

MARGINAL ADAPTATION OF METAL-CERAMIC RESTORATIONS FABRICATED THROUGH DIGITAL WORKFLOW

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ABSTRACT

Background: Marginal adaptation is a critical determinant of the biological and mechanical success of fixed prosthetic restorations. Inadequate marginal fit may increase plaque retention, cement dissolution, secondary caries, gingival inflammation, and restoration failure. **Objective:** This paper aims to describe and analyze the technological workflow involved in the fabrication of metal-ceramic restorations, with emphasis on the factors influencing marginal adaptation. **Materials and Methods:** A digital workflow was used, including intraoral/digital scanning, CAD design in Exocad, 3D printing of working models using Formlabs Model V3 resin and Formlabs 3B, fabrication of Co-Cr metal frameworks through CAD/CAM or SLM technology, sandblasting, opaquer application, ceramic layering with IPS Style ceramic masses, staining, glazing, and final verification of marginal adaptation on printed models. **Discussion:** Each technological stage may influence the final marginal fit, including scan quality, preparation margin tracing, cement space parameters, insertion axis, framework design, sintering/firing protocols, support placement, finishing, and ceramic firing cycles. Digital workflows may improve standardization and predictability, but errors remain possible when technical parameters are not controlled. **Conclusion:** Marginal adaptation of metal-ceramic restorations depends on the precision of both digital design and laboratory execution. A controlled CAD/CAM workflow can support improved fit and clinical longevity, but objective measurement protocols are necessary for stronger scientific validation.

Key words: Metal-ceramic restorations; marginal adaptation; fixed prosthetic restorations; CAD/CAM; cobalt-chromium framework; silicone replica technique.

INTRODUCTION

Fixed prosthetic rehabilitation remains an essential component of modern dentistry, particularly in patients affected by partial edentulism or extensive coronal tooth destruction. The loss of dental units may compromise mastication, phonetics, occlusal stability, facial aesthetics, and psychosocial well-being. Partial edentulism may vary from limited tooth loss to extended edentulous spaces, and its clinical management requires careful evaluation of the remaining teeth,

periodontal status, occlusion, and functional demands [1,2]. In this context, fixed partial dentures and single crowns are frequently used to restore function, preserve arch integrity, and improve the patient's quality of life [3,4].

Among the available restorative options, metal-ceramic restorations continue to hold an important place in contemporary prosthodontics. Their clinical success is largely related to the combination of a metallic substructure, which provides mechanical strength and resistance to masticatory forces,

and a ceramic veneering layer, which improves aesthetics and biocompatibility. Metallic alloys such as cobalt-chromium and nickel-chromium have been widely used for the fabrication of fixed prosthetic frameworks due to their mechanical resistance, durability, and dimensional stability [4,9]. At the same time, ceramic materials allow the restoration to reproduce the optical characteristics of natural teeth, contributing to improved aesthetic integration [9,13].

The success and longevity of fixed prosthetic restorations are strongly influenced by marginal adaptation. Marginal adaptation refers to the precision with which the cervical margin of a restoration fits the prepared tooth structure. A correct marginal fit is essential for maintaining periodontal health, reducing plaque accumulation, limiting cement dissolution, and preventing microleakage. Inadequate marginal adaptation may contribute to secondary caries, gingival inflammation, periodontal complications, restoration debonding, and eventual prosthetic failure [4,6]. Therefore, marginal adaptation should not be considered only a technical laboratory parameter, but a clinically significant factor directly related to biological integration and long-term treatment prognosis.

The quality of marginal adaptation is influenced by multiple clinical and laboratory factors. These include the accuracy of tooth preparation, impression taking or digital scanning, margin detection, cement space configuration, restoration design, framework fabrication, finishing procedures, ceramic firing cycles, and final adjustment. In conventional workflows, errors may occur during impression taking, cast fabrication, wax pattern production, investing, casting, and post-processing. Each of these stages can introduce dimensional changes that may affect the marginal accuracy of the final restoration [4,6].

The development of digital dentistry has

significantly changed the fabrication process of fixed prosthetic restorations. Computer-aided design and computer-aided manufacturing systems, three-dimensional printed models, milling technologies, and selective laser melting techniques allow a more standardized and controlled workflow. Digital design software enables margin tracing, controlled cement space parameters, insertion axis determination, and predictable framework design. Additive and subtractive manufacturing methods may reduce some of the inaccuracies associated with traditional laboratory procedures and may contribute to improved marginal and internal adaptation [17]. However, digital workflows are not free from error. Scanner calibration, software parameters, support placement, material behavior, sintering conditions, milling bur wear, and technician experience may all influence the final adaptation of the restoration.

Given the biological and mechanical importance of marginal fit, the evaluation of metal-ceramic restorations fabricated through digital workflows remains a relevant topic in prosthetic dentistry. Understanding the technological stages involved in their fabrication and identifying the factors that influence marginal adaptation may contribute to improving clinical outcomes and restoration longevity.

The aim of this paper is to analyze the marginal adaptation of metal-ceramic restorations fabricated through a digital laboratory workflow, with emphasis on the technological stages involved in design, framework production, ceramic layering, finishing, and final verification. The paper also discusses the main factors that may affect marginal accuracy and highlights the importance of controlled clinical and laboratory protocols in achieving durable and biologically compatible prosthetic restorations.

MATERIALS AND METHODS

This study was designed as an applied laboratory-based technical study focused on the fabrication workflow of metal-ceramic restorations and the assessment of factors influencing marginal adaptation. The protocol followed a digital laboratory workflow, beginning with digital acquisition of the prosthetic field and ending with the final verification of the restorations on three-dimensional printed working models.

The main objective of the methodology was to document the technological stages involved in the fabrication of metal-ceramic restorations and to identify the procedural factors that may influence the precision of marginal adaptation at the cervical margin.

Materials and equipment

The following materials, devices, and software were used during the laboratory workflow:

- Model V3 resin, Formlabs, used for printing the working models;
- Formlabs Form 3B three-dimensional printer;
- Containers for post-print washing of the models;
- Isopropyl alcohol, used for cleaning the printed models;
- Asiga Flash photopolymerization unit;
- Exocad dental CAD software with the Model Creator module;
- Milling machine and sintering furnace from a dental milling and sintering center;
- Aluminium oxide sandblasting particles, 125 µm;
- Renfert Basic Master sandblaster;
- Programat EP3010 Ivoclar Vivadent ceramic firing furnace;
- IPS Powder Opaquer Ivoclar;
- IPS Powder Opaquer Liquid Ivoclar;
- IPS Style Ceram Incisal A1;
- IPS Style Ceram Dentin A1;

- IPS Style Ceram Deep Dentin A1;
- IPS Build-Up Liquid for IPS Style Ceram Allround Ivoclar;
- IPS Ivoclar Glaze Powder;
- IPS Ivoclar Mixing Liquid Allround;
- IPS Ivoclar Shade Dentin SD2;
- IPS Ivoclar Shade Incisal SI1;
- Dental micromotor with diamond burs for ceramic finishing.

Digital acquisition and model generation

The first stage consisted of obtaining the digital impression of the prosthetic field. The maxillary arch intended for restoration, the mandibular antagonist arch, and the intermaxillary relationship were digitally recorded. The obtained digital data were transferred to the dental laboratory for further processing.

In the laboratory, the digital files were imported into Exocad software. Using the Model Creator module, the working model and antagonist model were generated digitally (Figure 1). These models were then prepared for three-dimensional printing.

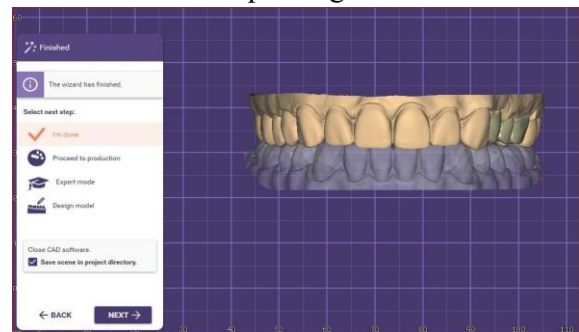


Figure 1. The digital models in occlusion prepared for printing.

Three-Dimensional printing of the working models

The generated digital models were aligned and prepared for printing. Printing parameters were configured, and support structures were added according to the requirements of the printing software and the geometry of the models.

The models were printed using a Formlabs

Form 3B printer and Model V3 Formlabs resin. After printing, the models were washed in isopropyl alcohol to remove uncured resin residues. The models were then photopolymerized using the Asiga Flash photopolymerization unit. After post-processing, the printed working models were used for the design, fabrication, and final verification of the metal-ceramic restorations (Figure 2).



Figure 2. The printed models.

Digital design of the metal-ceramic restorations

The design of the metal-ceramic restorations was performed in Exocad. The digital workflow included the following sequential steps:

1. Creation of the case file in Exocad;
2. Selection of the restoration type, namely metal-ceramic crowns;
3. Selection of the material and clinical parameters;
4. Import and alignment of the working and antagonist models;
5. Identification and tracing of the preparation margins;
6. Definition of the cement space parameters;
7. Definition of the cervical margin thickness;
8. Determination of the insertion axis;
9. Selection of the tooth morphology from the digital tooth library;
10. Individual anatomical modeling of the crowns;

11. Verification and adjustment of the marginal adaptation during the digital design stage;
12. Digital cut-back reduction of the anatomical crown design to create sufficient space for ceramic veneering;
13. Finalization of the metallic coping design;
14. Placement of connectors and preparation of the final framework design;
15. Export of the final design as an STL file.

Particular attention was given to the tracing of the preparation margin, the configuration of cement space, and the definition of the insertion axis, as these parameters directly influence the final marginal adaptation of the restoration.

Fabrication of the metallic framework

After completion of the digital design, the STL file was exported and sent to a dental milling and sintering center. The metallic frameworks were fabricated from cobalt-chromium alloy using CAD/CAM milling or selective laser melting technology.

After fabrication, the metallic frameworks were checked on the printed working model (Figure 3). The fit of the copings was verified, with particular attention to the cervical margin and seating of the framework. Any necessary adjustments were performed before ceramic application.



Figure 3. The check of the metallic framework on the model.

Surface treatment of the metallic framework

Before ceramic layering, the cobalt-chromium frameworks were subjected to mechanical surface treatment. Sandblasting was performed using 125 µm aluminium oxide particles at a pressure of 4 bar. This step was performed to increase surface roughness and improve the adhesion between the metallic substructure and the ceramic material.

After sandblasting, the frameworks were cleaned using a steam cleaner to remove surface contaminants and residual particles.

Opaquer application

Following surface preparation, ceramic opaquer was applied to the metallic framework. IPS Powder Opaquer Ivoclar and IPS Powder Opaquer Liquid Ivoclar were used. The opaquer was applied in two layers in order to mask the metallic color of the cobalt-chromium framework and to create a suitable bonding surface for the subsequent ceramic layers.

After opaquer application, the frameworks were fired in the Programat EP3010 Ivoclar Vivadent ceramic furnace using the “Style bond” program at 980°C.

Ceramic layering

Ceramic veneering was performed using IPS Style ceramic masses. The layering protocol included the application of dentin, deep dentin, and incisal ceramic materials.

The first ceramic layer consisted of IPS Style Ceram Deep Dentin A1 and IPS Style Ceram Dentin A1. These materials were applied according to the desired anatomical morphology of the restorations. After the first layering stage, the restorations were fired using the specific ceramic firing program for the first dentin/incisal firing at 790°C.

After the first firing cycle, IPS Style Ceram Incisal A1 was applied to reproduce the incisal and translucent areas of the restoration. The restorations were then fired again using the second dentin/incisal firing program at 780°C.

Additional ceramic corrections were performed where necessary in order to refine

the morphology, contour, and anatomical shape of the restorations.

Finishing, staining, and glazing

After ceramic layering and firing, the restorations were finished using a dental micromotor and diamond burs suitable for ceramic materials. The finishing stage aimed to refine the anatomical morphology, marginal contour, and occlusal morphology of the restorations (Figure 4).

Staining was performed using IPS Ivoclar Shade Dentin SD2 and IPS Ivoclar Shade Incisal SI1. Final glazing was performed using IPS Ivoclar Glaze Powder and IPS Ivoclar Mixing Liquid Allround.

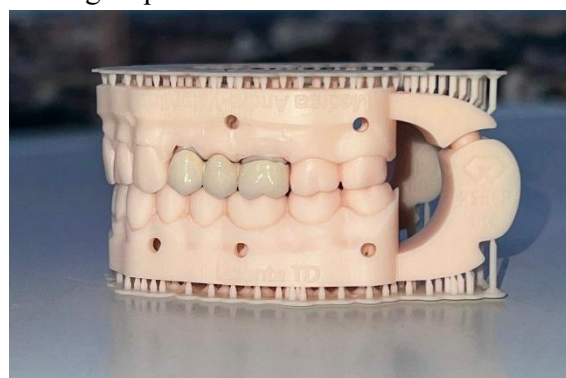


Figure 4. The final restoration on the model.

The restorations were then fired in the Programat EP3010 Ivoclar Vivadent furnace using the “Glaze firing / Add-On with Glaze firing” program at 770°C.

Evaluation of marginal adaptation

After completion of the ceramic layering, staining, and glazing stages, the metal-ceramic restorations were seated on the three-dimensional printed working models in order to evaluate their marginal and internal adaptation. The assessment was performed using an indirect silicone replica technique, which allowed estimation of the space between the internal surface of the metallic coping and the corresponding prepared abutment.

Instead of using luting cement, a light-body silicone impression material was inserted into the internal surface of each metallic coping.

The restorations were then positioned on their corresponding abutments and maintained in place until complete polymerization of the silicone material. After setting, the restorations were carefully removed, leaving a thin silicone film that reproduced the internal space between the restoration and the abutment surface.

The thickness of this silicone film was considered an indirect indicator of the space that would later be occupied by the cement layer during clinical cementation. Therefore, the silicone replica method provided information regarding both the internal fit of the restoration and the marginal adaptation at the cervical area.

Measurements were performed at two main regions: the cervical margin and the axial surfaces. The cervical measurements were used to assess the marginal fit of the restoration, as this area is directly related to marginal sealing, prevention of microleakage, and periodontal protection. The axial measurements were used to evaluate the internal adaptation and the uniformity of the cement space along the prepared abutment walls.



Figure 5. Measurements of the silicone thickness.

The silicone film was analyzed using a digital magnification camera. The device was equipped with a color CMOS sensor, eight white LED lights with adjustable intensity, USB 2.0 connectivity, and variable

magnification between 50X and 500X. The native image resolution was 640×480 pixels, with a maximum capture rate of 30 frames per second. Image acquisition and analysis were performed using dedicated software applications, including CoolingTech, AmCap, and CameraFi. The captured images were saved in standard image formats, including JPEG, PNG, and TIFF.

The evaluation focused on the measurement of silicone film thickness at cervical and axial levels. Reduced silicone thickness at the cervical margin was interpreted as favorable marginal adaptation, while increased thickness suggested a larger marginal discrepancy or less precise seating of the restoration. At the axial surfaces, the silicone thickness represented the internal space available for cement. Although a certain cement space is necessary for complete seating and cement flow, excessive or irregular internal spacing may negatively influence retention, stress distribution, and long-term stability.

In the analyzed measurements, silicone film thickness values ranged from 0.022 mm to 0.340 mm. The lower values recorded at the cervical level indicated close adaptation in the critical marginal region, while the higher values observed in axial areas reflected greater internal spacing. These axial values may be influenced by the internal geometry of the copings, the digital cement space settings, the fabrication method, and the pressure applied during seating.

The method allowed a semi-quantitative evaluation of marginal and internal adaptation before final clinical cementation. It also provided a practical way to detect visible discrepancies, incomplete seating, excessive internal spacing, or possible marginal overextension. Occlusal and aesthetic adjustments were performed when necessary after verification on the printed models.

Because this evaluation was performed

under laboratory conditions, the results should be interpreted as an indirect assessment of marginal adaptation. The method does not fully reproduce intraoral conditions, such as saliva, blood contamination, periodontal tissue response, clinical cementation pressure, or functional loading. Nevertheless, the silicone replica technique remains useful for estimating the future cement space and for verifying the precision of restoration seating before definitive cementation.

RESULTS

The marginal adaptation of the metal-ceramic restorations was evaluated indirectly by measuring the thickness of a light-body silicone film placed between the internal surface of the metallic coping and the corresponding prepared abutment. After complete polymerization of the silicone material, the restorations were removed, and the resulting silicone layer was examined using a digital magnification camera.

The silicone replica method allowed the visualization of the space existing between the internal surface of the restoration and the prepared tooth surface. This space represents the area that would be occupied by the luting cement during clinical cementation. Therefore, the thickness of the silicone film was considered an indirect indicator of internal and marginal adaptation.

The measurements were performed at two main levels: the cervical region and the axial surfaces. The cervical measurements were used to assess the marginal adaptation of the restoration, while the axial measurements provided information regarding the internal fit and the uniformity of the cement space.

The recorded silicone film thickness values ranged from 0.022 mm to 0.340 mm, corresponding to 22 μm and 340 μm , respectively. These values demonstrated variability between the measured areas, indicating that the adaptation of the restoration

was not completely uniform throughout the internal surface.

The lowest recorded value, 0.022 mm, indicated a very close adaptation between the metallic coping and the prepared abutment in the evaluated area. This suggests that, in certain regions, the digital workflow and subsequent framework fabrication allowed a high degree of precision. In contrast, the highest recorded value, 0.340 mm, indicated a wider internal space between the coping and the abutment surface. Such increased values may reflect localized discrepancies related to framework seating, cement space configuration, digital design parameters, fabrication inaccuracies, or post-processing effects.

At the cervical level, the evaluation focused on the continuity between the restoration margin and the preparation margin. The silicone film analysis allowed the identification of areas with reduced or increased material thickness, providing an indirect assessment of marginal fit. A thinner and more uniform silicone layer at the cervical margin was interpreted as a more favorable marginal adaptation, while thicker areas suggested less precise adaptation.

At the axial level, the presence of variable silicone thickness indicated differences in the internal fit of the restoration. Although internal spacing is necessary to allow cement placement, excessive or irregular spacing may influence the stability of the restoration and the uniformity of cement distribution during clinical cementation.

Overall, the obtained results showed that the digital workflow used for the fabrication of the metal-ceramic restorations was able to produce areas of close marginal and internal adaptation. However, the presence of values reaching 0.340 mm indicates that localized discrepancies may still occur despite the use of computer-aided design and manufacturing technologies.

The results support the importance of careful control of each technological stage, including margin tracing, cement space definition, insertion axis determination, framework fabrication, surface treatment, ceramic firing, and final verification on the working model. The silicone replica method proved useful for the qualitative and semi-quantitative assessment of restoration fit before final clinical cementation.

DISCUSSIONS

Marginal adaptation represents one of the most important criteria in the evaluation of fixed prosthetic restorations, because it directly influences periodontal health, cement stability, plaque retention, microleakage, secondary caries, and the long-term survival of the restoration. In metal-ceramic restorations, the precision of the marginal fit depends on both clinical and laboratory factors, beginning with the quality of tooth preparation and impression or scanning, and continuing with digital design, framework fabrication, ceramic layering, finishing, and final verification.

In the present study, the marginal and internal adaptation of metal-ceramic restorations was assessed using the silicone replica technique. The recorded silicone film thickness ranged from 0.022 mm to 0.340 mm, equivalent to 22 μm and 340 μm . This range demonstrates that the digital workflow was able to produce very close adaptation in certain areas, while also showing localized regions with increased discrepancy. Therefore, the results should be interpreted as evidence of variable adaptation rather than uniformly excellent fit.

The lowest recorded value, 22 μm , suggests that highly accurate adaptation can be achieved when the digital workflow is correctly controlled. This finding supports the potential advantages of CAD/CAM-based design and manufacturing, especially regarding the standardization of restoration

parameters, margin tracing, insertion axis control, and cement space configuration. Compared with conventional workflows, digital procedures may reduce some manual errors associated with wax pattern distortion, casting shrinkage, model inaccuracies, and repeated handling of the restoration [17].

However, the highest recorded value, 340 μm , indicates that digital fabrication does not automatically guarantee ideal marginal adaptation. This is an important point. A digital workflow can improve control, but it does not eliminate error. Discrepancies may occur because of scanner inaccuracies, incorrect margin detection, inappropriate cement space settings, software design errors, framework distortion, milling or sintering inaccuracies, support placement, post-processing, sandblasting, ceramic firing cycles, or manual finishing procedures.

The cement space parameter is particularly important in this context. An insufficient cement space may prevent complete seating of the restoration, while excessive cement space may result in increased internal discrepancy and a thicker cement layer. Although a certain internal gap is necessary to allow proper cement flow during clinical cementation, excessive or irregular spacing can compromise retention, stability, and marginal sealing. Therefore, the digital definition of cement space should be performed carefully and adapted to the restoration type, preparation geometry, and manufacturing method.

The preparation margin tracing stage also has a major influence on the final fit. In CAD software, the cervical margin must be identified accurately because this line determines the future marginal limit of the restoration. If the margin is traced incorrectly, even a well-manufactured framework may show overextension, underextension, or incomplete seating. In clinical practice, this problem may be amplified by poorly defined preparation margins, subgingival margins,

bleeding, saliva contamination, or scanning artifacts.

The fabrication of the metallic framework is another critical stage. Cobalt-chromium alloys provide high mechanical resistance, dimensional stability, and compatibility with ceramic veneering. However, the manufacturing method used to obtain the framework can influence the final accuracy. CAD/CAM milling and selective laser melting technologies may offer improved reproducibility compared with traditional casting, but they are still affected by technical variables such as machine calibration, material properties, milling bur wear, laser parameters, support design, and sintering conditions. As a result, even digitally manufactured restorations may require careful verification and adjustment before ceramic layering.

Ceramic application may also influence marginal and internal adaptation. Although the metallic framework determines the primary fit of the restoration, ceramic firing cycles expose the structure to repeated thermal changes. These changes may induce stress, distortion, or minor dimensional alterations, particularly if the framework design, ceramic support, or firing parameters are not properly controlled. The application of opaquer, dentin, incisal ceramic, staining, and glazing must therefore follow a strict protocol. Over-contouring or aggressive finishing near the cervical area may also affect the marginal profile of the final restoration.

The use of the silicone replica technique represents a practical and minimally destructive method for evaluating the adaptation of fixed restorations. It allows the indirect visualization of the space between the restoration and the prepared abutment and can be used before clinical cementation. In this study, it provided useful information regarding the distribution of the internal and marginal space. However, this method also has limitations. The accuracy of the measurement

may be influenced by the viscosity of the silicone material, seating pressure, polymerization behavior, sectioning technique, measurement points, and magnification method.

The interpretation of the recorded values must also consider the difference between marginal gap and internal gap. A value measured at the cervical margin has greater biological relevance than a value measured on an axial or occlusal internal surface. Internal spacing is expected and necessary for cementation, while marginal discrepancy is more directly associated with microleakage, cement dissolution, and periodontal complications. Therefore, future studies should clearly separate cervical marginal measurements from axial and occlusal internal measurements.

The results of the present study confirm the importance of controlling each technological stage in the fabrication of metal-ceramic restorations. The presence of low values indicates that accurate adaptation is possible, but the presence of higher values confirms that errors may still occur. This reinforces the idea that digital technology should be regarded as a tool for improving predictability, not as a substitute for technical precision and clinical judgment.

From a clinical perspective, marginal adaptation remains essential for the long-term success of metal-ceramic restorations. Even small discrepancies may become clinically relevant when they favor plaque accumulation, cement exposure, gingival inflammation, or secondary caries. For this reason, the final verification of the restoration on the working model, followed by intraoral clinical evaluation, remains mandatory before definitive cementation.

A major limitation of the present study is the lack of a larger sample size and the absence of complete statistical analysis. The available data provide a range of measured values but do

not allow calculation of mean marginal gap, standard deviation, or comparison between fabrication techniques. Another limitation is that the assessment was performed under laboratory conditions, on printed models, rather than directly in the oral cavity. Although printed models are useful for technical verification, they cannot fully reproduce the biological and clinical conditions present during intraoral cementation.

The present methodology describes a technical laboratory workflow and provides a qualitative assessment of marginal adaptation. The absence of quantitative marginal gap measurements represents a limitation of the study. Future research should include objective measurement methods, such as stereomicroscopy, digital microscopy, scanning electron microscopy, micro-computed tomography, or three-dimensional deviation analysis, in order to quantify marginal discrepancies in micrometers and allow statistical comparison between fabrication techniques.

Also, it should include a larger number of restorations, standardized measurement points, separate analysis of marginal and internal gaps, and objective microscopic or three-dimensional evaluation methods. Comparative studies between conventional casting, CAD/CAM milling, and selective laser melting would also be valuable. Such studies should include statistical analysis in order to determine whether the differences between fabrication techniques are clinically and scientifically significant.

The findings of this study suggest that a digital workflow can support the fabrication of metal-ceramic restorations with favourable marginal adaptation in certain areas. However, the variability of the recorded values demonstrates that precise adaptation depends on strict control of the entire workflow, from digital acquisition and design to framework fabrication, ceramic processing, and final

verification.

CONCLUSIONS

1. Marginal adaptation remains a critical factor in the biological, functional, and mechanical success of metal-ceramic restorations. A precise marginal fit contributes to periodontal health, reduces the risk of plaque accumulation and microleakage, limits cement dissolution, and supports the long-term stability of fixed prosthetic restorations.
2. The present study analyzed the fabrication of metal-ceramic restorations through a digital laboratory workflow, including digital design, three-dimensional model printing, cobalt-chromium framework fabrication, surface treatment, ceramic layering, staining, glazing, and final verification. The results obtained through the silicone replica technique showed values ranging from 0.022 mm to 0.340 mm, indicating that close adaptation can be achieved in certain areas, but that localized discrepancies may still occur.
3. These findings confirm that digital technologies such as CAD/CAM design, three-dimensional printing, and modern framework fabrication methods may improve workflow standardization and predictability. However, they do not eliminate the need for careful technical control. Accurate margin tracing, correct cement space configuration, appropriate insertion axis selection, precise framework fabrication, controlled ceramic firing, and careful finishing remain essential for obtaining favorable marginal adaptation.
4. The variability of the recorded values highlights that the final fit of a metal-ceramic restoration depends on the cumulative accuracy of every clinical and laboratory stage. Even when digital methods are used, errors may arise from scanning, design parameters,

manufacturing procedures, material behavior, post-processing, or ceramic firing cycles. Therefore, digital technology should be considered a valuable tool for improving precision, but not a replacement for clinical judgment, technical experience, and strict protocol control.

5. Within the limitations of this laboratory-based study, the digital workflow used for the fabrication of metal-ceramic restorations showed the potential to produce clinically relevant marginal adaptation. Nevertheless, the absence of a larger sample size, complete statistical analysis, and direct intraoral evaluation limits the strength of the conclusions.
6. Future studies should include standardized measurement points, separate evaluation of marginal and internal gaps, larger

sample groups, and objective microscopic or three-dimensional measurement methods. Comparative analysis between conventional casting, CAD/CAM milling, and selective laser melting would provide stronger evidence regarding the influence of fabrication technique on marginal accuracy.

7. In conclusion, the success of metal-ceramic restorations depends not only on the materials used, but also on the precision of the entire technological workflow. Proper control of each stage, from digital acquisition to final glazing and verification, is essential for achieving durable, functional, aesthetic, and biologically compatible prosthetic restorations.

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