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

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**Purpose:** This in vitro study was conducted to evaluate the marginal accuracy of all-ceramic onlay restorations and prototypes fabricated using additive and subtractive methods. **Materials and Methods:** Ten typodont first molars were prepared and scanned two times using two different scanners: ARCTICA AutoScan (KaVo Dental) and CEREC Omnicam (Dentsply Sirona). The two groups of virtual models were used to design two groups of virtual onlay restorations using two different CAD software (n = 10 each group) and exported in STL files. Each group of STL files was converted to physical onlay restorations and prototypes by using three different methods; these included two additive manufacturing techniques, stereolithography apparatus (SLA) and digital light processing (DLP), and one subtractive technique, e.max milling using the KaVo Everest system and the Dentsply Sirona inLab MC X5. A digital microscope was used to evaluate the marginal fit around the onlay restorations or prototypes on the typodont teeth. **Results:** All evaluated groups showed mean marginal gaps between 59 and 84 µm. No statistically significant differences were found when comparing the marginal accuracy of onlay restorations fabricated by the subtractive method and onlay prototypes from the two additive methods, SLA (P = .70) and DLP (P = .21). **Conclusion:** All the models evaluated produced marginal gaps within the reported acceptable clinical range. Thus, these subtractive and additive methods may be considered suitable for onlay restoration production. Int J Prosthodont 2023;36:293–300. doi: 10.11607/ijp.7633

Dental science has continued to explore new technologies with the aim to improve the quality of treatment and minimize time and costs. In recent years, researchers have extensively investigated digital methods like CAD/CAM to enhance the restoration fabrication process. From a clinical perspective, CAD/CAM technology allows scanning of the tooth surface before converting the data into signals for computer-assisted milling, which helps produce highly accurate restorations. This technology permits easy processing and handling in dental practice.

CAD/CAM systems today manufacture dental restorations using either a subtractive method (SM) or an additive method (AM). These approaches are favored over the lost-wax technique, which is used routinely to fabricate the metal supporting layer of porcelain-fused-to-metal restorations. For both SM and AM, the fabrication of a restoration starts by using a specific scanner to produce 3D stereoscopic images. The stereoscopic images are then arranged to support 3D modeling.

For SMs, the restoration fabrication process uses sharp rotary instruments that cut a block of material into the desired tooth-shaped prosthesis. The block can be made of different restorative materials used routinely in dentistry, such as zirconia and resin. Thus, the freedom to choose the material to use makes the SM the most...
used CAD/CAM system. However, one major limitation of SMs is the excessive amount of material discarded to produce the final prosthesis. In their study, Strub et al reported that around 90% of the starting material is wasted to fabricate the prosthesis using SM. The discarded materials cannot be reused, which could present environmental and economic problems.

Thus, additive manufacturing has emerged to overcome some limitations of SMs. The terms “3D printing” and “rapid prototyping technology” are routinely used to refer to machines that use AMs. For these methods, the material for the restoration begins as a powder or a liquid. Then, additive manufacturing builds the object one layer at a time until it reaches the desired shape. These methods do not produce excess material that must be discarded, since only the desired parts are produced.

The manufacturing techniques based on AM include stereolithography apparatus (SLA) and digital light processing (DLP). In SLA, a light-sensitive polymer is cured layer by layer by a scanning laser beam in a vat of liquid polymer. In DLP, a liquid resin is cured layer by layer by a projector (a high-power LED source), and the object is built upside down on an incrementally elevating platform. These methods require the formation of virtual 3D models using stereoscopic images. Moreover, all the data from this process is saved in stereolithography format, which will be used for prosthetic fabrication later.

Researchers have found DLP to be more precise than SLA after assessing dental models printed with these techniques, although the SLA technique yielded higher trueness than DLP for tooth measurements and arch measurements. Dikova et al found that both SLA and DLP technologies can be used for manufacturing polymeric dental restorations.

Regardless of the method of fabrication, accuracy is the main element to consider before cementing dental restorations. Having said this, dental restorations with an accurate marginal fit are the outcome of multiple digital workflows. The marginal fit of restorations fabricated using CAD/CAM technology is influenced by such factors as the cutting instrument size, milling unit precision, digital cast rendering, and image capturing system.

Numerous reports have shown that an inadequate fit can facilitate the accumulation of plaque, which can lead to marginal discoloration or even secondary caries. Furthermore, the gaps created from an inadequate fit have a great risk of microleakage or even marginal chipping of the ceramic restoration. Some studies have claimed it would be difficult to remove excess cement when the marginal gap exceeds 100 μm, which can lead to late clinical failure for dental restorations. In one review, Kosyfaki et al found a strong correlation between marginal fit and gingival inflammation. Thus, marginal adaptation plays an important role in the long-term success of dental restorations.

These CAD/CAM techniques and their progressive development have become an important topic in dentistry today. However, several studies of these techniques have revealed some variations in the reported values of marginal fit. Thus, more investigation is needed to evaluate their clinical acceptability. This study aimed to evaluate in vitro the accuracy of restorations fabricated using one SM (milling) and two AMs (3D printing), SLA and DLP. The null hypothesis for this study was that onlay restorations fabricated from these SMs and AMs would show equal values for marginal fit.

MATERIALS AND METHODS

In a standard working model (Frasaco) with interchangeable hard resin teeth, 10 all-ceramic onlay restorations were prepared on defect-free typodont mandibular left first molars. The all-ceramic onlay was prepared through occlusal reduction of approximately 4 mm, along with the removal of the mesiobuccal cusp, while preparing the internal axial walls with the recommended angle of divergence (between 6 and 10 degrees). In addition, all internal line angles were rounded. The resin teeth were finished with a smooth carbide finishing bur and polished with a nylon brush and a low-speed handpiece polishing paste.

The 10 prepared teeth were fixed and then scanned using a high-resolution optical surface blue-light scanner (ARCTICA AutoScan, KaVo Everest CAD/CAM system) to generate 10 3D files of the virtual teeth. The same prepared teeth were scanned using an intraoral scanner (CEREC Omnicam, Dentsply Sirona) to create another set of 10 3D files. The scanners were calibrated according to the manufacturer’s instructions and optimized in a fully automated fashion. Their average error was 0.006 mm in the sphere-spacing error test. The resolution was set to minimize stair stepping. Figure 1 presents a summary of all evaluated groups and the methods used for onlay restoration fabrication.

Based on the scanned files, the onlay restorations were designed using two CAD software programs with a 50-μm gap for the cement film: (1) KaVo MultiCAD Dental DB and (2) Dentsply Sirona inLab 15.1 (Fig 2). They were then exported in standard tessellation language (STL) format.

The STL files of the onlay restorations were converted into physical models using three methods: the two 3D printing (additive) techniques, SLA and DLP, and the milling (subtractive) technique. The two different 3D printing technologies were used for the remaining subgroups: SLA using a Form 2 (Formlabs) printer and DLP using an Asiga MAX UV printer. The milling (subtractive) method for the all-ceramic e.max onlay restorations was used with the KaVo Everest Engine milling machine and the Dentsply Sirona inLab MC X5 milling machine. The two types of 3D printing software processed the STL file by
**Fig 1** Diagram showing onlay restoration fabrication process for all evaluated groups.

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**Fig 2** (a) Virtual image of inLab software showing the prepared area with the occlusal view and the path of insertion of the onlay restoration. (b) Virtual image of onlay restoration including the block selection.
generating slices of the onlay restorations. The first layer of the physical prototype was created followed by the successive layers. This process was repeated until the whole onlay restoration was fabricated.

To evaluate the marginal accuracy, the restorations were seated on the prepared typodont teeth using finger pressure. All of 60 specimens were evaluated at six previously determined spots for marginal fit analysis (Fig 3) using direct measurement without cementation or sectioning the samples. All of the spots that were designated to be examined were imaged through direct viewing at high magnification using a digital microscope with a micro-ruler. The margins analyses were conducted using ImageJ software (Fig 4).

**Statistical Analysis**
The nonparametric Kruskal-Wallis test (SPSS Statistics v 22, IBM) was used to evaluate the differences in the measured marginal gaps between all subgroups scanned using the two main light scanners (KaVo and Dentsply Sirona). The Mann-Whitney U test was used to compare the detected marginal gap values within the same group fabricated using the milling (subtractive) technique and the two 3D printing (additive) techniques. The significance level was set at $P = .05$. All data were plotted as mean ± standard deviation.

**RESULTS**
Regardless of the scanning systems used in the manufacturing methods, all of the evaluated groups showed mean marginal gaps from 59 to 84 µm with no statistically significant differences when comparing all groups. The groups scanned using the Dentsply Sirona inLab showed a $P$ value of .079 while the groups scanned using the KaVo MultiCAD Dental DB showed a $P$ value of .054.
the onlay restoration features a gap of about 50 µm than full crowns. The CAD/CAM software used to design dental onlays, since they have a more complex geometry among the marginal fit values of the methods evaluated. was accepted, since there were no statistical differences evaluated subtractive and additive methods used for onlay hypothesis of the study, which stated that the evaluation of the same 3D technology used (Fig 7).

**DISCUSSION**

Recent applications of digital technology in the dental field have produced dramatic changes that have taken the clinical process to a different level. One of the main developments combines 3D printing and CAD/CAM technology, which are thought to improve productivity and allow the fabrication of complex restorations. Numerous reports have revealed good outcomes when fabricating dental restorations using these technologies. However, even when proper procedures are followed during the preparation and cementation stages, the potential for leaving small gaps between the surface of the tooth and the restoration remains a challenge.

In this study, the authors evaluated the marginal fit and precision of dental onlay models fabricated by different types of CAD/CAM and 3D printers. The null hypothesis of the study, which stated that the evaluated subtractive and additive methods used for onlay fabrication would exhibit similar degrees of marginal fit, was accepted, since there were no statistical differences among the marginal fit values of the methods evaluated.

This study involved the analysis of samples of actual dental onlays, since they have a more complex geometry than full crowns. The CAD/CAM software used to design the onlay restoration features a gap of about 50 µm for cement film. Some reports claimed that a cement space greater than 30 µm improves the marginal fit. In addition, finger pressure without cementation was used to obtain good adaptation of onlays during the evaluation of marginal fit. Cementation can influence the accuracy of the adaptation due to variations in cementation techniques.

The onlays from all of the scanners evaluated had the same degree of marginal gaps. Overall, the measured gaps, as measured with these scanners and 3D printers, ranged from 59 to 84 µm, which is in accordance with the values reported in the literature. Nevertheless, a comparison of onlay gap measurements obtained from the usage of different scanning and fabrication methods must be done carefully. In the literature, there is no agreement about the amount of marginal discrepancy that is acceptable in clinical settings. Many studies have suggested that the marginal gap should not exceed 120 µm to be clinically acceptable for a long-term fixed dental prosthesis. Thus, the gaps produced by all the tested subgroups were within this acceptable range.

Evaluation of the gaps was based on six reference points selected at different angles. Gaps around the onlay margins were measured by viewing them directly at high magnification using a digital microscope. Direct viewing is believed to be an easy and nondestructive method of measurement, since it does not require special instruments or software. Thus, it could be considered an applicable method for use in clinical settings. One potential limitation of this method is that the spots selected for gap measurements might not be truly representative of the entire marginal fit of the restoration. In addition, it was not possible to examine the internal fit using this method, so internal fit was not evaluated.

Figures 5 and 6 outline the results of the marginal gap assessment of the examined onlay restorations according to the manufacturing methods, which showed no significant differences between all groups. In addition, no significant differences were found in the comparison between marginal gaps measured in the subgroups with the same 3D technology used (Fig 7).
evaluated. Several studies have evaluated the use of silicone replicas to evaluate marginal and internal fit. The replica technique has been used widely because it allows evaluation of the internal marginal gaps within different regions of the restoration.

Numerous studies have applied 3D analysis to assess marginal fit. It is believed that 3D analysis can measure a large number of spots, which increases reliability and provides more representative measurements. A common 3D method used to assess marginal fit is the triple-scan protocol. This protocol includes the measurement of many spots, although some studies showed lower data dispersion using this method. Some other 3D methods used to assess marginal fit are digital calipers and American Board of Orthodontics cast-radiograph analysis tools.

The two methods of manufacturing evaluated in this study (additive and subtractive) are based on a sophisticated digital workflow. Thus, the marginal fit of onlays is an outcome of several digital processes. Meanwhile, the authors did not compare fabrication methods using the same technology or resolution. The methods that were evaluated in this study (CAD/CAM and two 3D printers) are commonly used in the field of digital dental technology for diagnostic and manufacturing purposes. For 3D printers, the manufacturers’ instructions indicate that about 3 hours of printing time is required for a pair of dental models, depending on the type of 3D printing.

With CAD/CAM technology, the precision of the milling unit is believed to have an important role in the accuracy of the marginal fit. In general, most of the other factors that determine the accuracy of restorations are also associated with CAD/CAM machines, such as the type of image capturing system and the size of the cutting instrument. The two methods of subtractive manufacturing used in this study—Everest (KaVo) and MC X5 inLab (Dentsply Sirona)—are both well known in the dental market and have been in clinical use for years. Of the similarities between these systems, the most important is the five-axis milling unit. This type of milling unit has better cutting characteristics than the three-axis unit. The additional axes enhance milling efficiency and precision. The five-axis units use the additional axes to access complex parts of restorations that would be difficult to reach with three-axis units. Five-axis milling has also been reported to improve surface texture and finish.

As with CAD/CAM machines, the characteristics of 3D printers play a crucial role in determining restoration accuracy. Each manufacturer equips their 3D printers with specific characteristics and resolution levels. Most 3D printers designed for dental applications are associated with various laser speeds, building directions, and numbers of layers. Additional variations between printers include the technology used and the materials available for printing. These differences make it difficult to equitably compare the results of published studies. However, some reports have claimed that AM technology applied in 3D printers shows better outcomes for complex geometry compared to subtractive methods.

In this study, two 3D printer systems were evaluated: the Form 2 by Formlabs and the Asiga MAX UV. The Formlabs 3D printer is based on SLA technology, while the Asiga system uses DLP technology. These two techniques have been investigated extensively in the literature, and they are believed to be the most common 3D technologies used for dental applications. In the SLA technique, a UV laser creates complex shapes by localized polymerization with high feature resolution. Among SLA models, Formlabs printers were clinically examined numerous times, and they yielded acceptable outcomes. Other SLA printers were associated with errors that affected their accuracy. The risk of errors with repeated printing is believed to be lower with the DLP technique since it cures the restoration material layer by layer. Some reports also claimed that the DLP technique is faster and more precise than the SLA technique. In the end, it is known that different factors can influence the accuracy of printed restorations, including laser speed, building angulation and direction, and the number of layers used in the fabrication process.

The evaluation in this study was a comparison of the marginal fit of onlay restorations and prototypes scanned with two scanning systems, the CEREC Omnicam and the KaVo Everest, before the fabrication process. According to the present evaluation, the scanning systems did not appear to affect the accuracy of the fabricated samples. Amin et al compared the accuracy of digital impression obtained by the CEREC Omnicam with conventional impressions. They found that the CEREC Omnicam yielded impressions that were significantly more accurate when compared to conventional impressions. As for the KaVo scanner, one study reported a relatively low rate of accuracy and some degree of distortion compared to other laboratory scanners.

In summary, this study found no scientific differences in accuracy among CAD/CAM and 3D printer systems commonly used for fabricating dental onlay prototypes. Only some of the commonly used fabrication methods were evaluated in this study. Future studies should evaluate additional digital technologies that have fewer differences in characteristics and processing methods, allowing for a fairer comparison.

CONCLUSIONS

Within the limitation of this study, no statistically significant differences were found when comparing the marginal accuracy of onlay restorations fabricated by the subtractive (milling) method and onlay prototypes...
fabricated using two additive methods (3D printing): SLA and DLP. All of the models evaluated produced marginal gaps within the reported acceptable clinical range. Thus, these subtractive and additive methods should be considered suitable for onlay restoration production.

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REFERENCES


Literature Abstract

Single and Partial Tooth Replacement With Fixed Dental Prostheses Supported by Dental Implants: A Systematic Review of Outcomes and Outcome Measures Used in Clinical Trials in the Last 10 Years

To evaluate outcome measures, methods of assessment, and analysis in clinical studies on fixed single- and multiple-unit implant restorations. Three independent electronic database searches (MEDLINE, EMBASE, and Cochrane) were done to identify prospective and retrospective clinical studies published from January 2011 up to June 2021 with ≥20 patients and minimum 1-year follow-up period on technical and clinical outcomes of implant-supported single crowns (SCs) and partial fixed dental prostheses (P-FDPs). An entire data extraction was performed to identify primarily the most reported outcome measures and later to define the choice of assessment methods of those outcome measures. The outcomes were analysed descriptively, and the strength of association was evaluated using the Pearson chi-square test (p ≤ .05). In a total 531 studies, 368 on SCs (69.3%), 70 on P-FDPs (13.1%), and 93 on both restoration types (17.5%) were included; 56.3% of all studies did not clearly define a primary outcome. The most frequent primary outcome was marginal bone level (MBL) (55.2%) followed by implant survival (5.3%), professional aesthetic evaluation (3.4%), and technical complications (2.1%). Peri-implant indices were the most reported secondary outcome (55.1%), followed by implant survival (39.9%), MBL (36%), and implant success (26.4%). Prosthetic failure (seven studies [3.9%]) was one of the least reported outcome measures. Outcome measures and their assessment methods showed high heterogeneity among studies. Primary outcomes were not often defined clearly, and the most frequently selected primary outcome was marginal bone loss. Prosthetic outcomes, implant survival, and patient-related outcomes were only infrequently reported.