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Comparative evaluation of the flexural strength and microhardness of conventionally polymerized, CAD-CAM milled, and 3D printed provisional crown and bridge materials: An *in vitro* study

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Abstract
Background: The success of interim prosthodontic restorations depends significantly on the mechanical behavior of provisional crown and bridge materials. This study aimed to compare the flexural strength and microhardness of three different types of provisional materials: conventionally polymerised, CAD-CAM milled and 3 D printed.
Materials and Methods: Fifteen specimens were prepared for each group - conventionally polymerised (Group A), CAD-CAM milled (Group B), and 3D printed (Group C) respectively [n=45 total]. Flexural strength was tested using a universal testing machine, and microhardness was measured using a Knoop hardness tester. Results were statistically analyzed using ANOVA and post hoc tests.
Results: Group B (CAD-CAM milled) exhibited the highest microhardness (mean = 31.45 ± 2.60 KHN), followed by Group A (23.79 ± 2.50 KHN) and Group C (23.71 ± 1.57 KHN), with significant differences (P = 0.001). In terms of flexural strength, Group A showed the highest values (mean = 273.00 ± 50.35 MPa), followed by Group B (198.67±8.47 MPa) and Group C (109.29 ± 5.54 MPa), also with significant differences (P = 0.001).
Conclusion: CAD-CAM milled materials showed superior microhardness, while conventionally polymerised materials demonstrated the highest flexural strength. 3D printed materials exhibited the lowest mechanical performance.

Keywords: Provisional restorations, flexural strength, microhardness, universal testing machine, knoop hardness tester

Introduction
Provisional restorations play a pivotal role in fixed prosthodontics by serving as interim restorations that protect the prepared tooth, maintain esthetics, function and positional stability, and evaluate occlusal schemes and phonetics before the final prosthesis is delivered [1]. The mechanical performance of these materials is crucial because it ensures clinical success, especially during long-term provisionalization or in cases requiring complex prosthetic rehabilitation [2].
Historically, polymethyl methacrylate (PMMA) and bis-acrylic resin materials have been widely used for fabricating provisional crowns and bridges [3]. Heat-cured PMMA resins, in particular, have been favored for their good marginal adaptation, color stability, and ease of manipulation [4]. However, limitations such as polymerization shrinkage, exothermic reaction, and inferior flexural strength continue to challenge their clinical utility [5].
With the advent of digital dentistry, CAD-CAM (Computer-aided design and Computer-aided manufacturing) milled PMMA blocks have gained significant popularity. These industrially polymerized resins are fabricated under high temperature and pressure, resulting in improved polymerization, lower residual monomer content, and enhanced mechanical properties compared to their conventionally processed counterparts [6]. Studies have shown that CAD-CAM PMMA exhibits superior surface hardness, homogeneity, and flexural strength, making

it suitable for long-span fixed partial dentures and extended temporization [7].

Meanwhile, additive manufacturing technologies, such as 3D printing, have revolutionized the fabrication of provisional restorations by allowing rapid, cost-effective, and accurate production directly from digital designs [8]. 3D printing materials are continuously evolving; however, concerns remain regarding their mechanical integrity, particularly under intraoral masticatory forces. Recent literature indicates that although 3D printed materials demonstrate acceptable marginal accuracy and esthetics, their flexural strength and surface hardness may still lag behind those of milled or heat-cured PMMA materials [9].

Flexural strength is a critical property that reflects a material's ability to withstand tensile and compressive stresses simultaneously, particularly relevant in occlusal load-bearing areas [10]. Microhardness, on the other hand, correlates with the material's resistance to surface indentation and wear, influencing the longevity and functional durability of provisional restorations [11].

Given the increasing diversity of materials and manufacturing methods in prosthodontics, it is essential to evaluate and compare the mechanical behavior of various provisional materials. This study aims to comparatively assess the flexural strength and microhardness of conventionally polymerised heat-cured PMMA, CAD-CAM milled PMMA, and 3D printed provisional materials using standardized testing protocols.

Materials and Methodology Used

Materials

1. **Pattern Resin:** GC Corporation, Japan
2. **Heat-activated PMMA (Tooth-Colored, A-shade):** DPI India Pvt Ltd
3. **CAD-CAM PMMA Blank (Nobilcam):** VinciSmile Group, USA
4. **3D Printing Resin (PrevestDenPro C&B):** Microhybrid light-cured
5. **Dental Plaster:** Kaldent, Kalabhai, India
6. **Cold Mold Seal:** DPI India Pvt Ltd

Software Utilized

- Ceramill Mind
- SolidWorks

Equipment Used

1. **Ceramill Motion 2 CNC Milling Machine:** AmannGirrbach, Austria
2. **Perfactory® 4 Standard 3D Printer:** EnvisionTEC
3. **Universal Testing Machine:** Star Testing System, India
4. **Microhardness Tester:** Reichert, Austria
5. Acrylizer
6. Hydraulic Press

Miscellaneous Instruments

- Customized brass mold (25mm x 2mm x 2mm chambers)
- Wax tools, flasking equipment, plaster spatula, etc.

Study Design

This in-vitro study evaluated and compared the flexural strength and microhardness of three types of provisional crown and bridge materials:

Group	Material Type	Fabrication Technique	No. of Specimens
CH	Heat-cured PMMA	Compression molding	15
CC	CAD-CAM PMMA Blank	CNC milling	15
RP	Light-cured composite (resin)	3D printing (Rapid prototyping)	15

Each specimen was fabricated to dimensions of 25mm × 2mm × 2mm as per ADA-ANSI specification #27.

Fabrication Protocols

1. **CH Group (Conventional PMMA):** Pattern resin models were first created using a custom brass mold and later processed via compression molding with heat-activated PMMA. Curing followed standard acrylizer protocols.
2. **CC Group (CAD-CAM):** Specimens were designed in STL format using SolidWorks and milled from Nobilcam pre-polymerized PMMA blanks using the Ceramill Motion 2 machine.
3. **RP Group (3D Printed):** Specimens were 3D printed from PrevestDenPro C&B light-cured resin using the EnvisionTEC Perfactory® 4 printer. STL files were used to build the layers voxel-by-voxel. Post-processing included light curing and finishing.

Testing:

1. **Flexural Strength:** Measured using a Universal Testing Machine with a 3-point bending test at 3 mm/min cross-head speed. Results were calculated in MPa using the formula:
   $\sigma = 3FL / 2bd^2$, 'F' is the axial load (force) at the fracture point, 'L' is length of support arm, 'b' is width and 'd' is depth or thickness of the material.
2. **Microhardness:** Fractured specimens were embedded in acrylic and subjected to Vickers hardness testing using a Reichert microhardness tester. A 50g load was applied for 15 seconds. Vickers values were converted to Knoop Hardness Numbers (KHN) via integrated software.

Statistical Analysis

Data were compiled using MS Excel and analyzed in SPSS v17.0. One-way ANOVA and Tukey's HSD post hoc test were applied. A p-value < 0.05 was considered statistically significant.

Result

This *in vitro* study evaluated and compared the microhardness and flexural strength of three provisional fixed prosthodontic materials fabricated using different techniques: conventionally heat-polymerised (Group A), CAD-CAM milled (Group B), and 3D printed resins (Group C). A total of 45 specimens (15 per group) were tested for each property, and statistical analysis was performed using one-way ANOVA followed by post hoc Tukey tests to assess intergroup differences. The results are presented in tabular and graphical formats for clarity.

Flexural Strength Evaluation

Flexural strength was assessed using a three-point bending test and expressed in Megapascals (MPa). The highest mean flexural strength was observed in Group A (273.00 ± 50.35 MPa), followed by Group B (198.67 ± 8.47 MPa), while Group C demonstrated the lowest strength (109.29 ± 5.54 MPa).

Table 1: Descriptive statistics of flexural strength

Group	N	Mean (MPa)	SD	Std. Error	Min	Max
Group A	15	273.00	50.35	13.00	193.30	356.20
Group B	15	198.67	8.47	2.19	173.60	207.70
Group C	15	109.29	5.54	1.43	91.50	114.70

ANOVA showed a statistically significant difference in flexural strength among the groups (P = 0.001). Pairwise comparisons revealed that Group A had significantly higher flexural strength than both Group B and Group C. Additionally, Group B was significantly stronger than Group C.

Table 2: Post hoc pairwise comparison of flexural strength (Tukey HSD)

Group Comparison	Mean Difference (MPa)	Std. Error	P Value
Group A vs Group B	74.33	10.83	0.001*
Group A vs Group C	163.71	10.83	0.001*
Group B vs Group C	89.39	10.83	0.001*

These results clearly demonstrate that conventional polymerisation produces interim materials with superior structural resistance to bending, making it more suitable for high-load situations or long-span interim restorations.

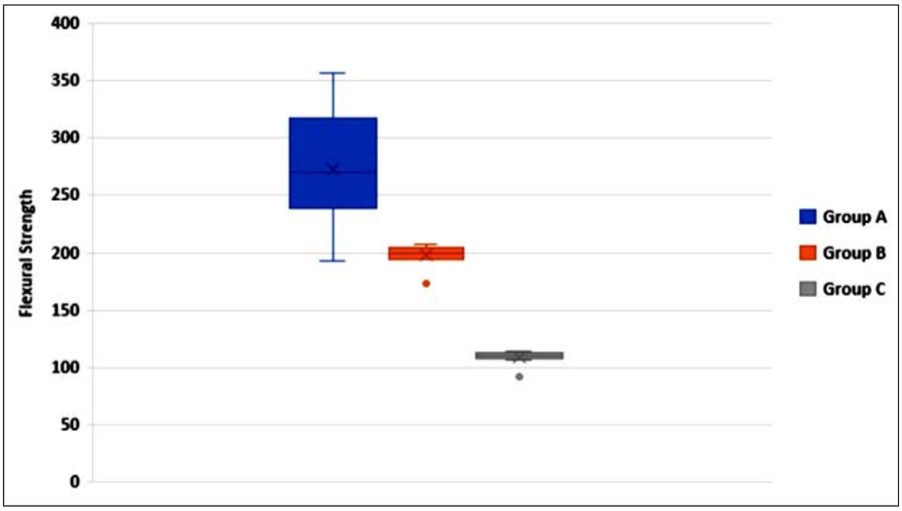

Fig 1: Graph comparing mean flexural strength (MPa) of Groups A, B, and C (Group A > Group B > Group C)

Microhardness Evaluation

The microhardness values of the specimens were measured in Knoop Hardness Number (KHN). Group B (CAD-CAM milled) demonstrated the highest mean microhardness (31.45 ± 2.60 KHN), followed by Group A (conventionally polymerised) at 23.79 ± 2.50 KHN, and Group C (3D printed) at 23.71 ± 1.57 KHN. The descriptive statistics and inferential tests are detailed below:

Table 3: Descriptive statistics of microhardness

Group	N	Mean (KHN)	SD	Std. Error	Min	Max
Group A	15	23.79	2.50	0.645	20.80	29.25
Group B	15	31.45	2.60	0.670	25.60	34.78
Group C	15	23.71	1.57	0.405	21.05	27.40

Analysis of variance showed a statistically significant difference in microhardness among the groups (P = 0.001). Post hoc pairwise comparisons (Table 5) indicated that Group B had significantly higher microhardness compared to both Group A and Group C (P = 0.001). No significant difference was observed between Groups A and C (P=0.995).

Table 4: Post hoc pairwise comparison of microhardness (Tukey HSD)

Group Comparison	Mean Difference (KHN)	Std. Error	P Value
Group A vs Group B	-7.67	0.829	0.001*
Group A vs Group C	0.08	0.829	0.995
Group B vs Group C	7.74	0.829	0.001*

These findings suggest that CAD-CAM milled resins offer superior resistance to surface indentation, making them more wear-resistant in clinical scenarios.

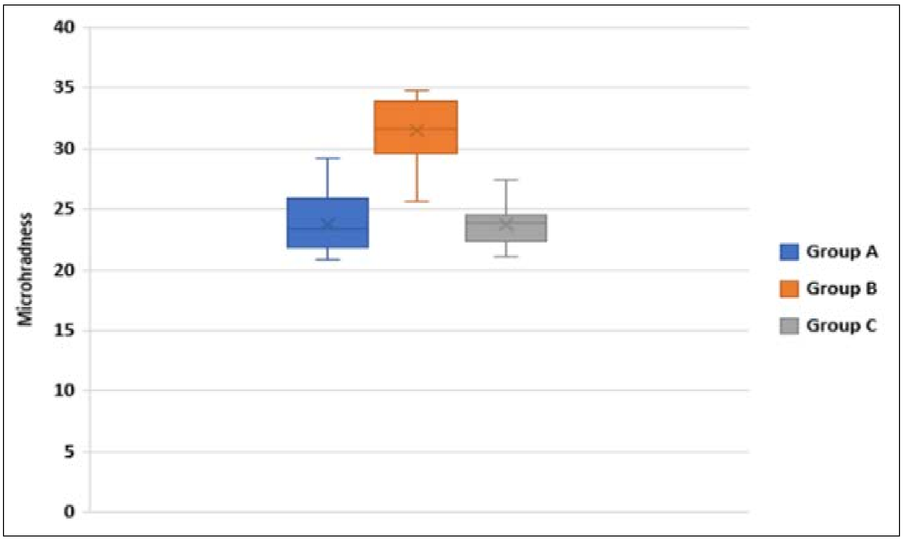

Fig 2: Graph comparing mean microhardness (KHN) of Groups A, B, and C (Group B > Group A ≈ Group C)

Statistical Significance Overview

Table 5: Comparison of properties

Property	Comparison	P Value	Significance
Microhardness	B vs A, B vs C	0.001	Significant
Microhardness	A vs C	0.995	NS
Flexural Strength	A vs B, A vs C, B vs C	0.001	Significant

(NS = Not Significant)

Discussion

The present *in vitro* study aimed to compare the flexural strength and microhardness of three types of provisional crown and bridge materials fabricated using different techniques: conventional polymerisation, CAD-CAM milling, and 3D printing. The results demonstrated significant differences among the groups, with conventionally polymerised resins showing the highest flexural strength and CAD-CAM milled resins exhibiting the highest microhardness. 3D printed materials showed the lowest performance in both parameters.

Flexural Strength Comparison

Flexural strength is a crucial mechanical property for any provisional material, particularly in long-span fixed partial dentures or cases where occlusal stresses are high. Our findings showed that Group A (conventionally polymerised) had a significantly higher flexural strength (mean = 273.00 MPa) than both Group B (CAD-CAM milled, 198.67 MPa) and Group C (3D printed, 109.29 MPa).

The superior flexural strength in Group A can be attributed to the manual polymerisation process, which allows careful control of curing conditions such as temperature and pressure. This process tends to result in higher degrees of polymerisation and cross-linking, contributing to enhanced mechanical properties [12]. Additionally, the heat-cured PMMA used in conventional methods tends to have fewer internal voids and greater structural uniformity than the additive layers of 3D printed materials.

Previous studies have also corroborated these findings. Haselton *et al.* [7] reported that conventionally polymerised PMMA exhibited superior flexural strength compared to other resin systems used for interim prostheses. Similarly, in a study by Givens *et al.* [13], heat-polymerised resins demonstrated better structural integrity and resistance to fracture under repeated loading, which is vital for extended use in the oral environment.

The intermediate flexural strength of CAD-CAM milled materials (Group B) observed in this study aligns with previous reports. CAD-CAM blocks are industrially polymerised under controlled pressure and temperature, which enhances polymerisation and minimizes residual monomer content [14]. However, because these blocks are often fabricated from pre-polymerised PMMA, they may lack the internal reinforcement provided by fiber incorporation or co-monomer additives seen in advanced conventional systems.

On the other hand, 3D printed materials (Group C) showed the lowest flexural strength. This may be due to the layer-by-layer polymerisation, which results in anisotropic mechanical properties. The interlayer bonding in 3D printed resins is often weaker, leading to poor resistance against flexural forces [15]. Additionally, the degree of polymerisation may not be uniform throughout the printed structure, contributing to its reduced mechanical performance [16].

Microhardness Comparison

Microhardness is an important property indicating a material's resistance to surface deformation, scratching, and wear. In our study, CAD-CAM milled materials (Group B) exhibited the highest microhardness (mean = 31.45 KHN), followed by Group A (23.79 KHN) and Group C (23.71 KHN). The differences between Group B and the other groups were statistically significant, whereas no significant difference was found between Groups A and C.

The high microhardness of CAD-CAM milled materials can be attributed to their homogeneous structure and higher degree of polymer conversion during industrial fabrication. As CAD-CAM blocks are manufactured under optimized and consistent conditions, they offer improved polymer chain density and minimal porosity, resulting in enhanced surface hardness [17]. This makes them more resistant to wear and suitable for patients with parafunctional habits such as bruxism.

In contrast, conventionally polymerised materials may have slight inconsistencies due to manual manipulation and potential air entrapment during polymerisation, which could account for the marginally lower microhardness values [18].

Interestingly, 3D printed materials, despite their modern appeal, did not show improved microhardness. This could be attributed to multiple factors: the degree of photo-polymerisation, presence of oxygen inhibition layers, and lower cross-linking density. During additive manufacturing, polymer chains may not fully convert, especially in deeper layers, leading to poor surface and bulk properties [19]. Furthermore, oxygen at the surface inhibits polymerisation, further reducing surface hardness [20].

A study by Alharbi *et al*. [8] supports our findings, showing that 3D printed provisional materials tend to demonstrate lower microhardness and wear resistance than CAD-CAM milled counterparts. Their research highlighted the importance of post-curing protocols, which, if not standardized, can negatively affect material performance.

Clinical Relevance

The choice of provisional material must be guided by the clinical situation. For long-span bridges, situations with heavy occlusal load, or delayed prosthetic rehabilitation, conventionally polymerised materials may be the most suitable due to their superior flexural strength. However, their time-consuming fabrication process and potential for dimensional instability due to polymerisation shrinkage are limitations.

CAD-CAM milled materials offer high microhardness, excellent marginal adaptation, faster turnaround time, and minimal porosity, making them ideal for short- to medium-term provisionals, especially in esthetic zones where wear resistance is crucial.

While 3D printing offers design flexibility, speed, and cost-effectiveness, its mechanical limitations suggest it may be best reserved for short-term use, such as diagnostic mock-ups or temporary restorations in low-stress areas. Improvements in resin formulations, printing technologies, and post-curing techniques are needed before 3D printed materials can consistently match or exceed the performance of conventional or CAD-CAM systems [21].

Limitations of the study

This *in vitro* study does not simulate intraoral conditions such as temperature changes, salivary enzymes, cyclic loading, or biofilm accumulation, all of which can affect the long-term performance of materials. Future studies should include thermocycling, artificial aging, and fatigue testing to better mimic the oral environment.

Future Perspectives

As digital dentistry evolves, advancements in resin chemistry, printer resolution, and polymerisation protocols are expected to enhance the mechanical properties of 3D printed materials. Additionally, hybrid materials, incorporating nanofillers or fibers, may bridge the current performance gap between traditional and digitally manufactured provisionals.

Conclusion

Within the limitations of this *in vitro* study, it can be concluded that the type of material and its method of fabrication significantly influence the mechanical properties of provisional crown and bridge materials. CAD-CAM milled materials exhibited the highest microhardness, indicating superior surface wear resistance, while conventionally polymerised materials demonstrated the greatest flexural strength, suggesting better resistance to masticatory forces. 3D printed materials showed the lowest values in both parameters, indicating they may be more suitable for short-term or low-stress clinical applications. The findings emphasize the need for careful selection of provisional materials based on clinical requirements, and support further research into enhancing the mechanical performance of 3D printed prostheses for broader applicability in prosthodontics.

Conflicts of Interest

None.

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