorations: A systematic review of in vitro studies. J Prosthet Dent 2019;121:590–597.

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35. Seo D, Yi Y, Roh B. The effect of preparation designs on the marginal and internal gaps in Cerec3 partial ceramic crowns. J Dent 2009;37:374–382.
36. Alajaji NK, Bardwell D, Finkelman M, Ali A. Micro-CT evaluation of ceramic inlays: Comparison of the marginal and internal fit of five and three axis CAM systems with a heat press technique. J Esthet Restor Dent 2017;29:49–58.
37. Uzgur R, Ercan E, Uzgur Z, Çolak H, Yalçın M, Özcan M. Cement thickness of inlay restorations made of lithium disilicate, polymer-infiltrated ceramic and nano-ceramic CAD/CAM materials evaluated using 3D x-ray micro-computed tomography. J Prosthodont 2018;27:456–460.
38. Mai HN, Lee KB, Lee DH. Fit of interim crowns fabricated using photopolymer-jetting 3D printing. J Prosthet Dent 2017;118:208–215.
39. Lee WS, Lee DH, Lee KB. Evaluation of internal fit of interim crown fabricated with CAD/CAM milling and 3D printing system. J Adv Prosthodont 2017;9:265–270.
40. Chaturvedi S, Alqahtani NM, Addas MK, Alfarsi MA. Marginal and internal fit of provisional crowns fabricated using 3D printing technology. Technol Health Care 2020;28:635–642.
41. Ryu JE, Kim YL, Kong HJ, Chang HS, Jung JH. Marginal and internal fit of 3D printed provisional crowns according to build directions. J Adv Prosthodont 2020;12:225–232.
42. Wu J, Xie H, Sadr A, Chung KH. Evaluation of internal fit and marginal adaptation of provisional crowns fabricated with three different techniques. Sensors (Basel) 2021;21:740.
43. Son K, Lee JH, Lee KB. Comparison of intaglio surface trueness of interim dental crowns fabricated with SLA 3D printing, DLP 3D printing, and milling technologies. Healthcare (Basel) 2021;9:983.
44. Sampaio CS, Niemann KD, Schweitzer DD, Hirata R, Atria PJ. Microcomputed tomography evaluation of cement film thickness of veneers and crowns made with conventional and 3D printed provisional materials. J Esthet Restor Dent 2021;33:487–495.
45. Revilla-León M, Olea-Vielba M, Esteso-Saiz A, Martínez-Klemm I, Özcan M. Marginal and internal gap of handmade, milled and 3D printed additive manufactured patterns for pressed lithium disilicate onlay restorations. Eur J Prosthodont Restor Dent 2018;26:31–38.
46. Eftekhar Ashtiani R, Nasiri Khanlar L, Mahshid M, Moshaverinia A. Comparison of dimensional accuracy of conventionally and digitally manufactured intracoronal restorations. J Prosthet Dent 2018;119:233–238.
47. Chou WT, Chuang CC, Wang YB, Chiu HC. Comparison of the internal fit of metal crowns fabricated by traditional casting, computer numerical control milling, and three-dimensional printing. PLoS One 2021;16:e0257158.
48. Haddadi Y, Ranjkesh B, Isidor F, Bahrami G. Marginal and internal fit of crowns based on additive or subtractive manufacturing. Biomater Investig Dent 2021;8:87–91.
49. Pelekanos S, Koumanou M, Koutayas SO, Zinelis S, Eliades G. Micro-CT evaluation of the marginal fit of different In-Ceram alumina copings. Eur J Esthet Dent 2009;4:278–292.
50. Demir N, Ozturk AN, Malkoc MA. Evaluation of the marginal fit of full ceramic crowns by the microcomputed tomography (micro-CT) technique. Eur J Dent 2014;8:437–444.
51. Kim JH, Cho BH, Lee JH, et al. Influence of preparation design on fit and ceramic thickness of CEREC 3 partial ceramic crowns after cementation. Acta Odontol Scand 2015; 73:107–113.
52. Contrepois M, Soenen A, Bartala M, Laviole O. Marginal adaptation of ceramic crowns: A systematic review. J Prosthet Dent 2013;110:447–454.
53. Nawafleh NA, Mack F, Evans J, Mackay J, Hatamleh MM. Accuracy and reliability of methods to measure marginal adaptation of crowns and FDPs: A literature review. J Prosthodont 2013;22:419–428.
54. Beschnidt SM, Strub JR. Evaluation of the marginal accuracy of different all-ceramic crown systems after simulation in the artificial mouth. J Oral Rehabil 1999;26:582–593.
55. Róth I, Czigola A, Fehér D, et al. Digital intraoral scanner devices: A validation study based on common evaluation criteria. BMC Oral Health. 2022;22:140.
56. Diker B, Tak Ö. Accuracy of six intraoral scanners for scanning complete-arch and 4-unit fixed partial dentures: An in vitro study. J Prosthet Dent. 2022;128:187–194.

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