INDONESIAN JOURNAL OF PROSTHODONTICS

ORIGINAL ARTICLE

Differences in milling speed and sintering speed using cad/cam technique on the marginal gap of zirconia dental crown

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Keywords: CAD/CAM, Marginal gap, Milling, Sintering, Zirconia

ABSTRACT

Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) is a digital approach to fabricating dental restorations, including zirconia crowns. Compared to conventional techniques, CAD/CAM offers a more efficient and precise workflow. The laboratory workflow in CAD/CAM process provides advantages such as high accuracy and a broader selection of materials, although it generally requires more time than chairside workflows. Manufacturing parameters—particularly milling speed and sintering speed— may influence the mechanical characteristics of restorations, especially marginal gaps, which are critical for long-term clinical success. Excessive marginal gaps can lead to restoration failure. This study aims to examine the effects of milling and sintering speeds on the marginal gap of zirconia crowns made using CAD/CAM technology. This experimental laboratory study involved 24 zirconia crowns divided into six groups based on combinations of three milling speeds (fast, normal, gentle) and two sintering speeds (conventional and speed). Marginal gaps were measured using micro-computed tomography (micro-CT), and data were analyzed with a two-way ANOVA followed by a Post-Hoc LSD test. Results revealed significant differences in marginal gaps related to both milling and sintering speeds ($p < 0.05$). The combination of gentle milling and speed sintering resulted in the smallest marginal gap (86.36 µm), while fast milling with conventional sintering produced the largest (118 µm). All values remained within the clinically acceptable range (50–120 µm). In conclusion, both milling speed and sintering speed significantly affect the marginal gap of zirconia dental crowns, highlighting the importance of optimizing these parameters for improved restoration quality. (IJP 2025;6(2):171-176)

Introduction

Tooth loss is an indicator of dental damage, which can be caused by caries. Molar teeth 1 and 2 are teeth that are at high risk of caries and ultimately tooth loss.[1] The impact of tooth loss without replacement with dentures can affect physical conditions such as reduced aesthetics, mastication, and speech ability. Additionally, tooth loss can affect both physical and psychological conditions, such as reduced self-confidence and limitations in social activities.[2]

Dental rehabilitation for tooth loss is generally divided into two types: removable dentures (RD) and fixed dentures (FD). The most functional rehabilitation for edentulous areas that closely resembles natural teeth is FD treatment. The supporting teeth, which serve as anchors, can be natural teeth or implant restorations.[3] FPDs are common and effective dental restorations that replace one or more teeth. Theoretically, FPDs can use dental implants or adjacent teeth as abutments to secure the prosthesis in place. These prostheses are typically made from durable and aesthetically pleasing materials, such as porcelain or ceramic. This effectively restores the functionality and aesthetics of the lost teeth.[4]

Zirconia is a ceramic material frequently used for dental restorations due to its similarity to the natural colour of teeth and its strength. Zirconia restorations have been widely used over the past few decades for FPD prostheses. This may be due to the optimal aesthetics and biocompatibility of zirconia.[5] Restorations can be fabricated conventionally or digitally. In recent years, Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) technology has evolved alongside its application in dentistry, including its use in full mouth rehabilitation.[6] CAD/CAM in dentistry can be used to enhance the effectiveness of dental restoration design and fabrication, particularly dental prosthetics, including crowns, veneers, inlays and onlays, dental bridges, dental implant restorations, removable dentures, and orthodontic appliances.[7]

This digital technology represents a modernization of existing conventional techniques, such as the method of obtaining impressions. Conventional techniques use impression materials, while digital techniques utilize intraoral scanners. Conventional prosthesis manufacturing involves waxing and conventional casting, whereas digital systems can employ CAD/CAM technology.[6] There are several advantages if operators use a digital workflow involving CAD/CAM, such as producing chair-side restorations and improving restoration quality.[7] Other advantages include faster treatment time, shorter patient visits, reduced patient discomfort, no need for plaster models, and more predictable final results.[6]

The restoration production process, choosing between laboratory-based CAD/CAM workflows and chairside workflows, is

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DOI 10.46934/ijp.v6i2.313

Table 1. Mean and standard deviation of marginal gap between groups (µm)

Milling group	Sintering group	n	Marginal gap (µm)	
			Mean	Standard deviation
Fast	Conventional	4	118.00	± 2.582
	Speed	4	104.14	± 0.712
Normal	Conventional	4	112.73	± 0.628
	Speed	4	113.80	± 0.845
Gentle	Conventional	4	101.22	± 1.970
	Speed	4	86.36	± 3.648

Note:
n = number of samples in each group

Table 2. Results of the two-way ANOVA test to determine the difference in milling speed and sintering speed on the marginal gap

Source	Sum of squares	df	Mean square	F	Sig.
Milling	1820.120	2	910.060	214.369	0.000*
Sintering	509.645	1	509.645	120.049	0.000*
Interaction millingsintering	318.424	2	159.212	37.503	0.000*

Note:
(*): significant (p<0.05) df: degrees of freedom
F: significance value
Sig.: significance

Table 3. Result of the Post-Hoc LSD test

Milling and sintering treatment	Milling and sintering treatment					
	FM+CS	FM+SS	NM+CS	NM+SS	GM+CS	GM+SS
FM+CS		13.86*	5.27*	4.20*	16.78*	31.64*
FM+SS			-8.59*	-9.66*	2.92	17.78*
NM+CS				-1.07*	11.5*	26.38*
NM+SS					12.58*	27.44*
GM+CS						14.86*

Note:
(*): significant (p<0.05)
FM+CS : fast milling + conventional sintering
FM+SS : fast milling + speed sintering
NM+CS : normal milling + conventional sintering
NM+SS : normal milling + speed sintering
GS+CS : gentle milling + conventional sintering
GS+SS : gentle milling + speed sintering

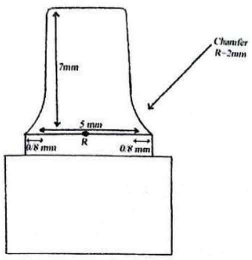

Figure 1. Die design

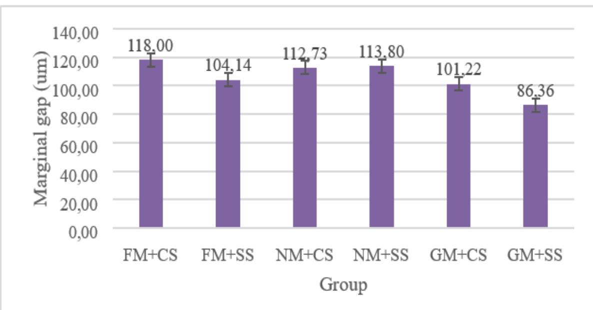

Figure 2. Diagram of the average marginal gap in micrometers between groups (FM+CS: fast milling + conventional sintering; FM+SS: fast milling + speed sintering; NM+CS: normal milling + conventional sintering; NM+SS: normal milling + speed sintering; GM+CS: gentle milling + conventional sintering; GM+SS: gentle milling + speed sintering)

an important consideration, particularly regarding time efficiency, cost, restoration type, and quality of results. Chairside workflow allows restorations to be completed in a single clinical visit since the entire process (from digital scanning, design, to milling) is performed on-site, making it highly time-efficient.[8] Conversely, laboratory workflow requires additional time as it involves transferring digital data to a dental laboratory for design and fabrication processes. However, laboratory workflow offers several significant advantages, such as a wider range of material options, the use of high-precision CAD/CAM equipment, and the involvement of professional dental technicians who can enhance morphological detail, aesthetics, and restoration margin fit. Therefore, despite requiring a longer processing time, the laboratory workflow remains the preferred choice for cases demanding high accuracy and maximum aesthetic results.[9,10]

The CAD/CAM process can be divided into three distinct steps: data acquisition, indirect restoration design, and restoration manufacturing. The manufacturing phase involves transforming the CAD model into a physical component through processing, finishing, and polishing. Two primary methods used to create these restorations are additive manufacturing (3D printing) and subtractive manufacturing (milling). Milling is a type of restoration fabrication that utilizes subtractive manufacturing technology from a large solid block.[7,11] Dry milling is more commonly used in zirconia manufacturing.[12] The milling speed of zirconia material using a laboratory milling machine workflow has three different speeds: fast, normal, and gentle.[13] In chairside production, milling speed is also divided into three categories: super-fast, fine, and extra-fine.

Sintering is a process that involves heating restorative materials such as ceramic and zirconia after the milling process. Heating is typically performed in a specialized oven at high temperatures below the melting point. The high heat causes the particles to bond tightly and fuse together, thereby strengthening the structure.[14] Conventional sintering of zirconia materials requires a long time, necessitating two restorative visits and temporary restorations.[15] Conventional sintering is performed at a heating rate of 10°C/minute and a waiting time of 120 minutes at a final temperature of 1550°C, with a total time of 8 hours. High-speed sintering, on the other hand, is performed at a heating rate of 120°C/minute and a holding time of 20 minutes at a temperature of 1600°C. High-speed sintering or speed sintering only requires 54 minutes to complete16. The processing of zirconia using a milling and rapid sintering system has now been developed. Faster processing times can reduce the number of patient visits and eliminate the need for lengthy procedures, thereby eliminating the need for two visits and temporary restorations.[15] Changes in milling speed and sintering speed in both chairside and laboratory workflows using CAD/CAM techniques will affect the

DOI 10.46934/ijp.v6i2.313

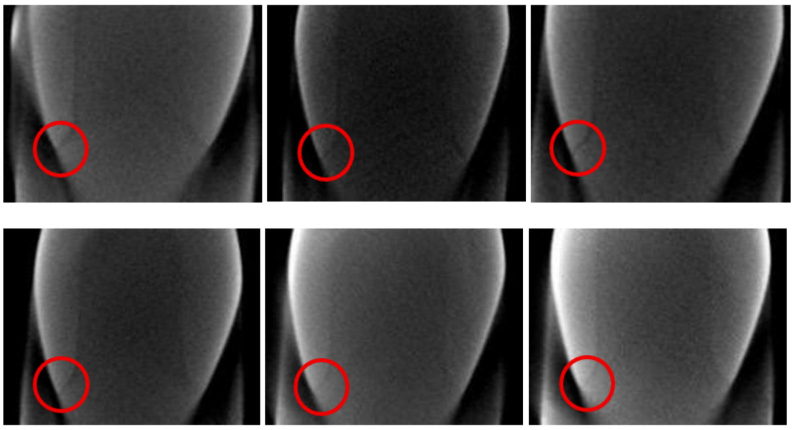

Figure 3. Marginal gap image using micro-CT (a) FM+CS: fast milling + conventional sintering; (b) FM+SS: fast milling + speed sintering; (c) NM+CS: normal milling + conventional sintering; (d) NM+SS: normal milling + speed sintering; (e) GM+CS: gentle milling + conventional sintering; (f) GM+SS: gentle milling + speed sintering

mechanical properties of zirconia. Additionally, the marginal gap in zirconia dental crowns can also be influenced by faster

milling and sintering14,15,17.

The marginal gap is defined as the vertical distance between the preparation margin and the cervical margin of the restoration. The clinically tolerated marginal gap range is 50 to 120 μm. Poor marginal adaptation can lead to plaque accumulation, microleakage, recurrent caries, and periodontal disease. Additionally, internal fit is a critical factor for restoration success, as a decrease in internal fit of the dental crown leads to reduced retention18. Marginal gap measurement can be performed using Micro-Computed Tomography (Micro-CT) scanning. This is a non-destructive tool that comprehensively depicts the 3D details of the scanned object. This examination is used to determine the marginal gap in a restoration by measuring the thickness or width of the luting cement localized at the adhesive interface19.

The marginal gap in zirconia crowns can be influenced by milling speed and sintering speed. Faster milling processes can result in cracks, chipping, and surface intaglio damage in zirconia material17. Sintering processes with shorter speeds or times and higher temperatures can affect the marginal gap14.

Research on milling speed and sintering speed in the fabrication of zirconia dental crowns in a laboratory workflow is important because both parameters directly affect marginal precision, mechanical properties, and production efficiency of restorations. Optimization of these parameters is necessary to improve restoration quality without compromising time efficiency in the laboratory workflow. This study was conducted to gain knowledge about the potential differences in milling speed and sintering speed using CAD/CAM techniques on the marginal gap of zirconia dental crowns in laboratory workflows.

Material and Methods

Stage 1. Obtaining Ethical Clearance

Ethical clearance was obtained from the Secretariat of the Ethics Committee of the Faculty of Dentistry – RSGM UGM Prof Soedomo, Universitas Gadjah Mada before commencing the research. The Ethical Clearance number is 244/UN1/KEP/FKGRSGM/EC/2024.

Stage 2. Creation of the metal master die

The metal master die for the research samples was made at Building B, Materials Laboratory, Faculty of Engineering, Department of Mechanical and Industrial Engineering, Gadjah Mada University, Yogyakarta. The metal die was made from stainless steel with a chamfered finishing line design figure 1 in a quantity of 24 pieces.

Stage 3. Zirconia fabrication and zirconia group division

Zirconia crown fabrication was performed at the CAD/CAM DLC Laboratory, Faculty of Dentistry, Gadjah Mada University. Zirconia disks (Upcera ST White) were placed in a 5-axis milling machine (milling machine inLab MC X5 Dentsply Sirona). The samples were divided into 6 groups: Group 1: zirconia fast milling dental crowns with conventional sintering (4 samples). Group 2: zirconia dental crowns with fast milling and speed sintering (4 samples). Group 3: zirconia dental crowns with normal milling and conventional sintering (4 samples). Group 4: zirconia dental crowns with normal milling and speed sintering (4 samples). Group 5: zirconia dental crowns with gentle milling and conventional sintering (4 samples). Group 6: Gentle milling zirconia dental crowns with speed sintering (4 samples) Sample preparation using CAD/CAM: Data acquisition. The model is placed on the table and scanned using the Intraoral Scanner Primescan (Dentsply Sirona) to perform the scanning process. This process transfers the data/condition of the die on the gypsum model to the computer. Computer-aided design (CAD). The scan results are entered into specialized software (InLab CAD) to design the restoration according to the model, size, and material desired by the operator. This process is referred to as CAD (computer-aided design assisted by the Biogeneric Copy feature). Computer-aided manufacturing (CAM). The fabrication of the crown sample is performed using CAM with a milling process (computer-aided restoration fabrication), which is fully controlled by the computer based on the data entered during the CAD process. The manufacturing process involves milling a monolithic zirconia disk in inLab MC X5 milling machine (Dentsply Sirona) using dry milling, divided into three milling speed groups: fast milling, normal milling, and gentle milling. Sintering. The sintering process involves placing the zirconia crown in the white stage (white chalk color) into a high-temperature sintering machine, resulting in densification (Dentsply Sirona sintering machine inLab

DOI 10.46934/ijp.v6i2.313

Profire). The crown is positioned with the inner surface facing downward. Specimens are sintered using different methods. Sintering is programmed according to the Dentsply Sirona inLab Profire sintering machine program as follows: Conventional sintering is performed at a heating rate of 10°C/minute and a waiting time of 120 minutes, with a final temperature of 1550°C, taking approximately 8 hours to complete. Speed sintering is performed at a heating rate of 120°C/minute and a waiting time of 20 minutes, with a final temperature of 1600°C, and takes approximately 54 minutes to complete.

Stage 4. Cementation of zirconia crowns

The zirconia dental crowns that have been produced are cemented onto the metal die using self-adhesive resin cement as recommended by the manufacturer. Preparation of the restoration and metal die. The surface to be cemented is sandblasted with 50-micron aluminum oxide at 30 psi to create a matte surface. The zirconia restoration is then cleaned with alcohol and dried. The metal die is cleaned of all debris using a chip blower. Application of resin cement. The resin cement is applied to the zirconia restoration. The zirconia restoration is then inserted into the prepared die. During restoration insertion, a specimen-holding mechanism is pressed with a 5 kg load for 6 minutes21. Tack curing is performed for 2 seconds, followed by removal of excess resin cement from the edges of the restoration. In the final insertion stage, light curing is performed for 20 seconds per surface (occlusal, facial, lingual), and polishing is performed using an Eve Diacomp polishing bur on the zirconia crown.

Stage 5. Radiographic imaging and micro-CT data processing

This stage was conducted at the Department of the Faculty of Mathematics and Natural Sciences (FMIPA) at the Bandung Institute of Technology (ITB). Radiographic imaging was performed using a μ-CT Scanner SkyScan 1173 High-Energy micro-CT. This device projects the structure of a material in three dimensions (3D projection) using X-ray irradiation. The zirconia crown is positioned to remain stationary and stable during the micro-CT test. The test is conducted in a single exposure with high resolution at 130 kV for 4 hours. Xrays are then emitted to capture the radiographic image. The X-rays are emitted from one side toward the receptor on the opposite side, while the sample rotates. Then, measurements of the marginal distance of the restoration from the finishing line on the mesial, distal, buccal, and lingual surfaces of each sample were taken. Measurements were taken by measuring perpendicularly from the internal margin surface of the crown or restoration to the outer edge of the tooth margin finishing line or by measuring the length of the radiolucent area at the edge of the restoration.

Measurements of the mesial and distal sides were taken using sagittal sections, while measurements of the buccal and lingual sides were taken using coronal sections. The middle slice of the sample was selected for marginal gap measurements.

Results

A study on the differences in milling speed and sintering speed using CAD/CAM techniques on the marginal gap of zirconia crowns has been conducted. This study was performed on 6 groups with different milling and sintering treatments. Marginal gap values were obtained by measuring the perpendicular distance from the internal margin surface of the crown or restoration to the outer edge of the final margin line of the tooth on all four sides of the sample (mesial, distal, buccal, and lingual sides), with the values averaged. The mean and standard deviation of the marginal gap values are presented in table 1.

Figure 2 illustrates the average marginal gap across six groups with different milling and sintering speeds. The highest average marginal gap was observed in the fast milling and conventional sintering group (FM+CS) at 118 μm. The lowest average was in the gentle milling and speed sintering group (GM+SS) at 86.36 μm. The marginal gap in the conventional sintering group was higher than that in the speed sintering group for both fast milling and gentle milling. However, in the normal milling group, the marginal gap in conventional sintering was lower than that in speed sintering, with an average difference of 1.07 μm.

The research results obtained are quantitative data tested using a two-way ANOVA analysis. The prerequisite for conducting this test is that the data must be normally distributed and homogeneous. The Shapiro-Wilk test results show that the mean marginal gap percentage in each treatment group is normally distributed. This is evident from the significance value, which is greater than 0.05 in both the milling and sintering groups. The Levene's test for homogeneity showed that the mean marginal gap had the same variance in both the milling and sintering groups. This was proven by a significance level greater than 0.05 ($p > 0.05$). Next, a two-way ANOVA test was performed because the data were normally distributed and homogeneous. The results of the two-way ANOVA test can be seen in table 2.

Table 2 presents the results of a two-way ANOVA test on the differences in milling speed and sintering speed on marginal gap. Based on the results of the two-way ANOVA test, it shows that: There is a significant difference in the effect of milling speed on the marginal gap in zirconia dental crowns ($p<0.05$). There is a significant difference in the effect of sintering speed on the marginal gap in zirconia dental crowns ($p<0.05$). There is a significant difference in the interaction between milling speed and sintering speed on the marginal gap of zirconia dental crowns ($p<0.05$). The data were further analyzed using the Post-Hoc LSD test

DOI 10.46934/ijp.v6i2.313

to determine the significance of differences between treatment groups, with the results presented in table 3.

Based on the results of the Post-Hoc LSD test in table 3, it was found that in the relationship between groups, all groups showed significant differences ($p<0.05$) and there were meaningful differences between each group ($p<0.05$) except between NM+CS and NM+SS, and FM+SS and GM+CS, which showed non-significant differences ($p>0.05$), indicating similarity in results between these two approaches. Overall, other comparisons between groups, particularly between the gentle milling + speed sintering (GM+SS) group and the other groups, showed significant differences in both milling speed and sintering speed.

Discussion

Research data were obtained from measurements of the marginal gap on each side of the sample after scanning using micro-CT. This device was chosen because it is the gold standard for measuring marginal gaps. It is a non-destructive, accurate tool for measuring small gaps such as marginal gaps. Micro-CT can reconstruct 3D images in great detail, including the gap between the crown and abutment. Micro-CT was chosen over CBCT, which operates using X-rays, because the structures projected by the micro-CT device show more accurate details, reaching 5 micrometers per pixel.[22]

Research findings on the differences in milling speed and sintering speed regarding marginal gaps in zirconia dental crowns have proven that milling speed (gentle milling) and sintering speed (speed sintering) reduce marginal gaps in zirconia dental crowns. The results of this study indicate that all treatment groups had clinically acceptable marginal gap values. The clinically tolerable marginal gap range is 50 to 120 μm.[18] The average marginal gap in the gentle milling and speed sintering groups was 86.36 μm. This average was the smallest value compared to all treatment groups, especially compared to fast milling and conventional sintering, which showed an average of 118 μm. This may be due to differences in milling speed and sintering speed.

Milling speed is divided into three categories: fast, normal, and gentle. There is a significant difference, as indicated by the variation in average marginal gaps across all treatment groups. Zirconia dental crown fabrication using gentle milling resulted in smaller marginal gaps compared to normal milling and fast milling in both the conventional sintering and speed sintering groups. When the milling bur rotates at a low speed, it tends to move slowly and produce smoother milling results. High milling speeds can cause vibrations or oscillations in the milling bur. These vibrations can cause deviations in the cutting path, especially in thin areas such as the crown edge surface. These results are consistent with the research,[13] who stated that zirconia crowns produced at faster milling speeds result in occlusal grooves and cusps with coarse overall anatomical details, more aggressive subtractive material removal processes, and surface imperfections, including in the restoration margin area. This is also consistent with the research,[17] who stated that fast milling produces restorations with significantly larger marginal gaps compared to slower milling speeds. Lowspeed milling has a smaller and more distributed cutting load on the tool, resulting in more stable outcomes. This will affect the compatibility of the restoration results with the original CAD design.[23]

Sintering speed is divided into two types: conventional sintering and speed sintering. The heating process in sintering has a sequence that must be determined according to factory regulations. Speed sintering uses two sequences with a temperature increase of 120 degrees per minute, while conventional sintering has five sequences with a temperature increase of 2-8 degrees per minute. Speed sintering shows a smaller or nearly identical marginal gap compared to conventional sintering in this study. Slower sintering or conventional sintering can lead to higher sintering shrinkage, resulting in greater inconsistency and unevenness. This aligns with the research,[14] who stated that speed sintering produces a smaller marginal gap in zirconia crowns compared to conventional sintering due to several interrelated factors, including grain size, crystal phase stability, and minimal dimensional distortion.

The speed sintering process has a high heating rate and a short peak temperature holding time, thereby limiting grain growth and producing a microstructure with smaller and more uniform grain sizes.[24] The smaller grain size in zirconia allows the densification process to occur uniformly, including in marginal areas, resulting in more homogeneous shrinkage during sintering. Larger grains can cause microcracks, leading to inconsistencies in the final product. Additionally, faster sintering maintains the stability of the tetragonal phase in zirconia, particularly in the 3Y-TZP type, thereby minimizing the transformation of the tetragonal phase back to the monoclinic phase, which can cause volume expansion and cracks. This phase stability also supports dimensional precision in the final product.[25] The combination of small particles, stable crystalline phase, and controlled shrinkage is the influencing factor of the speed sintering group in this study, resulting in zirconia crowns with smaller marginal gaps and better adaptation quality.

The conventional sintering group showed research results consistent with the theoretical explanation of milling and sintering speed. Unlike the speed sintering group, which had a marginal gap sequence from lowest to highest as gentle milling, fast milling, and normal milling. The results of this study are inconsistent with the findings,[17] who reported that fast milling

DOI 10.46934/ijp.v6i2.313

produced restorations with significantly larger marginal gaps compared to slower milling speeds. This discrepancy may arise due to differences in zirconia block density, which linearly affects zirconia shrinkage. The shrinkage process is determined by various factors, such as the material composition itself, density distribution, and sintering process parameters. Density distribution, known as the primary characteristic of the material, determines local shrinkage and dimensional accuracy after final sintering. Additionally, nonuniform sintering shrinkage can cause restoration mismatch.[26] The sintering process for the samples in this study was performed simultaneously for work efficiency and to avoid prolonged downtime for the milled zirconia crowns. During the sintering heating process, the heating direction in the system proceeds from the outside to the inside, ensuring temperature stability and enabling control of the material's microstructure.[14]

Conclusion

Based on the conducted research, it can be concluded that there are differences in milling speed and sintering speed using CAD/CAM techniques on the marginal gap of zirconia dental crowns. Gentle milling and speed sintering have the smallest marginal gap values.

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