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IN VITRO ASSESSMENT OF MARGINAL AND INTERNAL GAP OF MONOLITHIC ZIRCONIA CROWNS FABRICATED BY MILLING AND 3D PRINTING TECHNIQUES.

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ABSTRACT

Aim of the study: this invitro investigation aimed to assess how accurate monolithic zirconia restoration constructed by milling (subtractive) and printing (additive) techniques.
Materials and methods: twenty zirconium single unit restorations were constructed by subtractive (group 1) and additive technologies (group 2). The accuracy at the margin was evaluated at twelve measurement spots utilizing the vertical marginal gap method (VMGT). With regards the internal discrepancy, the replica approach was conducted, and it was measured in four areas: marginal, axial, axial-occlusal, and mid-occlusal areas. It was reported that the data followed a normal distribution, and an independent t-test was used to analyze the results.
Results: Using VMGT, group 1's mean marginal gap values were (56.9 ± 7.77 µm), which was significantly lower than group 2's (84 ± 13.5) µm ($p < 0.001$). Additionally, group 1's marginal gap (61.75 ± 13.45 µm) showed substantially lower values with the SRT than group 2's (82.65 ±12.53 µm). With the exception of the axial gap, the adaptation of the internal surface revealed a substantial disparity between both techniques.
Conclusions: Despite zirconia milled crowns performed better, clinically acceptable outcomes with regards accuracy of fit, can be achieved by the additive techniques.

Keywords: Three-Dimensional Printing, Prosthesis Fitting, Marginal Adaptation and zirconia.

INTRODUCTION

Dental zirconia ceramics are being used more and more nowadays. The materials' superior mechanical and biological characteristics, along with their pleasing esthetic properties, support its use as a dental material. The most important component of any material that should be used in dentistry; they must show proper mechanical and physical properties. Any constructed prosthesis should be properly shaped, with the proper internal and external shape, and fit without any gaps [(1)] .

Restorations constructed from zirconia are made employing the subtractive method, which involves using computer-aided designing/computer-aided manufacturing (CAD/CAM) to grind it from a blank [(2)] . A reliable method that reduces human intervention and decreases the susceptibility of faults associated with the conventional lost-wax technique is the construction using computer, utilizing zirconia discs or blocks. These could be partially sintered, the restoration constructed in the green-stage, and fully sintered, used for milling in hard state. Each of which has its own steps for production. For hard milling, the susceptibility for initiation of cracks in the final restorations, milling bur wear, prolonged milling procedures, and characteristics of the surface of the restoration can be considered drawbacks for hard milling [(3,4)] .On the other hand, for green-state milling, the restoration should be enlarged by about 25% to counteract shrinkage on setting. for both states, there are large amount of waste material produced after the milling procedure. Also, the size and configuration of the milling bur, how many axes used by the machine to mill, have a large effect on the final restoration shape, finish and configuration[(5,6)].

Recent developments in dental restoration manufacturing include the construction of the product in low thickness layers, then undergo processing, hardening, and then final stages of finishing. Often referred to as Layered manufacturing or Three-dimensional printing, this process uses a variety of methods, including powder bed fusion, binder and material jetting, vat photopolymerization, thermoplastic extruded material, and others. Variable additive manufacturing procedures are used in dentistry by lab technicians and restorative dentists to create metal prostheses, dentures, castings, and interim restorations. Recently, printing ceramic restorations—such as zirconia-based prostheses—has drawn more attention[7–9].

Many advantages have been provided by the additive manufacturing, including the removal of tool wear, reduced residual tensions, complicated geometries, mass production, and minimal material waste. But it should be noted that this technique of production has its limitation. These include dimensional inaccuracy, prolonged duration during the printing procedure, various inconsistent steps occur across different printing technologies, setting shrinkage during curing, distortions occur due to printing variables of the machine, and varied final product characteristics (surface and physical) [10,11]

Similar to traditionally manufactured restorations, internal adaptation and marginal fit are vital factors for the final dental restoration's performance in AM (additive manufacturing) or SM (subtractive manufacturing) restorations .So as to ensure proper response of the vital tissues including the periodontal ligament and the tooth pulp as well as superior cement performance, it's of prime importance to obtain a maximum adaptation between the restoration margin and the tooth finish line. The slight misalignment which may appear at the restoration margin can cause secondary caries, microleakage, cement dissolution, and pupal health risk. Various acceptable marginal gap ranges were described by many authors, dependent on type of the restorative material, material of the cement, and measurement method. There isn't a certain consensus, though. Indirectly made restorations with 50-120 µm misalignment at the marginal area could be considered clinically acceptable, however if the misalignment not more than 25 µm it can be considered ideal [12–14]

Despite limited practical and technological challenges, the milling process was able to create a single-unit, long span bridges and full arch patients with superior functional and cosmetic needs. On the contrary, the printing techniques of zirconia, have introduced recently in the dental practice, also the previous studies regarding this topic showed variable conflicting results versus the traditional milling process. This invitro investigation aimed to assess how accurate monolithic zirconia restoration constructed by milling (subtractive) and printing (additive) techniques. The study's null hypothesis was that there would be no difference in the internal and marginal gaps between monolithic zirconia single unit indirect restoration made additively and subtractively.

MATERIALS AND METHODS

Experimental design:

An observational, randomized and experimental in vitro assessment was carried out following the approval of The Research Ethics Committee of the Cairo University Faculty of Dentistry with number (40/10/25)].

Sample size calculation:

Based on a study conducted in 2023 by Refaei et al [15], with a power of 80% (β=0.20) and a level of significance of 5% (α error tolerable =0.05), the required sample size was 16 specimens per group. resulting in a total of 32 sample. To improve the dependability of the results and account for potential experimental mistakes, each group had 20 specimens. The sample size was computed using G*Power version 3.1.9.7.

Sample preparation and grouping:

Twenty upper second premolar acrylic teeth were prepared with a 1 mm deep chamfer finish line, 6° axial wall convergence, and occlusal clearance with 1.5mm reduction. The STL files, obtained using an intra oral scanner (Medit i500), were utilized for digital crown designing using CAD software (exocad version 3.0, exocad GmbH, Germany). A luting space of 70 µm was set, begin 1mm away from the preparation margin. The samples were divided into two groups:

For Group 1 (n=20):

To begin the construction of the milled crown, and in the Millbox software, the block type (Nacera blanks, Germany) and the disc's scale factor (1.25) were manually entered and confirmed by choosing the (√) mark. A zirconia disc of the appropriate size was chosen, inserted into the milling chamber of the Roland DWX-510 milling machine (Roland, Japan), and fastened with a screw. After milling, an abrasive tool was used to separate the restorations from the block. Then the crowns were cleaned in US cleaner for 60 seconds and were left to completely dry before sintering. The Mihm Vogt Tabeo Sintering furnace (Germany) was used for the sintering step. The crucible rack was filled with a layer of sintering beads and crowns put so that the occlusal aspect looking downwards. The sintering tray was put on the shelf in the furnace. The furnace door was manually closed, the desired program was chosen in accordance with the manufacturer's instructions, and the program was started by pressing the start button. Sintering was done at maximum temperature of 1530ºC. Once the cycle was finished, the furnace door was opened, and the sintering tray was raised and left to bench cool. The crowns were examined for cracks, faults, and defects.

For Group 2 (n=20):

The 3D-printed zirconia crowns (Lithoz 210 3Y, Austria) produced using a CeraFab7500 (Lithoz, Austria) three-dimensional printer, with 1mm base thickness with supports placed on the crowns' lingual aspect perpendicularly for stabilization and carrying crowns during printing, during which the occlusal aspect directed upwards. To compensate for shrinkage in X and Y axes, the scale was 1.27, while in the Z axes was 1.3 as recommended by the manufacturer. The layer thickness set was 25 µm, with 36 seconds curing time, the exposure intensity was 110 mj/cm^2 and 90^o build direction. The printed crowns were sintered consecutively in three ovens (Nabertherm, Germany) after being cleaned using ethylene-glycol solvent in an ultrasonic bath and compressed air. First oven where preconditioning was commenced at 120°C spanning 2h, and then temperature raised till 300 °C and held for 1h, then raised till 600°C and held for 2h. Then specimens were transferred to the second furnace for binding removal at 1000 °C spanning 1h, and finally zirconia crowns were sintered at temperature of 1450 °C and spanning 2h. Then left to bench cool till room temperature.

Following sintering, no modifications were made to the inside surface of any crown. The crowns were then sandblasted with 50 µm alumina particles at 2 bar for 10 seconds. All crowns were subsequently seated over the prepared acrylic teeth and verified for proper seating using a dental explorer.

Vertical Marginal gap distance:

Holmes et al. [16] illustrated this gap as the extension from the edge of the restoration till the outer end of the prepared finishing line. For gap distance evaluation, we used USB digital microscope connected to digital camera, by which the specimens were photographed.

Technique:

The following imaging system was used to take a proper image:

1) Digital camera (***U500x Digital Microscope, China***) with resolution of 3 Mega Pixels, positioned in a vertical direction with 2.5cm distance away from the specimens and with 90^o angle between light source and the lens axes.
2) Eight light emitting diode lambs were used as a source of light with approximately color rendering index of 95%.

After that, these images were transferred to IBM computer. These images were with 35x magnification and 1280 × 1024 pixels resolution. To analyze the captured image, we used Image J software to assess the gap dimensions. This software used the pixels to demonstrate sizes, measure parameters, frames and limits within the image. To be measurable, these pixels should be expressed in micron meters, this was done by calibration process done by modifying the pixels with the aid of a known size sample with a ratio created by the software. For each specimen, marginal areas were imaged, a quantitative evaluation for the marginal area was done for each image at three points placed away from each other with the same distance for each surface. After collecting data, these were tabulated and subjected to statistical analysis (Figure 1).

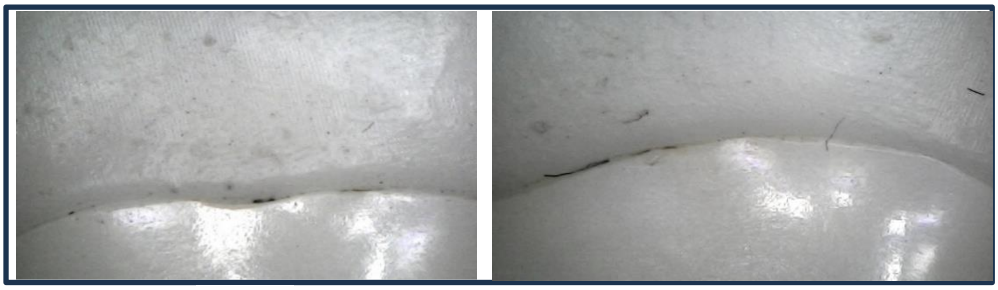

Figure 1. Vertical marginal gap under digital microscope for milled (a) and printed (b) crowns

Internal gap:

Internal gap is defined as the gap between the intaglio crown surface and the external prepared surface. Silicon replica technique was used to quantitively evaluate the internal fit. A light consistency silicon impression material was used to fill the intaglio surface of the crown, then insert over the prepared acrylic teeth with the aid of a modified papallellometer. This device permitted the application of a standardized constant load of 750 grams for ten minutes. After polymerization of the light consistency impression material, the restoration was separated from the prepared teeth. Due to its very low thickness and strength, and to avoid its distortion, the light consistency silicon material was stabilized using a heavy consistency impression material. After setting, this replica was cut into two parts. This was done using a razor blade (no. 15), then the internal fit was evaluated for each part in four areas, the marginal, axial, axio-occlusal and mid occlusal. Then measurement of the light consistency impression material was done with digital microscope with 30 X magnification (Figure 2). To analyze the captured image, we used Image J software to assess the gap dimensions. This software used the pixels to demonstrate sizes, measure parameters, frames and limits within the image. To be measurable, these pixels

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Figure 2. Digital microscopic picture showing the internal adaptation for milled (a) and printed (b) crowns.

RESULTS

This research was performed to evaluate the accuracy of fit of zirconia crowns constructed by milling and printing techniques, marginally and internally. Data were coded and entered using the statistical package for the Social Sciences (SPSS) version 28 (IBM Corp., Armonk, NY, USA). Data was summarized using mean and standard deviation. Comparisons between milled and printed fabrication methods applied to each tooth were done using paired t test. P-values less than 0.05 were considered as statistically significant.[17,18]

Vertical marginal gap:

The results showing the marginal discrepancy comparisons between the two groups were shown in Table 1. Three dimensionally printed restorations showed higher mean values of discrepancy of 84.3 µm but milled restorations showed a mean discrepancy of 56.90 µm ($p < 0.001$) (Figure 3).

Table 1 Mean, standard deviation, and 95% confidence interval of vertical marginal gap for milled and printed groups.

		Milled	printed	P value
Vertical Marginal Gap	**Mean** (µm)	56.90	84.30	< 0.001
	Standard Deviation	7.77	13.50	
	Standard Error of Mean	1.74	3.02	
	95.0% Lower CL for Mean (µm)	53.26	77.98	
	95.0% Upper CL for Mean (µm)	60.54	90.62	

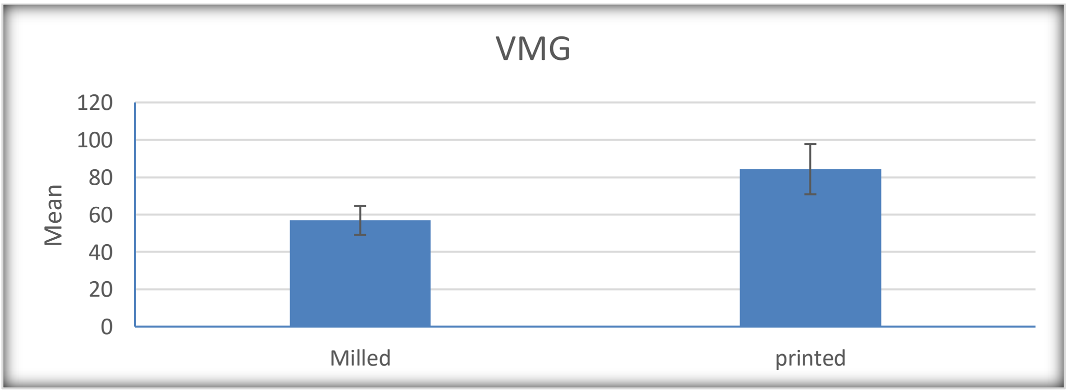

Figure 3. Bar chart showing the vertical marginal gap for milled and printed zirconia crowns

Internal gap:

Table (2) and figure (4) demonstrated the mean and standard deviation and 95% confidence interval of the internal discrepancy in the two groups marginally, axially, axio-occlusally, and mid-occlusally. Intergroup assessment of internal fit showed that the mean gap values for printed crowns were substantially higher than the milled group at the marginal, axio-occlusal, and mid-occlusal surfaces ($p<0.001$ in these areas). However, the difference observed axially was not statistically significant ($p=0.405$)

Table 2.Mean, standard deviation and 95% confidence interval of internal gap in milled and printed groups at marginal, axial, axio occlusal and mid occlusal areas.

		Milled	printed	P value
Internal marginal	**Mean** (µm)	61.75	82.65	< 0.001
	Standard Deviation	13.54	12.53	
	Standard Error of Mean	3.03	2.80	
	95.0% Lower CL for Mean (µm)	55.41	76.79	
	95.0% Upper CL for Mean (µm)	68.09	88.51	
Internal axial	**Mean** (µm)	82.65	84.65	0.405
	Standard Deviation	7.47	6.91	
	Standard Error of Mean	1.67	1.54	
	95.0% Lower CL for Mean (µm)	79.15	81.42	
	95.0% Upper CL for Mean (µm)	86.15	87.88	
Internal axio occlusal	**Mean** (µm)	88.10	119.10	< 0.001
	Standard Deviation	7.82	18.57	
	Standard Error of Mean	1.75	4.15	
	95.0% Lower CL for Mean (µm)	84.44	110.41	
	95.0% Upper CL for Mean (µm)	91.76	127.79	
Internal occlusal	**Mean** (µm)	237.00	294.65	< 0.001
	Standard Deviation	25.14	18.73	
	Standard Error of Mean	5.62	4.19	
	95.0% Lower CL for Mean (µm)	225.24	285.88	
	95.0% Upper CL for Mean (µm)	248.76	303.42	

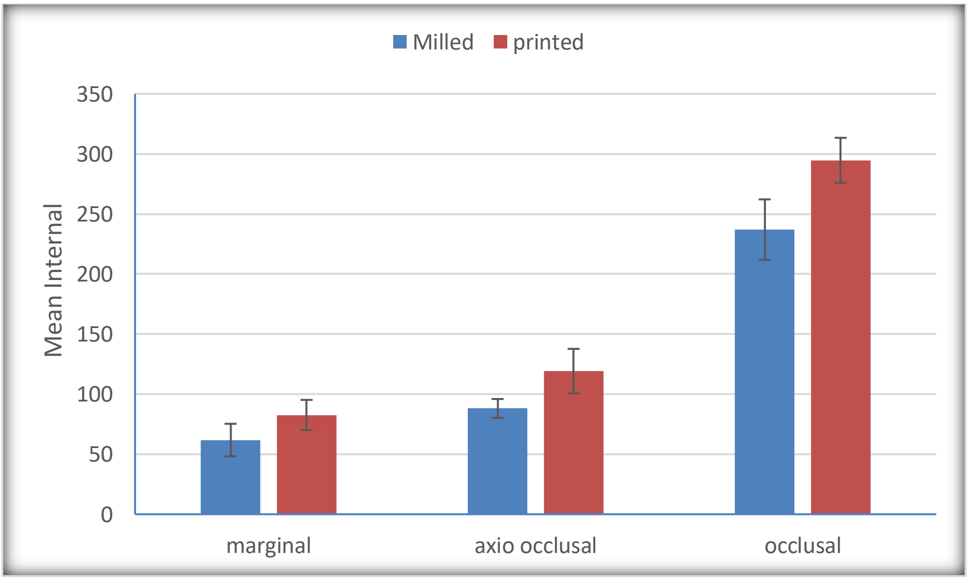

Figure 4. Bar chart showing the mean internal gap for milled and printed zirconia crowns

DISCUSSION

As a result of their strength, biological compatibility, and its aesthetically pleasing qualities, monolithic zircon crowns are one of the most popular remedies in contemporary dentistry. Subtractive grinding using computer-aided design and manufacturing is the conventional approach for creating zirconium crowns. Although constituting a relatively dependable process, subtractive grinding offers several disadvantages, including high costs of production, excessive damage on the milling cutters, wasted material, as well as obstacles in grinding complicated shapes. Plenty of attempts were undertaken to generate dental crowns utilizing recent technologies such as additive manufacturing, often known as methods of 3D printing, in order to get over these problems[1,19]

Because CAD-CAM has several benefits, including time efficiency, high precision, and more efficient, it has become an important development in the modern construction business[20].

Additive manufacturing, a different acronym for 3D printing, is a sophisticated process that uses a computer to submit a digital file to build a three-dimensional real product. Its basic idea is a speedy production method that employs successive layers of printing. Layered printing, which produces directly, quickly, and without sacrificing raw materials, entails assembling primary elements of production to make an object with three dimensions. Selective laser melting, selective laser sintering, fused deposition modeling, stereolithography, and digital light processing are just a few of the 3D printing approaches obtainable today [21]

For printed indirect restorations and to guarantee appropriate adaptation and a sufficient proper oral tissue reaction, the crown restoration needs to be provided with a precise fit. The number, placement, and size of supports, the digitizing method/scanner, and the printing technique all affect how precise a printed object is [22]

The finish line utilized is the deep chamfer finish line due to its increased dimension and inner angles are rounded, a deep chamfer enhances the mechanical functionality of posterior zirconia restorations and offers enough cervical space for appropriate crown contouring allow an improved adaptation of the restoration margin [(23)].

Medit I 500 scanner was used for acquisition due to its high accuracy related to the superior performance of the triangulation and structured light scanning. This scanner also allows video stream scanning which offer speedy, easy handling and time efficient scanning [24].

Exocad's was used as the designing program, as it allows to construct a prosthesis with best fit and accuracy, enhanced efficiency, more fast process, allow for the same-day restorations, and freedom and adaptability because of its open system that works with a variety of devices [25].

The unique characteristics of CAM dental systems could impact the end result of milled indirect restorations. The format, size, and quality of milling burs, how many milling unit axes, and the expected adhesive space are all significant factors influencing the fit of the reconstruction [19].

In this investigation a 5-axis milling machine was used as it allows construction of complex forms, which also has better surface finishes, more efficiency, and more precision because it requires fewer setups. These machines improve tool life while reducing manufacturing time, labor, and the possibility of error due to work piece repositioning as they can manufacture parts from various angles in just one setup [26,27].

The printable zirconia represented as high-performance zirconium oxide ceramics fabricated by Lithography-based Ceramic Manufacturing (LCM), which is a three-dimensional printing technique relay mainly on stereo lithography. This material comprises 3 mol% yttria-stabilized tetragonal zirconia polycrystalline (3Y-TZP), which is well known to be with excellent biological compatibility, mechanical qualities, and prosthesis longevity. The printable zirconia presented as a powder which is embedded in a resin (binder) that is light curable in a layer-by-layer fashion to produce a densely packed, with excellent details and superior clarity ceramic slurry (up to 25–50 µm). To completely get rid of the resin polymers (called debinding), the zirconia is sintered at a very high temperature degree after being printed (about 1500°C) creating a ceramic with superior density (green state) [28,29] .

This research examined the adaptation of single crown restoration created either via additive printing and subtractive milling approaches. To guarantee uniformity and standardization of the fabricated crowns, the samples were created utilizing two production processes (subtractive and additive) with exactly the identical STL file.

When planning a prosthodontic restoration, two of the most essential elements to take into account is the fit either marginal or internal. The interior gap, which is the measurement that is obtained perpendicularly from the material's internal surface to the preparation's exterior wall, is the same as the marginal gap, according to Holmes [16]. Poor marginal fit diminishes the prostheses' longevity by generating leakage that causes recurrent decay, mucosal irritation, and luting agent dissolution, and inadequate internal fit increases the risk of prosthesis fracture [30].

The material of construction, the preparation geometry, properties of cements, shrinkage following sintering production and the subsequent finishing and processing characteristics are some of the factors that is related to crown fit and marginal adaption[31].

There are various ways for evaluating the restoration fit either, marginal or internal, which can be divided into destructive or non-destructive, as well as 2D or 3D. This includes direct view with microscope; indirect view on resin duplicates; silicone replica technique with optical scanning; micro-CT analysis, silicone replica approach, and the triple scan technique [21].

It can be difficult to assess a crown's marginal fit. While the replica method has been proven to be effective in verifying the internal and marginal fit of crowns, there are various shortcomings and can be technique-sensitive. One of the shortcomings of this technique is a limited number of measurement points for each restoration, therefore it may not represent the true circumferential fit of a crown; however, as the technique has been used extensively in prosthodontics, it makes comparisons to other studies easier [32].

The vertical gap located at the margin was assessed with a digital microscope as it is regarded as reliable and non-destructive measuring device. Additionally, Yucel et al. claimed that using the microscope along with software for image analysis enables non-invasive numerous examinations through direct imaging[33].

Regarding the fitting of the zirconia crowns, whether vertical or internal, each of the tested samples remained within the accepted clinical range, as well as the marginal gap values of crowns fabricated by both methods were not more than 120 µm. The milled crowns' marginal gap ranged from 56.9 ± 7.77 µm, researchers whom examined the monolithic zirconia crowns marginal discrepancy; for CAD/CAM restorations, the gap varied from 30 to 150 µm. Additionally, for the crowns created by the additive technique, their marginal gaps were within the range of 84 ± 30 µm, that was consistent with the findings of Ryu et al., who examined the impact of various build orientations on the internal and marginal fits of 3D printed resin crowns[34–37]

In comparison to the additive techniques, the mean marginal gap of the subtractive crowns was much less. This could be related to diminishing accuracy during 3D printing result from errors accumulating at several stages of production, design segmentation by printing software, processing, and printing itself. The shrinkage that happened during construction and after curing resulted in a larger marginal gap, the material becoming too polymerized during manufacture, which causes light to scatter and more material to harden than expected. These results were in accordance with Savencu et al. and Refaei et al [15,38] .

On the other hand, other authors reported that the milled restorations have a higher vertical marginal gap than 3D-printed restorations. This can be explained by the intrinsic variations in material handling and production techniques. The subtractive manufacturing method employed in CAD/CAM milling, which is used in traditional construction, can produce small errors, especially at complex shapes and tiny margins. The diameter of milling tools frequently limits their precision in creating thin edges and complex designs, which may lead to greater marginal discrepancy[32,39,40]

Regarding the internal gap, the milled crowns had lower values than the 3D printed crowns in the discrepancy at the margin, axial occlusal discrepancy, and mid occlusal discrepancy this could be related also to the previously mentioned causes. Accordingly, the null hypothesis of this research was rejected.

Conclusions and clinical relevance:

With the inherent restrictions of this invitro study, the following could be concluded:

1- All milled specimens showed clinically accepted results regarding the internal and the marginal discrepancy values
2- All 3D printed specimens showed clinically accepted results regarding the internal and the marginal discrepancy values can be considered a therapeutically suitable substitute.
3- The milled crowns had improved internal fitting than the 3D printed crowns
4- The milled crowns had improved marginal fitting than the 3D printed crowns

Limitations of the study:

1- This research was in vitro and did not mimic the intra oral complex conditions such as the saliva, masticatory forces, temperature changes etc.
2- Use of acrylic resin teeth rather than natural teeth, did not resemble the natural oral conditions
3- No thermocycling or dynamic loading was applied.
4- 2-dimensional evaluation of the discrepancies was done rather than the 3-dimensional evaluation.

Further recommendation:

1-To evaluate the internal and the marginal discrepancy in real scenario human cases including in vivo studies.

2-Evaluation of the tensile, compressive strength and fracture resistance of the novel 3D printed zirconia crowns.

3-Evaluation of the internal and marginal fitness with thermocycling and dynamic loading for the novel 3d printing nano zircon.

DECLARATION

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Conflicts of interest.

No conflicts of interest.

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