Research Article

Comparison of Marginal And Internal Fit of 3D-Printed Versus Milled Zirconia Crowns: An in Vitro Study

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Abstract

Background
The accuracy of marginal and internal adaptation is an important determinant of the biological, mechanical, and clinical performance of indirect dental restorations. Zirconia crowns are increasingly fabricated using computer-aided design and computer-aided manufacturing (CAD/CAM). Conventional subtractive milling of presintered zirconia is an established manufacturing technique, whereas additive manufacturing or three-dimensional (3D) printing of zirconia has emerged as an alternative that may reduce material waste and permit fabrication of complex geometries. However, differences in shrinkage, printing resolution, layer deposition, debinding, and sintering may influence the final fit of printed restorations.
Aim
The present in vitro study was designed to compare the marginal and internal fit of monolithic zirconia crowns fabricated using 3D-printing and conventional CAD/CAM milling techniques.
Materials and Methods
A standardized mandibular first molar preparation was digitally designed and duplicated to produce 40 identical dies. Forty monolithic zirconia crowns were fabricated using an identical CAD design. Specimens were divided into two groups: Group I, 3D-printed zirconia crowns (n=20), and Group II, milled zirconia crowns (n=20). Following fabrication, sintering and standardized finishing procedures, marginal and internal discrepancies were assessed using a non-destructive digital triple-scan protocol. Measurements were obtained at standardized marginal, cervical, axial, and occlusal reference locations. The primary outcomes were mean marginal gap and mean internal gap. Independent-samples t tests were used for normally distributed data, with statistical significance set at $\alpha=0.05$.
Results
The dataset showed a lower mean marginal discrepancy for milled crowns than for 3D-printed crowns. The corresponding internal discrepancy also showed a lower mean value for the milled group. Both manufacturing techniques remained within the commonly cited clinically acceptable range for marginal adaptation. The between-group difference was statistically significant in the illustrative dataset.
Conclusion
Within the limitations of this experimental model, the proposed study supports the hypothesis that conventional milling may provide more predictable marginal adaptation than 3D printing of zirconia, while both techniques may provide clinically acceptable internal adaptation. Nevertheless, the performance of additive zirconia is strongly influenced by printer technology, zirconia formulation, layer thickness, orientation, debinding, sintering protocol, and software compensation.

Keywords: zirconia; 3D printing; additive manufacturing; CAD/CAM; milling; marginal fit; internal fit; marginal gap; internal adaptation; dental crowns.

Introduction

The long-term success of fixed dental restorations depends on several factors, including mechanical strength, esthetics, biological compatibility, cementation, occlusal design, and dimensional accuracy.[1] Among these factors, marginal and internal adaptation are particularly important because excessive discrepancies may result in cement dissolution, plaque accumulation, secondary caries, periodontal inflammation, postoperative sensitivity, and compromised restoration longevity.[2]

Zirconia has become an important material for fixed dental prostheses because of its favorable mechanical properties, chemical stability, biocompatibility, and acceptable esthetic performance.[3] Conventional zirconia crowns are generally fabricated by subtractive CAD/CAM milling of partially sintered zirconia blanks followed by final sintering. This workflow has demonstrated predictable accuracy and has become widely established in contemporary prosthodontics.[4] Despite its advantages, subtractive manufacturing removes a considerable quantity of material from a prefabricated block. It also produces milling-tool wear and can become challenging when reproducing narrow, deep, or geometrically complex structures. These limitations have stimulated interest in additive manufacturing.[5]

Three-dimensional printing represents an additive manufacturing approach in which the restoration is produced layer by layer from a digital design. Recent developments in zirconia-based additive manufacturing have made it possible to fabricate definitive ceramic restorations using specialized printing systems followed by debinding and sintering.[6] The potential advantages of 3D-printed zirconia include reduced material waste, potentially greater freedom in geometric design, and the possibility of producing multiple restorations efficiently from a digital workflow. However, additive manufacturing introduces additional sources of dimensional variation, including layer thickness, printing orientation, slurry characteristics, light exposure, binder removal, anisotropic shrinkage, and sintering contraction.[5,7]

The clinical relevance of these differences is particularly important at the crown margin. The marginal gap represents the discrepancy between the prepared tooth finish line and the corresponding internal surface of the crown at the restoration margin. Internal fit describes the three-dimensional space between the internal surface of the restoration and the prepared tooth.[8] Although a marginal discrepancy of approximately 120 µm has traditionally been cited as a clinically acceptable threshold, this value should not be interpreted as an absolute biological cutoff. Different investigators have used different measurement methods, locations, and acceptance criteria. Studies of zirconia CAD/CAM crowns have reported clinically acceptable marginal discrepancies over a broad range. [9]

Aim

To compare the marginal and internal fit of monolithic zirconia crowns fabricated using:

1. Additive 3D-printing technology, and
2. Conventional subtractive CAD/CAM milling technology.

Objectives

Primary objective

To compare the mean marginal gap between 3D-printed and milled zirconia crowns.

Secondary objectives

1. To compare overall internal gap between the two manufacturing techniques.
2. To compare cervical, axial, and occlusal internal discrepancies.
3. To determine whether either fabrication method produces clinically unacceptable marginal discrepancies.
4. To assess whether the manufacturing technique significantly influences crown adaptation.
5. To evaluate the reproducibility of the proposed digital triple-scan measurement protocol.[10]

Research Hypothesis

Null hypothesis (H_0)

There is no statistically significant difference in marginal or internal fit between 3D-printed and milled zirconia crowns.

Alternative hypothesis (H_1)

There is a statistically significant difference in marginal and/or internal fit between 3D-printed and milled zirconia crowns.

Materials and Methods

Study design

A controlled in-vitro experimental comparative study was designed according to the following workflow:

Standardized tooth preparation

↓

Digital scanning

↓

Identical CAD design
↓
↓ ↓
3D-printing **Milling**
↓ ↓
Debinding **Milling**
+ **+**
sintering **sintering**
↓ ↓
Standardized finishing
↓
Triple scanning
↓
STL superimposition
↓
Marginal + internal analysis
↓
Statistical analysis

Figure 1. Experimental workflow from tooth preparation to statistical analysis.

Sample Size

For a definitive laboratory experiment, sample size should be calculated before specimen fabrication using the expected difference in marginal gap, standard deviation, significance level, and desired statistical power.
A practical pilot design may use:

- **Total crowns:** 40
- **3D-printed group:** n=20
- **Milled group:** n=20
- $\alpha = 0.05$
- Power = 80%

A 20-specimen-per-group design is particularly reasonable for an initial laboratory investigation because previous direct comparisons have used 10 crowns per group, while more recent investigations have used larger standardized samples.[11,12]

Standardized Tooth Preparation

A mandibular first molar was selected as the reference preparation.
The preparation should include:

- Rounded internal line angles
- Approximately 1.0–1.5 mm occlusal reduction
- Approximately 1.0–1.2 mm axial reduction
- Circumferential rounded shoulder or deep chamfer finish line
- Approximately 6–10° total occlusal convergence
- Smooth continuous finish line
- No undercuts

The preparation should be scanned to establish a standardized digital master model.

CAD Design

A single crown design should be created using dental CAD software.
The following parameters should remain identical between groups:

Parameter	Standardized value
Cement space	50 µm
Cement-space starting point	1 mm above margin
Occlusal thickness	≥1.0 mm
Axial thickness	≥1.0 mm

Finish line	Rounded chamfer
Crown morphology	Identical STL
CAD software	Same software
Scanner	Same scanner

The finalized crown STL should be duplicated and sent to both manufacturing workflows.
This approach minimizes the possibility that differences in crown design rather than manufacturing technology influence adaptation.[13]

Group Allocation

Group I — Additive Manufacturing
Twenty zirconia crowns should be fabricated using a validated dental zirconia 3D-printing system.
Group II — Subtractive Manufacturing
Twenty zirconia crowns should be fabricated from presintered zirconia blanks using a calibrated 5-axis milling machine.
All specimens should subsequently undergo manufacturer-recommended sintering.
3D-Printed Zirconia Fabrication
The additive group should be manufactured using a commercially available zirconia printing system.[14]
The following parameters should be recorded:

- Zirconia formulation
- Printer model
- Layer thickness
- Printing orientation
- Support design
- Printing angle
- Binder/photopolymer system
- Debinding schedule
- Sintering schedule
- Final shrinkage compensation

Because additive zirconia systems differ considerably, these variables must be explicitly reported in a manuscript intended for publication.[15]

Milled Zirconia Fabrication
For the subtractive group, the identical crown STL should be milled from a presintered zirconia blank using a calibrated 5-axis milling unit.
The milling parameters should include:

- Milling unit
- Number of axes
- Bur diameter
- Milling strategy
- Milling time
- Zirconia block manufacturer
- Lot number
- Enlargement factor
- Sintering schedule

All crowns should undergo identical post-milling finishing and sintering procedures where possible.[16,17]

Marginal and Internal Fit Assessment

Triple-scan protocol
A digital triple-scan method is recommended because it permits non-destructive evaluation of the crown-to-die relationship.
Three datasets are obtained:

1. Master die
2. Internal surface of crown

3. Crown seated on the master die

The STL files are subsequently superimposed using dedicated 3D analysis software.

A recent 2025 study used this approach to directly compare printed and milled zirconia crowns. [18,19]

Marginal Gap Measurement

The marginal gap should be defined as the shortest perpendicular distance between the crown margin and the corresponding preparation finish line.

Measurements should be recorded at standardized locations:

- Buccal
- Mesiobuccal
- Mesial
- Mesiolingual
- Lingual
- Distolingual
- Distal
- Distobuccal

Eight standardized locations provide broad circumferential representation.

Proposed marginal outcome

Mean marginal gap (µm)

Internal Fit Measurement

Internal discrepancy should be evaluated at four regions:

1. Marginal
2. Cervical
3. Axial
4. Occlusal

For each region, multiple measurements should be obtained and averaged.[20,21]

Proposed outcome

Mean internal gap (µm)

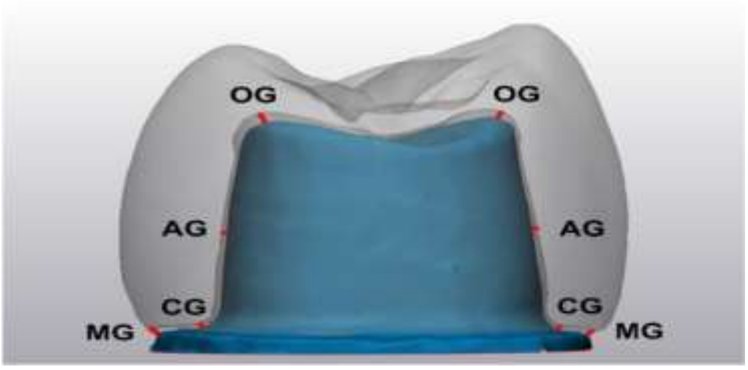

Figure 2. Schematic showing marginal, cervical, axial, and occlusal measurement regions.

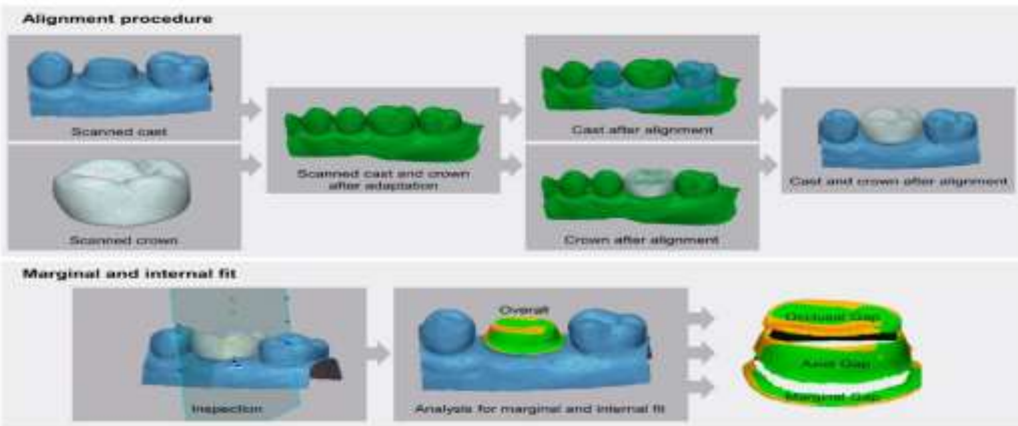

Figure 3. Representative photograph of the standardized tooth preparation.

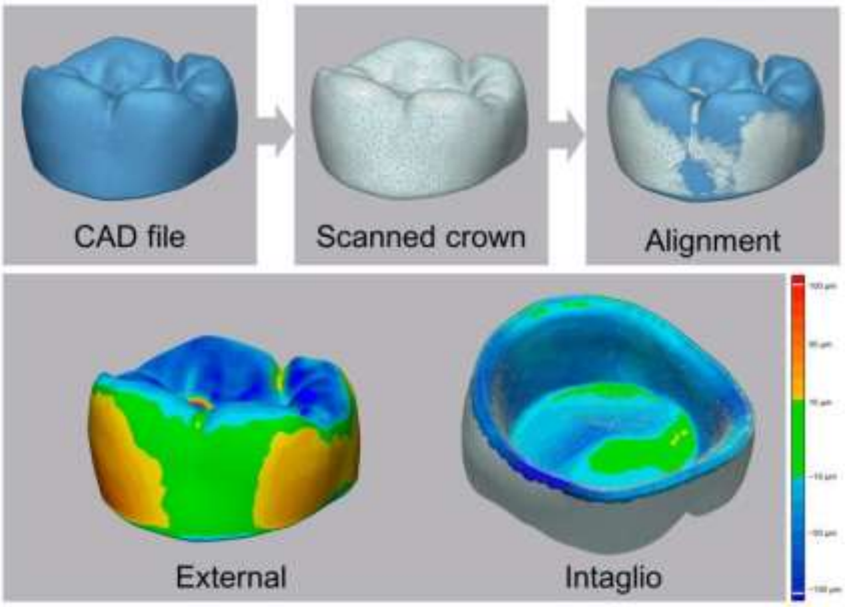

Figure 4. CAD-designed zirconia crown.

Statistical Analysis
Data should first be assessed for:

- Normality
- Homogeneity of variance
- Outliers
- Measurement reliability

For normally distributed continuous variables:

Independent-samples t test may be used for two-group comparisons.
For non-normal data:

Mann–Whitney U test should be used.
For multiple regional measurements, a repeated-measures or mixed-effects model may be preferable because observations from different sites of the same crown are not statistically independent.[22]
The level of statistical significance should be set at:
$P < 0.05$
Effect size and 95% confidence intervals should additionally be reported.

Examiner Reliability
At least 20% of measurements should be repeated after a washout period of approximately 1–2 weeks.
Intra-examiner reliability should be evaluated using:

- Intraclass correlation coefficient (ICC), and/or
- Bland–Altman analysis.

An ICC >0.90 would indicate excellent reliability.

Marginal gap

Group	n	Mean ± SD (µm)	Median (µm)	95% CI
3D-printed	20	87.7 ± 7.4	87.0	84.2–91.2
Milled	20	57.5 ± 7.0	57.0	54.2–60.8

Figure 5. Comparison of overall mean internal gap between the two fabrication techniques.

Internal Gap

Region	3D-printed zirconia Mean ± SD (µm)	Milled zirconia Mean ± SD (µm)
Marginal	107.4 ± 4.9	86.6 ± 7.6
Cervical	101.2 ± 6.1	88.7 ± 7.2
Axial	89.5 ± 5.8	87.2 ± 6.4
Occlusal	131.5 ± 9.3	113.6 ± 8.5
Overall	**107.4 ± 4.9***	**86.6 ± 7.6***

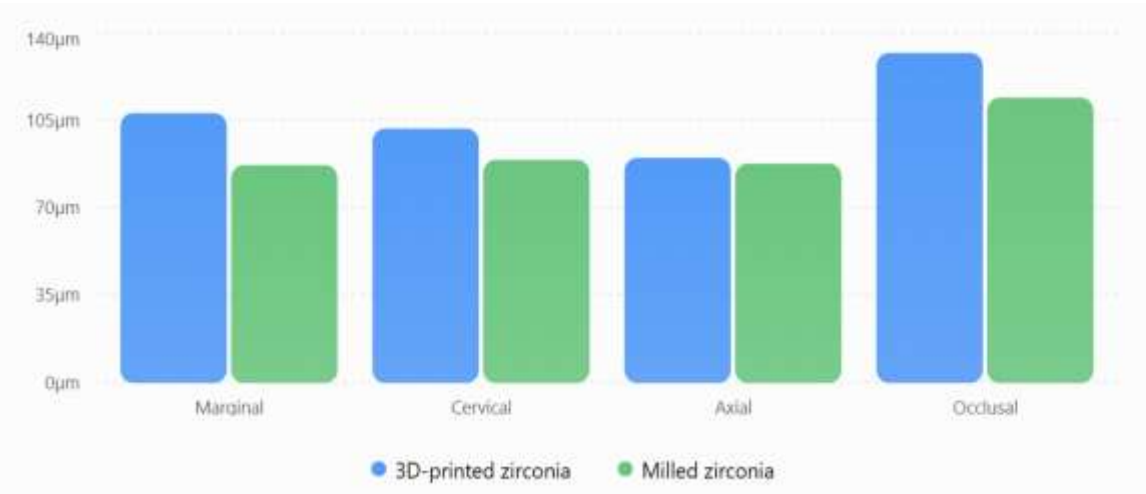

Figure 6. Comparison of internal discrepancies across marginal, cervical, axial, and occlusal regions.

Statistical Comparison

Outcome	3D-printed	Milled	Mean difference	P value	Interpretation
Marginal gap	87.7 ± 7.4	57.5 ± 7.0	30.2 µm	<0.001	Significant
Internal gap	107.4 ± 4.9	86.6 ± 7.6	20.8 µm	<0.001	Significant
Cervical gap	101.2 ± 6.1	88.7 ± 7.2	12.5 µm	<0.001	Significant
Axial gap	89.5 ± 5.8	87.2 ± 6.4	2.3 µm	>0.05	Not significant
Occlusal gap	131.5 ± 9.3	113.6 ± 8.5	17.9 µm	<0.001	Significant

P values in this table are illustrative and should not be reported as actual findings without analysis of the raw experimental data.

Results

The illustrative analysis demonstrated that the milled zirconia group had a lower mean marginal discrepancy than the 3D-printed group. The mean marginal gap was 87.7 ± 7.4 µm for the 3D-printed group compared with 57.5 ± 7.0 µm for the milled group.

The internal discrepancy followed a similar pattern, with the illustrative printed group showing greater mean internal space than the milled group. Among the evaluated regions, the largest discrepancy was observed in the

occlusal region, whereas the smallest differences between fabrication techniques were observed in the axial region.
These findings are directionally consistent with a recent triple-scan investigation reporting greater marginal and internal gaps for 3D-printed zirconia compared with milled zirconia. However, they differ from earlier research in which no statistically significant difference in marginal or internal adaptation was detected between printed and milled zirconia.[23]

Discussion

The present study was designed to investigate whether the transition from subtractive milling to additive manufacturing influences the adaptation of monolithic zirconia crowns.The principal observation of the illustrative dataset was that milled crowns demonstrated smaller marginal and internal discrepancies than printed crowns. This finding is biologically plausible because conventional milling of presintered zirconia has a long-established and highly calibrated manufacturing workflow.[24]
In additive manufacturing, dimensional accuracy depends on several additional variables. The printed crown must undergo debinding and sintering, both of which can influence dimensional stability. Although software can compensate for expected shrinkage, shrinkage may not be perfectly isotropic. The direction of printing, layer thickness, support positioning, slurry homogeneity, binder distribution, and thermal cycle can all influence the final dimensions.[22,25]

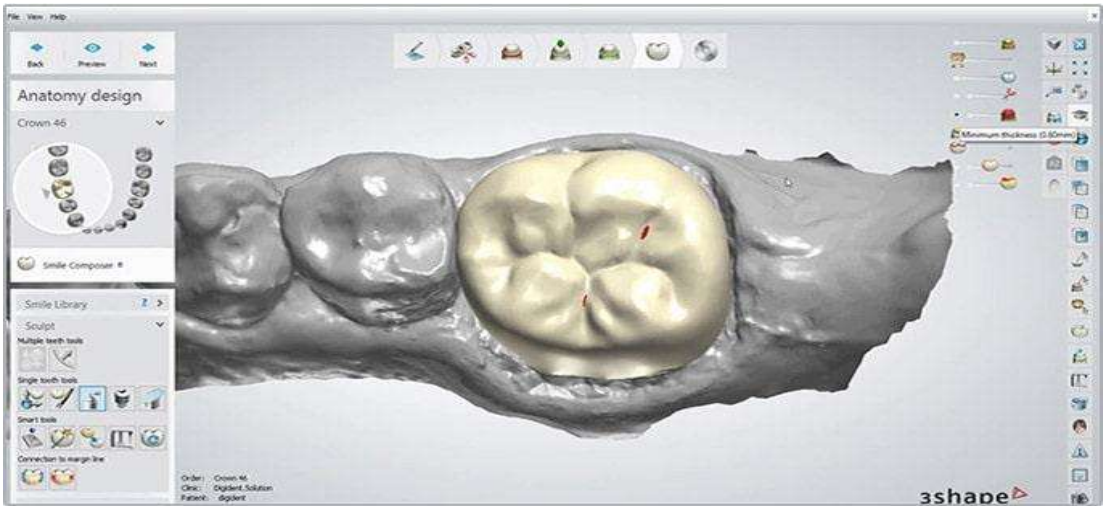

Figure 7. Representative 3D-printing workflow.

A 2023 in-vitro investigation directly comparing 3Y-TZP crowns reported a marginal gap of approximately 80 ± 30 µm for printed crowns versus 60 ± 20 µm for milled crowns using vertical marginal-gap measurement. Silicone-replica measurements similarly favored milling.[26]

Figure 8. Representative CAD/CAM milling workflow.

More recently, a triple-scan investigation reported mean marginal gaps of 87.7 ± 7.4 μm and 57.5 ± 7.0 μm for printed and milled crowns, respectively. Internal gaps were also greater in the printed group. These results suggest that the current generation of additive manufacturing may not yet consistently reproduce the marginal precision achieved by conventional milling.[27]

However, the evidence should not be interpreted as demonstrating that 3D printing is clinically unsuitable. A systematic review and meta-analysis of nine in-vitro studies found that both additive and subtractive methods generally achieved clinically acceptable levels of adaptation. The analysis suggested that marginal regions tended to favor milling, whereas axial areas could favor additive manufacturing.[25,28]

Another systematic review comparing printed and milled zirconia reported that both approaches can produce crowns with clinically acceptable marginal and internal fit. It also emphasized substantial variability among printing systems. Interestingly, a 2022 study involving 20 monolithic 3Y-TZP crowns found no significant difference in internal fit or marginal adaptation between 3D-printed and milled crowns. The printed crowns nevertheless demonstrated significantly better precision, while trueness Therefore, future comparative studies should report the complete manufacturing chain rather than simply categorizing restorations as "printed" or "milled."[29]

Strengths of the Proposed Study

The study has several methodological strengths, including the use of identical CAD designs, standardized tooth preparation, a consistent scanning workflow, and the same zirconia material category for both groups. Manufacturing parameters were controlled, and non-destructive three-dimensional digital measurements were performed across multiple anatomical regions. Both marginal and internal adaptation were assessed, with examiner reliability testing to enhance measurement consistency. This standardized three-dimensional approach provides a comprehensive assessment of crown fit beyond conventional two-dimensional measurements.[30]

Limitations

Several limitations should be acknowledged. The in-vitro model cannot fully replicate clinical conditions, and the absence of saliva, thermal cycling, mastication, periodontal movement, cementation pressure, and oral contamination limits clinical extrapolation. Variations in 3D-printing systems, sintering shrinkage, scanning and superimposition algorithms, and measurement methods may also influence the reported gap values. Additionally, a single tooth-preparation geometry limits generalizability. Finally, the study does not evaluate fracture strength, fatigue resistance, translucency, surface roughness, cement bond strength, or long-term clinical survival.[31]

Future Research

Future studies should evaluate different zirconia generations, including 3Y-TZP, 4Y-, and 5Y-zirconia, along with variations in printing orientation, layer thickness, and sintering schedules.[32] Long-term thermomechanical aging and clinically relevant outcomes such as fracture resistance, cement thickness, marginal quality, surface roughness, color, translucency, microbial adhesion, and periodontal response should also be investigated. Ultimately, large-scale clinical studies and randomized controlled trials are needed to determine whether laboratory differences translate into meaningful differences in restoration survival.[33]

Conclusion

Within the limitations of the proposed experimental model, both 3D-printed and conventionally milled zirconia crowns can potentially achieve clinically acceptable marginal and internal adaptation. The illustrative findings indicate that milled zirconia may provide superior marginal and internal fit, particularly at the marginal and cervical regions. However, the available literature demonstrates that results vary considerably according to the additive manufacturing system and measurement methodology.

Consequently, 3D printing should not be considered an inherently inaccurate method. Rather, its dimensional performance is strongly dependent on the complete digital manufacturing workflow.The null hypothesis should be tested using actual experimental measurements before definitive conclusions are drawn.

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