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CAD/CAM Technology in Dentistry: A Comparative Analysis of Milling and 3D Printing Techniques

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Abstract:

This review compares CAD/CAM technology in dentistry, focusing on milling and 3D printing regarding precision, material performance, clinical applications, and efficiency. Milling, a subtractive process, is renowned for its high precision, durability, and ability to produce restorations like crowns, bridges, and veneer that require long-term stability. In contrast, 3D printing, an additive process, offers greater design flexibility and efficiency, especially in the fabrication of temporary and complex restorations. The findings show that both methods are essential in modern dental practice, but the choice between milling and 3D printing depends on the specific clinical needs, the type of restoration, and advancements in material technology. Future research should prioritize the development of new composite materials that balance the durability of milled ceramics with the flexibility of printable resins. Additionally, investigating the integration of real-time feedback systems during the 3D printing process could further enhance precision in dental restorations. Exploring these avenues will help create more effective solutions tailored to diverse clinical needs.

Keywords: CAD/CAM technology, Dental restorations, Milling, 3D printing, Clinical efficiency.

1. Introduction

Computer-aided design (CAD) and computer-aided manufacturing (CAM) technology in dentistry has fundamentally transformed the way dental restorations are designed and fabricated. Previous studies have demonstrated that 3D-printed materials and CAD/CAM-milled materials exhibit distinct mechanical and optical properties [1]. The aid of computer aided designing and manufacturing (CAD/CAM) technology was first evaluated in the 1990s. Since François Duret first introduced CAD/CAM to dentistry in the 1970s with the Sopha System, the technology has undergone significant advancements . One major milestone was the development of the CEREC system in the 1980s by Dr. Werner Mörmann and Marco Brandestini, which allowed dentists to produce simple inlays and veneers directly in the clinic. However, early versions of these systems, such as CEREC 1 and CEREC 2, had limitations, including the inability to automatically fabricate occlusal surfaces [2].

Over time, modern CAD/CAM systems have gradually overcome these initial limitations, leading to improved performance in clinical applications. With improvements in computer processing power, material sciences, and integration with other technologies such as cone beam computed tomography (CBCT), current systems can produce complex restorations like crowns, onlays, and implant abutments. They offer higher precision, reduced fabrication time, and increased cost-efficiency. In particular, the development of newer milling and 3D printing technologies has expanded the applications of CAD/CAM in dentistry. Milling remains standard for its precision and durability in long-term restorations. On the other hand, 3D printing, an additive process, offers greater design flexibility and efficiency, especially in the fabrication of temporary and complex restorations [3]. This review compares milling and 3D printing technologies in CAD/CAM dentistry, focusing on their clinical applications, precision, and material performance to guide optimal restoration choices [3] (Fig, 1).

Fig. 1 The zirconia milling process, illustrating the subtractive manufacturing technique used to achieve high precision in durable restorations.

2. Literature Review and Recent Developments

2.1 Overview of CAD/CAM Technology

CAD/CAM technology has played a crucial role in modernizing dental practices, providing enhanced precision and efficiency in the design and fabrication of dental restorations. These systems are widely used in dental clinics to improve the quality of care. A key component of CAD/CAM systems is the ability to capture digital information from patients through Intraoral Scanners (IOS) and Extraoral Scanners (EOS).

These digital tools allow for the generation of highly accurate 3D images of the patient's oral structures, which are then imported into CAD software for restoration design. Once the design is complete, the system utilizes CAM technology to fabricate the restorations [4]. Compared to traditional methods such as lost-wax casting, the digital workflow of CAD/CAM systems not only enhances efficiency but also reduces the risk of inaccuracies associated with material distortion. In the following sections, the processes of CAD/CAM, milling, and 3D printing will be explored in more detail, highlighting their key functions and applications in modern dentistry [5].

CAD/CAM systems utilize an optical camera to capture a virtual impression of the tooth, generating a 3D image that is then imported into specialized software for designing dental restorations . The process begins with intraoral scanners (IOS), which are digital tools used to directly scan teeth and oral structures. These scanners capture 3D images instantly within a clinical setting, making them ideal for same-day restorations due to their convenience and efficiency. On the other hand, extraoral scanners (EOS) are employed primarily in dental laboratories to scan physical models or impressions, often for more complex restorations that require higher precision and the handling of larger cases. These scanners use laser or visible light technology, adding flexibility to the scanning process by offering options like blue or white light [6] (Fig. 2A).

When it comes to the actual manufacturing processes, milling is the key subtractive technique, where rotating

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tools carve restorations from blocks of material. This method excels in producing durable, long-term dental restorations [7]. Studies have shown that CAD/CAM-milled zirconia has superior marginal fit and lower micro-leakage, making it suitable for permanent restorations [7]. In contrast, 3D printing within CAD/CAM systems is an additive process, which builds dental restorations layer by layer [8]. It offers significant advantages in handling complex shapes and intricate designs, which has led to its growing adoption in restorative dentistry [8] (Fig. 2B). Despite these differences, both milling and 3D printing play crucial roles in modern dental restorations, offering diverse solutions depending on the clinical requirements.

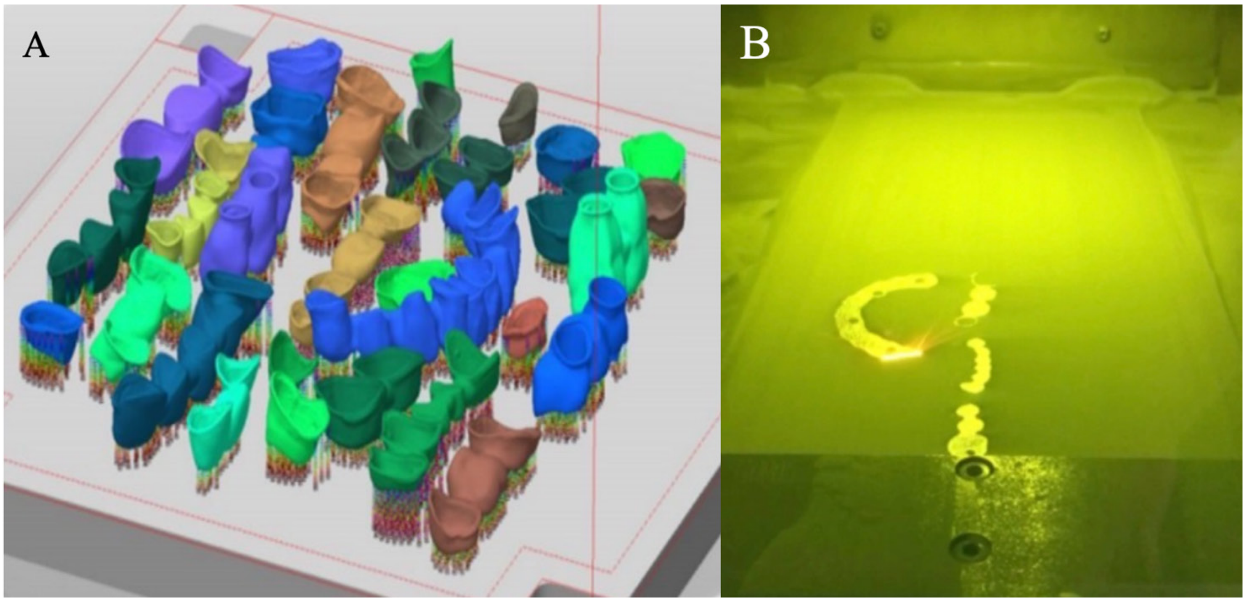

Fig. 2. (A) The arrangement of cobalt-chromium restorations before 3D printing, showing the setup for creating multiple complex structures in a single print job. (B) The 3D printing process of cobalt-chromium dental restorations, captured during the additive manufacturing phase.

3. Restoration

3.1 Precision and Trueness: Comparison of Temporary Restorative Material Performance Between 3D Printing and Milling

Studies suggest that 3D-printed materials, such as certain resins, may outperform some CAD/CAM-milled materials, like zirconia, in terms of flexibility and fracture resistance. However, 3D-printed materials often show lower surface finish quality and durability, making them less suitable for permanent restorations compared to milled zirconia. As a result, 3D printing is often preferred in situations requiring rapid production and design flexibility, while milling is favored for applications demanding long-term durability and precise surface finish, such as permanent crowns and bridges (Table 1.) [9].

Table 1. Comparative Analysis of 3D Printing and Milling in Terms of Mechanical Properties, Physical Properties, Production Speed, and Application.

Comparison	3D Printing	Milling
Mechanical Properties	Often superior in flexibility and rapid production.	Generally stable, ideal for strength and durability
Physical Properties	May have inferior surface finish and durability.	High precision and durability, suitable for permanent restorations.
Production Speed	Typically faster, especially for complex shapes.	Slower, particularly for precise structures.

Application	Best for temporary restorations and complex structures.	Ideal for permanent restorations requiring precision.

3.2 Accuracy of CAD/CAM-Fabricated Bite Splints

One investigate the accuracy of CAD/CAM-fabricated bite splints by comparing different fabrication methods (milling vs 3D printing).The results indicated that milled splints are more accurate, while 3D printed splints excel in consistency. Hence, milled splints provide better accuracy, while 3D printed splints are better for reproducibility (Table 2) [10].

Table 2. Assessment of Factors Affecting the Accuracy of CAD/CAM-Fabricated Bite Splints Using 3D Printing and Milling Techniques

Aspect	Details
Objective	To assess the impact of fabrication method, positioning, material selection, and measurement method on the accuracy of CAD/CAM-fabricated bite splints.
Fabrication	3D Printing (horizontal and vertical) vs. CNC Milling
Materials	4 resins for 3D printing (Dental LT, Ortho Clear, Freeprint Splint, V-Splint); ProArt CAD Splint for CNC milling
Accuracy Measurement	Scanning and measuring trueness and precision using cloud-to-cloud and cloud-to-mesh methods

Another study, „Accuracy of 3D Printing Compared with Milling — A Multi-Center Analysis of Try-In Dentures", conducted across multiple centers compared the accuracy of 3D printing and milling in the fabrication of try-in dentures. The results demonstrated that milled dentures generally exhibited higher trueness and precision, while 3D-printed dentures, though within clinically acceptable limits, provided more flexibility in production. Geometrical accuracy was evaluated using trueness (Root Mean Square, RMS) and precision (standard deviation). The results showed that milled dentures had higher trueness and precision in most centers, with an average trueness difference of 17-89 μm and a precision difference of 8-66 μm compared to 3D-printed dentures. However, all 3D-printed dentures were within the clinically acceptable range. In conclusion, while milling remains more precise, 3D printing offers sufficient clinical reliability and greater flexibility in production [11].

3.3 Mechanical Strength and Durability

3.3.1 Differences in Trueness of Full Dentures Fabricated by Milling vs. 3D Printing Performance Between 3D Printing and Milling

The methods used involved fabricating two groups of maxillary complete dentures (3D-printed and milled), with 10 samples in each group. The intaglio surfaces were scanned, followed by additional scans after 21 days of immersion and wet-dry cycles. Trueness was analyzed using 3D software, followed by statistical analysis. The Result shows that Under current manufacturing standards, CAD-CAM milled complete dentures have superior trueness of the intaglio surface compared to 3D-printed dentures [12].

3.3.2 Comparison of Survival Rates for Tooth-Supported and Full Crown Restorations

In a comparative study, the survival rates of zirconia restorations produced by both milling and 3D printing were examined. This research analyzed nine clinical studies and six in vitro studies, focusing on key parameters like survival rates and marginal integrity. Significant differences were observed between the two techniques, with both milling and 3D printing showing good marginal integrity and favorable periodontal conditions. The results highlighted that milled zirconia crowns demonstrated better overall performance and higher survival rates, despite some limitations associated with 3D milling. There was no significant correlation found between the type of cement used and the survival rates, further underscoring the role of the fabrication process itself [13].

When considering the application of these findings, it is important to differentiate between types of restorations. For single tooth restorations, such as crowns, milling is particularly suitable for restorations requiring high precision and long-term stability. Conversely, for partial tooth restorations, such as bridges, both milling and 3D printing can be employed depending on the clinical needs, with milling often preferred for complex structures due to its

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durability [14].

3.4 Design Flexibility and Efficiency

While milling provides high precision, 3D printing excels in producing complex designs with efficient material use. This makes it particularly suitable for temporary restorations and cases requiring intricate geometries [15].

3.5 Results of Material Performance

These studies mentioned earlier indicate that while 3D printed materials can exhibit strong mechanical properties, they often lack the superior surface finish and durability associated with milled restorations (Table 3.)[9- 15].

Table 3. Comparison of Precision, Material Performance, Design Flexibility, Efficiency, and Ideal Applications Between 3D Printing and Milling

Aspect	Milling	3D Printing
Precision	Higher precision and trueness	Lower precision, but higher reproducibility for temporary restorations
Material Performance	Superior physical properties (e.g., surface finish, durability)	May have better mechanical properties, but inferior in physical aspects
	Less flexible for complex designs	Highly flexible, ideal for complex structures
Design Flexibility		More efficient in material use, faster for complex shapes
Efficiency	Generates material waste, slower for complex designs	Temporary restorations, complex structures
Ideal Applications	Long-term, permanent restorations	Lower precision, but higher reproducibility for temporary restorations

As shown in Table 3, 3D printing demonstrates flexibility and speed, making it ideal for temporary restorations and complex structures, especially in situations where rapid production is required. Meanwhile, milling remains superior in precision and durability, which is essential for long-term restorations like crowns and bridges. This supports the use of milling in cases requiring high precision, while 3D printing offers a more efficient solution for less permanent restorations.

4. Dental implant surgery and research

Based on the comparison of milling and 3D printing in terms of accuracy, material performance, and applications, we will now explore how these technologies perform in specific clinical scenarios, particularly in implant surgeries and other dental restorations.

4.1 Implants

This review analyzed studies on additively manufactured (AM) zirconia, primarily focusing on 3 mol% Yttria-stabilized Tetragonal Zirconia Polycrystals (3Y-TZP), with some inclusion of 4 mol% Yttria-stabilized Zirconia (4YSZ) and 5 mol% Yttria-stabilized Zirconia (5YSZ). From 1736 records, 38 studies were included, mostly laboratory-based, with only two short-term clinical trials. The clinical results showed no mechanical or biological complications for 3D-printed 3Y-TZP zirconia crowns. Thinner specimens had higher flexural strength, and fracture resistance improved when restorations were adhered to teeth. The bond strength of veneering ceramics was comparable to milled zirconia. Long-term randomized trials are needed to validate the mechanical performance of 3D-printed restorations [16].

4.2 Bridges

This study compared the flexural properties and fatigue resistance of denture materials made by 3D milling and 3D printing. Specimens were tested through three-point bending and fatigue limit evaluations. Results indicated that the 3D-milled Ivotion material outperformed in fatigue resistance, showing a 25% higher limit compared to the 3D-printed Flexcera material, despite similar static properties. In conclusion, while both methods are effective, 3D milling offers superior durability [17].

4.3 Full Arch Restorations

This study compared the effectiveness of milling and 3D printing for complete denture fabrication. Fifteen edentulous patients were randomly assigned to receive both treatments, with a crossover after six weeks. Results showed that 3D-printed dentures required more adjustments and maintenance, but there were no significant differences in patient satisfaction or oral health quality. In conclusion, both techniques are effective, but 3D printing demands more post-treatment care, while patients are more willing to pay for milled dentures [18].

4.4 Results of Clinical Applications

Before diving into the specific advantages of milling and 3D printing in different clinical scenarios, it is crucial to reference the comparative table (Table 4. and 5.). This table summarizes the key differences in their clinical applications, including aspects such as precision, durability, and production speed. The following discussion will analyze these differences in greater detail and explain how these technologies can be applied most effectively in various dental treatments [9-18].

Table 4. Filtered Milling vs 3D Printing in Clinical Situations

Clinical Situation	Temporary Restorations	Denture Fabrication	Single or Partial Tooth Restorations
Milling		Used for denture bases and teeth, less flexible for complex structures	High precision, suitable for long-term restorations
3D Printing	Ideal for temporary restorations, cost-effective and fast	Ideal for rapid fabrication of complete dentures, flexible	Suitable for temporary restorations, faster but less durable

Table 5. Filtered Milling vs 3D Printing in Clinical Situations

Clinical Situation	Implants	Bridges	Full Arch Restorations
Milling	Used for implant abutments and superstructures, ensures high precision	Main technique for long-term bridges, excellent durability	Preferred for long-term restorations, superior aesthetics and durability
3D Printing	Common for surgical guides, fast and flexible	Mainly for temporary bridges or wax-up models	Fast and flexible, suitable for temporary full arch restorations

For long-term restorations such as crowns and bridges, milling remains the preferred option due to its high precision and durability, ensuring long-term stability and superior aesthetics. However, for temporary restorations and complex structures, 3D printing excels in speed and design flexibility, making it ideal for temporary solutions. When considering implants and surgical guides, milling provides the precision required for implant abutments, while 3D printing allows faster production of surgical guides.

Beyond restorative and implant dentistry, CAD/CAM technologies, especially 3D printing, have also revolutionized orthodontics. The ability to design and manufacture customized orthodontic appliances, such as indirect bonding trays and custom brackets, has significantly improved the precision and efficiency of orthodontic treatments. The following section will explore the various applications of CAD/CAM technology in orthodontics, highlighting how these advancements have transformed clinical workflows and treatment outcomes.

5. Orthodontic Applications of CAD/CAM and 3D Printing

The application of 3D printing in dentistry, particularly in orthodontics, has significantly transformed traditional workflows into more efficient and precise digital processes. The typical workflow begins with digital data acquisition through technologies such as Cone Beam Computed Tomography (CBCT), 3D facial scans, intraoral scans, or model scans to capture the anatomical structure of the patient‘s mouth. This digital information is then imported into CAD software, where the virtual treatment plan is created. Clinicians can design custom-made orthodontic devices, such as indirect bonding trays, custom brackets, or even robotically bent archwires. Once the design is complete, CAM technology is used to transform the digital plan into a 3D-printed model or device. The 3D printing process builds the object layer by layer, allowing for precise fabrication of the designed appliances. After printing, the orthodontic tools are used in the clinical setting to execute the planned treatment, such as applying the custom brackets or using printed models for case monitoring. This integration of 3D printing in orthodontics has led to more accurate treatment outcomes and improved patient experiences [19].

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6. Discussion

Recent advancements in 3D printing technology have significantly impacted the field of dental restorations, particularly in temporary restorations and complex structures. Alghauli et al. demonstrated that 3D-printed zirconia restorations achieved clinically acceptable internal and marginal fit, especially in anterior restorations where aesthetic requirements are crucial [20]. However, despite these advantages, 3D-printed zirconia still shows limitations in high-load areas like molars due to its relatively lower mechanical strength and long-term durability compared to conventionally milled zirconia [20]. This mechanical deficiency limits its application in posterior restorations that require higher resistance to occlusal forces.

Sartori et al. highlighted the superior precision and durability offered by milling technology in producing long-term restorations such as crowns and bridges [21]. Milled restorations demonstrated better marginal adaptation and higher resistance to wear and occlusal forces, making them ideal for permanent restorations in stress-bearing areas like molars and bridges [21]. This contrasts with 3D-printed materials, which, while flexible and cost-effective for temporary restorations, are less durable in the long term. Kalberer et al. conducted a comprehensive comparison of milling and 3D printing technologies in the fabrication of dentures and found that milled dentures exhibited better trueness and precision, with fewer post-fabrication adjustments required [22]. The study showed that while 3D-printed dentures are within clinically acceptable limits, milled dentures provide higher geometrical accuracy and structural stability, making them the preferred option for long-term use.

Reinhard et al.'s multi-center study on CAD/CAM-fabricated splints showed milled splints provide superior accuracy over 3D-printed ones, especially in surface finish and trueness [23]. While 3D printing allows faster production and reproducibility, milling offers greater precision, making it better for splints and restorations where accuracy is crucial. Thus, while milling excels in precision and durability for permanent restorations, 3D printing offers distinct advantages in temporary restorations and rapid prototyping. In clinical settings where speed and cost-effectiveness are priorities, 3D printing is particularly suitable for temporary solutions and cases requiring immediate restorations [20] (Fig. 3).

Fig. 3 Completed 3D-printed cobalt-chromium dental restorations, demonstrating the final restoration product. This image highlights the design flexibility of 3D printing, making it particularly advantageous for complex restorative structures.

7. Future Research and Challenges

Looking ahead, future research can focus on three key areas: first, exploring how to combine the precision of milling with the flexibility of 3D printing to create more effective dental restorations; second, improving material durability and surface finish while reducing material waste; and lastly, conducting studies on different patient groups to ensure these technologies meet various clinical needs.

7.1 Hybrid Techniques

Explore combining milling's precision with 3D printing's flexibility to create more effective dental restorations. One potential direction for this research could involve the development of a hybrid manufacturing system that uses milling for high-precision areas like occlusal surfaces, while employing 3D printing for complex or intricate substructures. Additionally, the integration of real-time feedback mechanisms during the manufacturing process could enhance the accuracy of restorations. Cost analysis will also be crucial, as hybrid systems may incur higher initial setup costs, but could potentially reduce long-term expenses through material efficiency and shorter production times.

7.2 Material Optimization

Improve material properties like durability and surface finish for both 3D printing and milling. This could include exploring new composite materials that offer the strength of milled ceramics but with the flexibility and design adaptability of printable resins. Future studies might also focus on improving surface finish through post-processing techniques such as thermal or chemical treatments to ensure smoother, more durable restorations. Another key challenge is reducing material waste during milling operations, possibly through advanced recycling systems that repurpose leftover material for future restorations.

7.3 Clinical Decision-Making

The choice between milling and 3D printing depends on the clinical scenario and patient needs. Milling is ideal for permanent restorations like crowns and bridges, where precision and durability are key. In contrast, 3D printing is better suited for temporary solutions, intricate designs, and cases requiring fast production. The clinician's choice must also consider factors such as material properties, aesthetics, and cost to ensure optimal outcomes for each individual patient.

8. Conclusion

To conclude, both milling and 3D printing are essential technologies in modern dentistry, each excelling in different areas. Milling offers unmatched precision and durability, making it the preferred choice for long-term restorations like crowns and bridges. Meanwhile, 3D printing stands out for its speed, flexibility, and cost-effectiveness, especially for temporary restorations and intricate designs. As we look forward, future research should focus on optimizing materials for both technologies and exploring hybrid techniques that combine the precision of milling with the flexibility of 3D printing. These advancements will enable dental professionals to tailor treatment solutions more precisely to the needs of each patient, enhancing clinical outcomes and efficiency.

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