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Review article

A Review on the Power of CAD/CAM Technology and the Material Science in Modern Manufacturing

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ABSTRACT

Computer-aided design/computer-aided manufacturing (CAD/CAM) technology has revolutionized restorative dentistry by enabling the creation of precise dental prosthetics from biocompatible materials. This integration allows for the design of complex 3D models and restorations using CAD software, which are then transferred to the CAM software to fabricate the restorations using milling machines. Critical milling settings like spindle speed, feed rate, and coolant selection are crucial for achieving optimal results based on the chosen biocompatible material. These materials, including glass ceramics, composite resins, hybrid ceramics, and zirconia, each play a specific role based on their properties. This synergy between CAD/CAM and biocompatible materials has led to significant advancements in dental restorations, improving accuracy, efficiency, and the ability to customize treatment for individual patients. The current review explores the synergistic relationship between the material science, manufacturing settings within the domain of CAD/CAM technology. Besides, it provides a comprehensive examination of various materials commonly employed in CAD/CAM, highlighting their advantages, disadvantages, and specific applications.

Keywords: CAD/CAM, Milling machines, Biocompatible Materials, glass ceramics, Zirconia.

1. Introduction

The introduction of digital CAD/CAM technologies and the concurrent development of materials with superior mechanical and aesthetic properties have significantly impacted the field of prosthetic restorative dentistry. This synchronized progress between material science and digital design tools has demonstrably accelerated the incorporation of chairside CAD/CAM systems into routine dental workflows. Manufacturers are continuously expanding the material varieties to achieve a dual objective through minimizing treatment duration while upholding the highest levels of precision and aesthetics.(1)

The fabrication process within CAD/CAM dentistry is remarkable. CAD/CAM technology in dentistry represents a digital workflow encompassing three primary steps. A digital impression of the patient's dentition is captured, either through intraoral scanning or traditional methods followed by digitalization using extraoral scanner. This digital data is then utilized in specialized software to design the restoration, taking into account individual patient needs and anatomical considerations. Once the design is finalized, the data seamlessly integrates with the manufacturing phase. Through computer-controlled milling machines, various biocompatible materials are sculpted into the designed restoration with precise control over milling parameters. These parameters, such as toolpath strategy, rotation speed, and cutting force, can be meticulously adjusted to optimize the machining process for different materials. This technology offers increased precision, efficiency, and the exploration of complex designs compared to traditional methods.(2)

Milling machines translate digital designs into physical restorations. They are categorized as open or closed systems, with open systems offering flexibility and compatibility with various tools and materials, while closed systems prioritize ease of use with the manufacturer's components. Milling processes can be dry or wet, with dry milling preferred for faster processing of zirconia and wet milling favored for heat-sensitive materials like lithium disilicate. Spindle speed, feed rate, and the number of milling axes (3, 4, or 5) are crucial parameters influencing material removal efficiency, surface quality, and the potential for tool or material damage.(3)

Chair-side CAD/CAM prioritizes speed and patient convenience, with same-day restorations achievable. Conversely, laboratory CAD/CAM allows for intricate designs and a wider material selection, typically requiring multiple appointments. Milling machines employed in these settings differ, with chair-side units often utilizing simpler 3-axis machines for faster turnaround times, while laboratories might leverage advanced 5-axis machines with wet milling for complex restorations. (4)

A diverse range of biocompatible materials are available for CAD/CAM restorations, each with unique properties and clinical applications. The synergy of biocompatible materials with CAD/CAM technology is a key factor in its success. This allows dentists to select the most suitable material for each specific restoration, balancing factors like strength, aesthetics, and biocompatibility. For instance, zirconia, renowned for its strength, can be precisely milled for posterior crowns requiring high wear resistance. Conversely, for restorations prioritizing aesthetics, translucent ceramics or composite resins can be employed with optimized milling settings to achieve a natural-looking finish. This review aims to provide a concise overview of these continually evolving materials, offering dental professionals a comprehensive understanding of the diverse restoration options available today with the evolution of CAD/CAM systems.(5)

2. CAD/CAM Technology

Computer-aided design and manufacturing (CAD/CAM) technology has revolutionized dentistry by offering several advantages over traditional methods. These include increased design accuracy and precision, facilitated by digital modeling and computer-controlled machining. This translates to improved marginal fit and reduced risk of marginal leakage in restorations, a critical factor for long-term success. Additionally, CAD/CAM workflows can significantly enhance efficiency, enabling faster turnaround times for prosthetic fabrication compared to manual techniques. This can benefit both dentists and patients by reducing chair time and accelerating treatment processes. Furthermore, the technology allows for exploration of complex designs and facilitates the use of biocompatible materials, expanding the possibilities for restorative dentistry.(6,7)

The process typically begins with digital impression capture, utilizing intraoral scanners or cone-beam computed tomography (CBCT) to generate high-fidelity 3D models of the patient's dentition or traditional impression techniques followed by digitalization of the physical cast into 3D model using extraoral scanner. These virtual models are then meticulously analyzed within CAD software, allowing for precise design of the restoration with consideration of anatomical features, functional requirements, and biocompatibility. Once finalized, the design data is seamlessly transferred to the CAM unit, where computer-controlled milling machines or 3D printers utilize biocompatible materials to fabricate the restoration with exceptional accuracy and reproducibility. This digital workflow ensures meticulous attention to detail throughout each stage, supporting predictable outcomes and improved clinical efficacy.(8)

3. Milling Machines in Dental CAD/CAM

Dental CAD/CAM workflows rely on computer-controlled milling machines to translate digital prosthetic designs into physical restorations. These machines operate based on the principle of subtractive manufacturing, where material is removed from a solid block to achieve the desired final geometry and anatomy. Due to the varied material properties and geometric complexities of dental restorations, milling machine settings and parameters like spindle speed, feed rate, number of axes and coolant selection must be adjusted to optimize cutting efficiency and minimize the risk of material fracture or microcrack formation as presented in table (1).(9)

Feature	**Milling Machine Systems**	**Details**	**Sources**
Open/Closed System	Open	Compatible with various materials and tools from different commercial brands	(4,10)
	Closed	Optimized for specific materials and tools from the same commercial brand	
Number of Axes	3-Axis (X, Y, Z)	Simpler designs and softer materials	(4)
	4-Axis (X, Y, Z, A)	More complex designs with rotational capabilities	
	5-Axis (X, Y, Z, A, B)	Highly complex designs with full rotational freedom	
Cooling System	Dry	Suitable for materials like zirconia, PMMA, wax	
	Wet	Necessary for materials prone to heat generation or cracking, like titanium, lithium disilicate	
Settings	Vary depending on material, design complexity, and desired finish.		

3.1 Open and Closed Systems of Milling Machines

Milling machines are categorized into two primary architectures: open and closed systems. Closed systems, exemplified by Sirona's CEREC® system or Dentsply Sirona's InLab® system, representing a vertically integrated approach. Here, the scanner, design software, and milling machine are all from the same manufacturer, ensuring seamless compatibility and streamlined workflows. This facilitates predictability and ease of use, particularly for less experienced users. However, closed systems limit flexibility, as users are restricted to the manufacturer's materials and tools. Conversely, open systems, such as those offered by YenDent or Roland DG, prioritize user control and versatility. These systems utilize neutral file formats (e.g., STL) for data transfer, enabling compatibility with scanners and design software from various vendors. Additionally, open systems allow for the selection of milling tools and materials from a wider range of suppliers, potentially offering cost benefits and material property customization. However, open systems often require a higher level of technical expertise to ensure proper integration and optimal milling parameters for diverse materials. The choice between open and closed systems depends on individual needs and priorities. Closed systems provide a user-friendly, streamlined experience, while open systems offer greater flexibility and control over the workflow.(4)

3.2 Dry and Wet Milling

The milling process can be categorized into dry and wet milling based on the environment surrounding the cutting tool. Dry milling utilizes pressurized air to remove debris and cool the cutting zone. This method is generally faster and more efficient for machining hard and brittle materials due to the absence of a coolant film hindering chip evacuation. This is crucial because trapped chips can cause microfractures during cutting. However, dry milling can generate significant heat, potentially leading to microcrack formation within the restoration. Conversely, wet milling employs a liquid coolant, typically water-based solutions, to lubricate the cutting tool and surface interfaces, minimizing frictional heat. This approach is preferred for milling temperature-sensitive materials like lithium disilicate (Li_2SiO_3), metals and some resin composites. Wet milling is ideal for processing materials such as glass ceramics, titanium & cobalt chrome, and pre-milled implant abutments. Meanwhile, dry milling is preferred for materials such as Peek, lower pre-sintered zirconia, PMMA, and wax. However, wet milling can be slower compared to dry milling due to the additional time required for coolant removal from the milled restoration. The selection between dry and wet milling depends on the properties of the materials and the desired clinical outcome. For instance, lithium disilicate restorations typically favor wet milling to minimize heat generation and ensure optimal material integrity. Conversely, zirconia processing, milling techniques are categorized as dry or wet based on the milling environment. Dry milling, ideal for lower pre-sintered zirconia blanks, offers cost benefits and eliminates pre-drying steps. However, it can lead to higher shrinkage during sintering. However, wet milling with higher pre-sintered zirconia minimizes shrinkage and distortion during sintering, leading to improved dimensional accuracy. (11,12)

3.3 Spindle Speeds and feed rates

Spindle speed and feed rate are critical parameters in dental CAD/CAM milling processes, directly influencing material removal efficiency, surface quality, and potential for tool or material damage. Spindle speed, measured in revolutions per minute (RPM), dictates the rotational velocity of the cutting tool. Higher spindle speeds are generally preferred for harder materials like zirconia (ZrO_2) due to their increased chip removal capacity. However, excessively high speeds can generate excessive heat, leading to microcrack formation in zirconia. Conversely, softer materials like lithium disilicate (Li_2SiO_3) benefit from lower spindle speeds to minimize frictional heat and potential material degradation. Feed rate, measured in millimeters per minute (mm/min), determines the speed at which the workpiece advances past the rotating cutting tool. A balanced feed rate is crucial. A slower feed rate allows for better chip evacuation and reduces heat generation, but can also be less efficient. Conversely, a faster feed rate can improve machining speed but may lead to chip re-adherence and increased tool wear, particularly with harder materials like zirconia. Therefore, optimizing spindle speed and feed rate requires careful consideration of the material properties being milled. For each material, a specific range of optimal settings exists to achieve efficient and high-quality restorations with minimal risk of tool or material damage. (13,14)

3.4 Number of Milling Axes:

Milling devices are categorized by the number of milling axes they possess, which influences the range of geometries they can machine with precision.

3.4.1 *3-axis* milling machines:

The foundation of milling technology lies in 3-axis devices. These reliable machines offer movement along the three primary spatial axes (X, Y, and Z). This allows for milling along linear paths defined by these coordinates. Their simple design translates to several advantages: lower cost due to less complex mechanics, faster milling times for simpler geometries, and simplified control for users. However, their limitations become apparent when dealing with complex geometries. Undercuts, features with converging or diverging walls, and restorations requiring specific angulations present challenges. For such situations, virtual blocking of unsupported areas becomes necessary, adding processing steps and potentially compromising efficiency.

Additionally, milling is restricted to perpendicular planes, limiting the ability to follow the natural curvatures of teeth, which can impact the final restoration's fit and aesthetics.(11,12)

3.4.2 *4-axis* milling machines

4-axis milling machines introduce a level of sophistication by incorporating a fourth axis - a rotatable tension bridge for the component (X, Y, Z and A). This allows for strategic maneuvering of the milling block, optimizing material usage by accommodating tall structures within standard milling blocks. Additionally, by adjusting the bridge angle, milling paths can be minimized, leading to shorter processing times. (11,12)

3.4.3 *5-axis* milling machines

The most advanced milling capabilities reside in 5-axis devices. These machines offer all the features of 4-axis devices with the added capability of rotating the milling spindle itself. They incorporate two additional rotary axes (A and B) that allow for tilting and rotating the workpiece during milling, enabling access to areas not reachable with a 3-axis machine (X, Y, Z, A and B directions). This unlocks the ability to mill intricate geometries with undercuts, converging/diverging walls, and angulated surfaces. This is particularly beneficial for complex restorations like lower jaw FPDs on tilted abutments. Furthermore, 5-axis milling allows for the creation of enhanced restoration designs that are anatomically accurate and require minimal tooth reduction, ultimately improving aesthetics and patient comfort. (11,12)

While the number of axes might suggest a direct correlation with restoration quality, it is not the sole factor. The overall quality depends on the entire workflow, encompassing digitalization, data processing, and production parameters. However, selecting the appropriate milling axis capability is crucial for achieving the desired level of design complexity and material efficiency. Ultimately, the choice between different milling devices depends on the specific demands of the restoration being created.

4. Chair- Side and Laboratory CAD/CAM

The first generation of chairside CAD/CAM systems emerged in the 1980s, with limited capabilities for designing and producing only ceramic inlays. Today's leading chairside systems (e.g., PlanScan, Carestream, CEREC) boast a "full-digital workflow" enabling the fabrication of diverse prosthetic devices including inlays/onlays, veneers, endocrowns, bridge crowns, and implant abutments(15,16).

Chairside CAD/CAM prioritizes efficiency and patient convenience. The dentist starts by preparing the tooth for the restoration, ensuring optimal hygiene and minimal tooth structure removal. Next, a digital 3D model of the prepared tooth and surrounding dentition is captured using an intraoral scanner. This digital impression allows for immediate design of the restoration using specialized software on-site. Dentists can make real-time adjustments and involve patients in the design process. Finally, the designed restoration is milled from a compatible biocompatible material within the chairside milling unit, followed by finalization, surface treatment, and cementation onto the prepared tooth. This streamlined workflow often allows for same-day restoration delivery. (17)

Laboratory CAD/CAM, on the other hand, prioritizes design complexity and material selection. The dentist begins by taking either digitalized scan or a conventional impression, capturing the details of the prepared tooth and surrounding structures. This impression is then poured with a suitable material to create a physical cast of the dentition. A dedicated dental laboratory scanner subsequently digitizes the physical cast, generating a 3D model. Using CAD software, a dental technician or dentist meticulously designs the restoration on the digital model. This process allows for incorporating complex design features compared to chairside workflows. The designed restoration is then milled from a chosen biocompatible material in a dedicated laboratory milling unit, offering a wider range of material options compared to chairside systems. Finally, the dentist receives the milled restoration from the laboratory and cements it onto the prepared tooth, typically requiring multiple appointments due to the turnaround time involved.(18)

Chairside settings typically utilize simpler 3-axis machines with dry milling for faster turnaround times for crowns and inlays. Conversely, laboratory settings might employ advanced 5-axis machines with wet milling for fabricating highly intricate bridges and implant components requiring exceptional precision. These settings, along with the chosen milling machine type, all contribute to a streamlined clinical workflow, ensuring the creation of high-quality, durable dental prosthetics. (4)

The following table provides a comparison of some commercially available CAD/CAM systems, highlighting their milling characteristics and compatible materials.(4,19) as shown in Table (1)

Table 1: showing examples of commercially available CAD/CAM systems, with their milling characteristics and compatible materials.

System Name	Manufacturer	Milling Axis	Open or Closed System	Chairside or Laboratory	Milling Milieu	Material Compatibility
Lava™ CNC 500	3M ESPE	3 to 5	Closed	Laboratory	Wet	Lava™Zirconia, Lava™ Ultimate (PMMA), Lava™ Wax Block, Lava™ Digital Veneering System
Ceramill Mikro 4X	Amann Girrbach	4	Closed	Laboratory	Dry	dry processing blanks and single blocks such as zirconia, hybrid ceramics or dry millable composite materials.
DWX-52DC	DGSHAPE	5	Open	Laboratory	Dry	zirconia, wax, PMMA, PEKK, gypsum, composite resin, and chrome cobalt, sinter metal
CORITEC 140i	imes-icore	4	Open	Laboratory	Dry/Wet	Zirconia, Glass Ceramics, PMMA, resins, PEEK, composites, wax, hybrid ceramics, Titanium
CORITEC 650i	imes-icore	5	Open	Laboratory	Dry/Wet	Zirconia, Glass Ceramics, PMMA, resins, PEEK, composites, wax, hybrid ceramics, Titanium, sintered metal, chrome cobalt
PrograMill PM7	Ivoclar Vivadent	5	Open	Laboratory	Wet & Dry	Zirconia, Lithium Disilicate, Glass Ceramics, PMMA, CoCr Alloys
PrograMill DRY	Ivoclar Vivadent	5	Open	Laboratory	Dry	Zirconia, PMMA
Planmeca Planmill	Planmeca Oy	5	Open	Chairside & Laboratory	Wet & Dry	discs, blocks and prefabricated titanium or cobalt-chrome implant, zirconium dioxide, glass ceramics, composites, and wax.
DWX-4W Wet Dental Mill	Roland DG	5	Open	Laboratory	Wet	Zirconia, Glass Ceramics, PMMA
SilaMill N4	Siladent	4	Open	Laboratory	Wet & Dry	Zirconium oxide, glass ceramic, titanium
CEREC® Primemill	Dentsply Sirona	4-5	Closed	Chairside	Wet & Dry	zirconia, lithium disilicate, or any glass ceramic restorations
inLab MC X5	Sirona	5	open	Laboratory	Wet&dry	Zirconia, Glass Ceramics, PMMA, CoCr Alloys

5. Additive manufacturing:

Additive manufacturing (AM), often referred to as 3D printing, has become a game-changer in prosthetic dentistry. Unlike traditional subtractive methods like milling, which remove material from a solid block, AM builds restorations layer-by-layer based on a digital design. This innovative approach offers several distinct advantages.

Firstly, AM provides significantly increased design freedom. Complex geometries and internal structures can be readily incorporated into the design, allowing for highly customized restorations with enhanced functionality. This can be particularly beneficial for complex cases or restorations that require specific features to improve fit and performance.

Secondly, AM boasts a significant reduction in material waste. Material is only used where needed during the printing process, minimizing waste compared to subtractive techniques that discard large portions of the original material block. This not only improves cost-efficiency but also aligns with a more sustainable approach to manufacturing.

Finally, AM facilitates mass customization. With the ability to rapidly produce patient-specific restorations based on digital designs, AM streamlines workflows and potentially reduces chair time for patients. This allows for a more efficient and personalized dental experience.

The choice of material for 3D printing in dentistry depends on the specific application. Here are some commonly used materials and their indications:

- Resin Composites: Offer a cost-effective option for temporary restorations, crowns, and inlays/onlays due to their ease of printing and good aesthetics.
- PEEK (Polyetheretherketone): This biocompatible polymer exhibits impressive strength and radiolucency, making it suitable for implant components and certain types of crowns and bridges.

However, limitations exist. Resolution limitations in some printers can affect the surface finish of restorations, and some materials require post-processing steps for optimal performance.

6. Hybrid manufacturing:

Hybrid milling machines are revolutionizing dental restoration by merging the established precision of subtractive milling with the limitless design freedom of additive manufacturing (3D printing) within a single unit. This innovative technology allows dental labs to create highly complex and detailed restorations that may have been difficult or impossible with traditional methods. An example of hybrid machines is DMG MORITA LYthos. The LYthos is based on Exclusive LASERTEC build-up strategies where it boasts 5-axis milling alongside high-resolution 3D printing, enabling the creation of intricate restorations from diverse materials like zirconia and resins.(20,21)

Biocompatible Materials used for Final Coronal restorations and esthetics in CAD/CAM Technology

6.1 Glass Ceramics

Glass-ceramics are comprised of nanosized crystals embedded within a glassy matrix. The chemical composition of these materials is similar to glass, often containing oxides of silicon (SiO2), aluminum (Al2O3), and various metal ions like lithium (Li2O) or zinc (ZnO). This composition allows for a controlled heat treatment process that triggers crystallization. The size and distribution of these crystalline phases significantly influence the physical properties of the final material. Glass-ceramics can exhibit superior strength, hardness, and chemical resistance compared to their glassy counterparts, while retaining some of the glassy phase's machinability and thermal properties. This unique combination of structure and properties makes glass-ceramics valuable for a wide range of applications.

The integration of computer-aided design and computer-aided manufacturing (CAD/CAM) has significantly transformed the landscape of dental restorations. This technology allows for the fabrication of highly precise and biocompatible prosthetics from a diverse range of materials. Within this domain, feldspathic ceramics, leucite-reinforced ceramics, and lithium disilicate ceramics represent distinct material classes, each has unique properties that fit to specific clinical applications. They are compatible with most open CAD/CAM systems, providing flexibility in choosing compatible milling equipment within a dental practice or laboratory workflow.

6.1.1 Feldspathic ceramics

Feldspathic porcelain is a glass ceramic material consisting primarily of potassium feldspar ($KAlSi_3O_8$), quartz (SiO_2) and kaolin ($Al_2Si_2O_5(OH)_4$). Kaolin imparts favorable plasticity during shaping before firing. Additional metal oxides (Na_2O, K_2O, CaO, Al_2O_3, MgO) are included to control the thermal expansion coefficient, aiming to match that of the underlying structure (often metal). Pigments (ZnO, Fe_2O_3, CuO, TiO_2, NiO, MnO, CoO) and opacifiers (SnO_2, ZrO_2, TiO_2) are also incorporated to achieve desired color and opacity. Due to its inherent brittleness, feldspathic porcelain is primarily used as a veneering material in metal-ceramic and metal-free ceramic systems.(22)

Fabrication involves mixing finely ground powders with water or a binder to form a moldable paste to be sculpted to the desired tooth shape. The shaped porcelain undergoes a precisely controlled heating process (sintering) in a microprocessor-controlled oven, following manufacturer's recommendations. Vacuum-based sintering can further reduce porosity. Sintering essentially fuses the particles together, increasing the material's density and leading to a volumetric shrinkage of 20-40%. Minimizing air bubbles and voids during paste formation is crucial, as they act as stress concentrators and weaken the final restoration. Sintering promotes densification by partially melting the powder particles, which reduces surface energy and causes pores to collapse, resulting in a denser material.(22)

Feldspathic porcelain, traditionally used for its outstanding aesthetic properties in dental restorations, has seen limited integration into CAD/CAM workflows due to its inherent brittleness. This brittleness stems from the material's microstructure, which lacks the enhanced strength offered by newer glass-ceramic materials like lithium disilicate. Despite this limitation, there are commercially available feldspathic porcelain blocks designed for CAD/CAM applications. These blocks cater to specific clinical scenarios were aesthetics reign supreme. However, their use is often restricted to veneers for anterior teeth or restorations in low-stress areas, due to the need for optimal strength and durability in posterior restorations.(23) Various techniques can enhance the strength of feldspathic porcelain and improve its resistance to crack initiation and propagation. These include:

- Ionic exchange: Replacing smaller sodium ions with larger potassium ions in the surface layer, creating a compressive stress layer.

- Thermal tempering: Rapid cooling of the porcelain to induce compressive stresses.
- Air-injection tempering: Introducing compressive stresses by interrupting crack propagation with a controlled air blast (22).

6.1.2 leucite-reinforced glass ceramics

To overcome the limitations of feldspathic ceramics, leucite-reinforced ceramics were developed. they provide a balance between aesthetics and strength. They are characterized by a high-volume fraction (35%) of leucite crystals, a form of potassium aluminosilicate, embedded within a feldspathic glass matrix. This matrix is primarily composed of silicon dioxide (SiO_2 - 63%), alumina (Al_2O_3 - 19%), potassium oxide (K_2O - 11%), sodium oxide (Na_2O - 4%), with minor amounts of other oxides. Leucite crystals are intentionally introduced by their addition to the alumina component.

Traditionally, fabrication involves a heat-pressing technique utilizing an investment mold. The mold is filled with a specially formulated, plasticized glass-ceramic, eliminating the need for a conventional sintering process and its associated pore formation. Strengthening is achieved through a mechanism known as dispersion strengthening. In this process, the leucite crystals (dispersed phase) act as barriers to crack propagation within the material due to their superior hardness compared to the glass matrix. Since leucite crystals are incorporated during the initial processing, there is no need for a separate ceramming step to induce their growth. Recently, pressed glass-ceramics have become available in the form of blocks or discs, making them compatible with CAD/CAM (Computer-Aided Design/Computer-Aided Manufacturing) technology.(22)

The presence of leucite crystals functions as a reinforcement phase, significantly enhancing the material's flexural strength compared to conventional feldspathic ceramics. This improvement in strength expands the clinical applications of leucite-reinforced ceramics to include inlays, onlays, and single crowns in areas subjected to moderate occlusal forces. However. their aesthetics may be slightly compromised due to the presence of leucite crystals compared to feldspathic porcelain.(24)

6.1.3 Lithium disilicate glass ceramics

Similar to pressed leucite reinforced glass-ceramics, this material is also fabricated using a heat-pressing technique. However, it boasts a significantly higher content (60%) of lithium disilicate crystals within a glassy matrix. The pressing process promotes the formation of an interlocking network of these crystals, contributing to enhanced fracture strength of the final material. Lithium oxide (Li_2O) and silicon dioxide (SiO_2) play a crucial role in promoting the crystallization of the desired lithium disilicate phase. Additionally, barium oxide (BaO) and cesium oxide (Cs_2O) function as stabilizers for the residual glassy phase, while alumina (Al_2O_3) and boron oxide (B_2O_3) contribute to the material's overall chemical durability. The crystallization process itself is a two-step procedure: nucleation occurring at 645°C for one hour, followed by crystal growth at 850°C for four hours.(22) During controlled heat treatment, these components trigger the formation of nanosized lithium disilicate ($Li_2Si_2O_5$) crystals dispersed throughout the glassy matrix. The size, volume fraction, and distribution of these crystals significantly impact the physical properties of LDCS. Compared to pure glass, LDCS boast enhanced mechanical strength, fracture toughness, flexural strength and wear resistance, making them ideal for dental restorations. Additionally, the presence of the glassy phase contributes to good aesthetics by mimicking the light-transmitting properties of natural teeth. This unique combination of chemical structure and physical properties makes LDCS a valuable material in dentistry and other applications requiring strong, biocompatible, and aesthetically pleasing materials.(25)

Lithium disilicate (Li2SiO3) glass ceramics represent a significant advancement in CAD/CAM materials. They are formulated with a high percentage of lithium disilicate crystals leading to a substantial increase in flexural strength compared to both feldspathic and leucite-reinforced ceramics. Furthermore, lithium disilicate glass-ceramics are now available in pre-crystallized forms as CAD/CAM (Computer-Aided Design/Computer-Aided Manufacturing) blocks. This compatibility with CAD/CAM technology offers advantages like efficient and precise design and fabrication of dental restorations.

6.2 Composite Resin (Bis-GMA Composite)

Composite resin, particularly formulations based on Bis-GMA (bisphenol A diglycidyl methacrylate), has emerged as a prominent material that is composed of a resin matrix reinforced with inorganic filler particles. Their chemical structure revolves around the Bis-GMA molecule, a dimethacrylate monomer. This means it contains two methacrylate groups (chemical groups prone to bonding) and a central Bisphenol A core. This core provides rigidity and stability, while the methacrylate groups enable cross-linking with other monomers during light-activated polymerization. Other key components include diluent monomers, like TEGDMA, which reduce viscosity for easier handling. Fillers, typically silica or zirconia particles, are incorporated to enhance strength, wear resistance, and mimic the natural tooth's optical properties. The final cured resin exhibits a dense, three-dimensional network due to the cross-linking between monomers. This network structure grants Bis-GMA composites good mechanical strength, dimensional stability, and polishability. However, Bis-GMA itself can be relatively brittle and have high shrinkage upon polymerization, necessitating formulation with other monomers and careful handling techniques.(26)

Despite its advantages, composite resin has limitations that require careful evaluation before material selection. While advancements in material science have led to improved formulations with enhanced strength, composite resins generally exhibit lower flexural strength compared to their ceramic counterparts. This inherent limitation may restrict their suitability for high-stress applications such as posterior bridges or occlusal surfaces of molars that experience significant biting forces. Furthermore, composite resin can experience wear and degradation over time due to masticatory forces and exposure to dietary factors. This wear may necessitate replacement of the restoration sooner compared to restorations fabricated from ceramic materials. Maintaining a polished surface on composite restorations is crucial for optimal aesthetics and longevity. Regular dental appointments for polishing may be necessary to counteract the effects of wear and maintain a desirable appearance.(27)

Composite resin for CAD/CAM applications is typically supplied in pre-fabricated blocks or discs of various sizes and thicknesses. These blocks are designed for milling in open CAD/CAM systems, offering compatibility with a wide range of milling units. A significant advantage of composite resin blocks is the extensive variety available. Manufacturers provide a spectrum of shades, translucencies, and even pre-characterized options to facilitate the creation of natural-looking restorations. Additionally, some manufacturers offer multi-layered blocks with varying degrees of translucency within a single block. These multi-layered options allow for even more lifelike emulation of the natural gradient in tooth structure, further enhancing the aesthetics of the final restoration(26)

6.3 Hybrid ceramics

The evolution of CAD/CAM dentistry have introduced novel materials like hybrid ceramics. These materials bridge the gap between conventional ceramics and resin composites, offering a unique combination of properties between aesthetics and functionality in dental restorations. The primary advantages of hybrid ceramics lie in their ability to deliver exceptional aesthetics while exhibiting improved mechanical properties compared to traditional resin composites. Hybrid ceramics often incorporate nano-scale filler particles that mimic the light scattering properties of natural teeth. This translates to superior aesthetics compared to traditional ceramics, offering excellent color match and a high degree of translucency, resulting in highly natural-looking restorations. Furthermore, the inclusion of a polymeric network within Polymer-Infiltrated Ceramic Networks (PICNs) or the finer ceramic grain structure in nanoceramics leads to increased flexural strength compared to resin composites. This expanded strength allows for potential use in posterior restorations subjected to moderate occlusal forces, expanding their applicability beyond just the anterior region. Additionally, similar to composite resins, hybrid ceramics may require less tooth reduction due to their bonding properties to tooth structure, potentially offering a more conservative approach to restorative procedures.(28)

Despite their advantages, hybrid ceramics have limitations that require careful evaluation before material selection. While improved over traditional composites, wear resistance of hybrid ceramics may still be inferior to ceramics. This can necessitate earlier replacement of the restoration, particularly in areas exposed to significant wear. Additionally, some hybrid ceramics, despite advancements, may exhibit a slightly higher risk of fracture compared to some well-established ceramic materials. Careful consideration of the occlusal load and functional demands of the restoration is essential when selecting a hybrid ceramic material.(29)

Hybrid ceramics are becoming increasingly available from various dental material manufacturers. They are typically supplied in pre-fabricated blocks or discs designed for milling in open CAD/CAM systems. Manufacturers provide a spectrum of shades, translucencies, and even pre-characterized options to facilitate the creation of natural-looking restorations that seamlessly integrate with the surrounding dentition.

6.4 Zirconia

Zirconia (ZrO_2) is a naturally occurring ceramic material known for its toughness. The mineral form, baddeleyite, contains a high concentration of zirconium oxide (80-90%) with minor impurities like titanium dioxide (TiO_2), silicon dioxide (SiO_2) and iron(III) oxide (Fe_2O_3). At room temperature, pure zirconia exists in a monoclinic crystal structure. However, upon heating to around 1200°C, it transforms to the tetragonal phase, and then to the cubic phase at even higher temperatures (2370°C). During cooling, the tetragonal phase can undergo an unwanted transformation back to the monoclinic phase, causing a volume expansion of 3-4% and potentially leading to crack formation. (30,31)

To address this issue, zirconia can be stabilized by adding dopants like calcium oxide (CaO), magnesium oxide (MgO), yttrium oxide (Y_2O_3), and cerium oxide (CeO_2). These additives create a multiphase material known as Partially-Stabilized Zirconia (PSZ). PSZ typically consists of a dominant cubic zirconia phase with minor precipitates of monoclinic and tetragonal phases at room temperature. The tetragonal phase is metastable at room temperature, meaning it can transform to monoclinic under external factors like pressure or elevated temperatures.

This transformation toughening mechanism plays a crucial role in zirconia's strength. The transformation from tetragonal to monoclinic phase generates a localized compressive stress around a crack tip, hindering its propagation. Additionally, the energy required for this transformation further strengthens the material. However, a phenomenon known as ceramic aging can occur, where the metastable tetragonal phase spontaneously transforms to monoclinic zirconia over time, potentially leading to a decrease in mechanical properties. Studies by Ardlin (32) suggest that while aging may affect the crystalline structure and surface of the ceramic, it may not significantly impact its strength.

There are two primary crystal structures that play a crucial role in the microstructure of zirconia: Cubic Zirconia (CZ) and Tetragonal Zirconia (TZP).

6.4.1 The Cubic Zirconia (CZ)

Cubic zirconia, existing in a stable cubic crystal structure, lacks the transformation toughening mechanism of TZP. Consequently, CZ possesses lower strength compared to its tetragonal counterpart. However, this trade-off comes with a significant aesthetic advantage. The cubic structure promotes superior translucency, allowing for more natural-looking restorations. This characteristic makes CZ a suitable choice for restorations in the anterior region, where achieving a lifelike appearance is paramount. Furthermore, CZ exhibits good machinability, facilitating efficient milling and creation of intricate restoration designs.(33)

6.4.2 Tetragonal Zirconia (TZP)

This metastable phase of zirconia possesses a tetragonal crystal structure. A key property of TZP is a phenomenon called transformation toughening. When subjected to mechanical stress, TZP undergoes a phase transformation to a monoclinic structure. This transformation absorbs energy and enhances the material's fracture resistance, making TZP the strongest of the zirconia types. This exceptional strength translates to its primary clinical application – high-stress restorations like posterior bridges and crowns. Additionally, zirconia exhibits excellent biocompatibility, making it a safe choice for long-term use within the oral cavity.(34,35)

Yttria (Y_2O_3) is a particularly effective dopant for stabilizing zirconia in the tetragonal phase at room temperature. This stabilized ceramic is called Tetragonal Zirconia Polycrystal (TZP). When doped with 2-3 mol% yttria, it is specifically referred to as Yttrium-stabilized Tetragonal Zirconia Polycrystal (3Y-TZP). The amount of yttria directly influences the transformation capacity of the tetragonal phase and consequently, the material's toughness. 3Y-TZP typically consists of submicron-sized tetragonal grains without a surrounding glassy phase. The amount of tetragonal phase remaining at room temperature depends on factors like grain size, yttria content, and the internal stresses within the material.(36)

Zirconia materials for dental applications can be categorized into four generations based on their chemical composition, crystal structure, and manufacturing processes. This generational evolution reflects ongoing efforts to address limitations and achieve improved properties.

There are four main generations of zirconia in dentistry based on their chemical composition, crystal structure, and manufacturing processes with a new multilayer generation emerging to address limitations and achieve improved properties.

First Generation (3Y-TZP 0.25Al_2O_3): Introduced two decades ago, this generation uses 3 mol% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP) for high strength (around 1200 MPa). However, the presence of alumina (0.25%) makes it opaque, limiting aesthetics. Alumina acts as a sintering aid during processing whereas Yttria (Y_2O_3) content plays a crucial role in stabilizing the tetragonal phase, leading to the material's high strength (around 1200 MPa). Examples of Commercial Names: Vita YZ (Vita Zahnfabrik), IPS e.max Zir (Ivoclar Vivadent) (37).

Second Generation (3Y-TZP 0.05Al_2O_3): Introduced between 2012 and 2013, this builds upon the first generation by reducing alumina content (0.05%) to improve translucency. However, this reduction in alumina may have slightly compromised strength compared to the first generation. Examples of Commercial Names: InCeram Zirconia (Vita Zahnfabrik), Zenostar (Sirona). (37)

Third Generation (5Y-TZP 0.05Al_2O_3): Introduced between 2014 and 2015, this generation (also known as Anterior Zirconia, High Translucent Zirconia, or Cubic Stabilized Zirconia (CSZ)) prioritizes aesthetics by increasing yttria to 5 mol%. This achieves high translucency but comes at the expense of strength (around 600 MPa) due to the increased cubic phase, which is less mechanically robust than the tetragonal phase. It's important to note that while offering superior translucency, the lower strength of this generation limits its use in applications requiring high mechanical loads. Examples of Commercial Names: Lava Plus (3M ESPE), Katana Zirconia (Kuraray Noritake Dental Science). (37)

Fourth Generation (4Y-TZP 0.05Al_2O_3): This generation offers a balance between strength (around 1300 MPa) and translucency by using 4 mol% yttria. By incorporating a slightly lower yttria content (around 4 mol%), manufacturers sought to improve translucency (around 45%) compared to 5Y-TZP while maintaining good strength. This makes it suitable for a wider range of clinical applications where both aesthetics and strength are important. Examples of Commercial Names: ZirCAD (Dentsply Sirona), Everest Zirconia (GC America).(37)

Gradient Technology

While zirconia boasts impressive mechanical strength for dental restorations, its inherent brittleness and limited translucency can be drawbacks. Gradient technology emerges as a solution, aiming to create a functionally graded zirconia material. This approach involves meticulously changing the composition or microstructure of zirconia throughout its thickness. The most common method involves a gradual decrease in yttria (Y_2O_3) content from the inner core outwards.

This creates a zirconia framework with a strong, high-yttria core for withstanding biting forces, and a more translucent outer layer with lower yttria content that mimics natural tooth light transmission, enhancing aesthetics. Additionally, the gradual change in composition creates a built-in stress gradient, potentially reducing the risk of fracture. Manufacturing techniques like multi-layer deposition and slip casting are used to achieve this graded structure.(38)

Multi-layered Zirconia

Multilayer zirconia represents a significant advancement in dental materials, leveraging gradient technology to address the inherent limitations of zirconia. Traditionally, zirconia offered excellent strength but suffered from lower translucency, limiting its aesthetic potential. Multilayer zirconia tackles this issue by incorporating a functionally graded structure within a single disc. This structure typically features a core layer of 3Y-TZP (3 mol% yttria-stabilized tetragonal zirconia polycrystal) for superior strength, often followed by a gradual transition to a more translucent outer layer made from materials like 5Y-TZP (5 mol% yttria-stabilized tetragonal zirconia polycrystal) or even zirconia with lower yttria content. This gradient allows for a natural-looking restoration with improved light transmission, mimicking the aesthetics of natural teeth. Some commercial examples of multilayer zirconia include IPS e.max ZirCAD Prime (Ivoclar Vivadent) and Katana Zirconia Multilayer (Kuraray Noritake Dental Science).(39)

The selection of zirconia for CAD/CAM applications hinges on a careful consideration of the restoration's location, functional demands, and desired aesthetics. Understanding the different generations and crystal structures of zirconia allows for informed decision-making. While earlier generations like 3Y-TZP may be suitable for high-stress applications due to their strength, newer generations and CZ offer improved aesthetics for anterior restorations. Multi-layered zirconia emerges as a versatile option for restorations requiring a balance between strength and aesthetics. The widespread availability of zirconia blocks in various configurations, from homogenous to multi-layered, allows for customization and efficient workflows in dental practices and laboratories. As research continues to refine zirconia properties and processing techniques, its role in achieving both functional and aesthetically pleasing dental restorations is likely to solidify even further. (39)

6.5 Polymethyl Methacrylate (PMMA)

Polymethyl methacrylate (PMMA) has long served as a cornerstone material in denture fabrication due to its affordability, ease of processing, and biocompatibility. Traditionally, PMMA dentures are created through a "heat-cure" technique, involving flask packing, pressing, and polymerization under heat and pressure. While this method is well-established, it can be labor-intensive and susceptible to human error during processing. In recent years, computer-aided design and computer-aided manufacturing (CAD/CAM) technology has revolutionized the production of PMMA restorations. CAD/CAM PMMA utilizes pre-polymerized resin discs that are milled by a computer-controlled machine according to a digital design. This approach offers several advantages. CAD/CAM milling ensures high dimensional accuracy and eliminates potential inconsistencies arising from manual processing in the conventional method. Studies suggest that CAD/CAM PMMA exhibits superior mechanical properties compared to conventional heat-cured PMMA. This includes increased hardness, flexural strength, and impact resistance, potentially leading to more durable restorations. CAD/CAM technology allows for faster and more efficient denture fabrication compared to the conventional method. However, some limitations exist for CAD/CAM PMMA. The initial cost of the milling equipment can be higher compared to conventional techniques. Additionally, the color options for pre-polymerized resin discs may be more limited compared to the flexibility of custom tinting achievable with conventional methods.(40)

6.6 Polyetheretherketone (PEEK)

Polyetheretherketone (PEEK) offers a biocompatible and lightweight alternative for implant frameworks and denture frameworks. Its good strength and fatigue resistance make it a viable choice for these applications. While generally compatible, some concerns exist regarding PEEK's long-term stability in the mouth, requiring further research. Additionally, specific milling tools might be necessary compared to other materials. (41)

6.7 Cobalt-Chromium (Co-Cr) alloys

Cobalt-Chromium (Co-Cr) alloys are known for their exceptional strength and durability. This makes them the ideal choice for long-term restorations like crowns, bridges, and implant frameworks, particularly in areas experiencing high occlusal forces. However, Co-Cr's metallic color might not provide the most aesthetically pleasing result, and some patients might have concerns about potential allergies to components of the alloy.(42)

6.8 Titanium

Titanium is a biocompatible metal which is well known for its excellent strength-to-weight ratio. These properties make it ideal for implant components like abutments and bars, where a lightweight but strong material is essential. While generally biocompatible, there's a small risk of peri-implant complications like peri-implantitis associated with titanium implants. Additionally, titanium can be expensive to mill compared to other materials. (43)

Selecting the most appropriate material for CAD/CAM restorations requires careful consideration of the specific clinical situation, patient requirements, and desired properties. Dentists must weigh factors like strength, aesthetics, biocompatibility, and cost to ensure a successful and long-lasting restoration.

The followings tables provide some commercially available materials for CAD/CAM systems(5,44). Tables (2)

Table 2: some commercially available materials for CAD/CAM systems

Category	**Description**	**Commercial Names**	**Manufacturer**
Glass Ceramics	***Feldspathic Ceramic:*** • Traditional material for CAD/CAM restorations. • Lower mechanical strength compared to other categories.	Vitablocs Mark II, CEREC Blocs, Vitablocs Triluxe, Vitablocs RealLife	Vita Zahnfabrik, Dentsply Sirona, Amann Girrbach
	Leucite-Reinforced Ceramic	IPS Empress CAD, Initial LRF Block, IPS InLine	Ivoclar Vivadent, Wieland Dental
	Lithium Disilicate	IPS e.max CAD, Amber Mill, Tessera, IPS e.max ZirCAD, Initial LiSi	Ivoclar Vivadent, HASS, Dentsply Sirona, Amann Girrbach, GC
Composite Resin	***Bis-GMA Composite*** • Offers ease of intraoral repair and	Paradigm MZ100, Brilliant Crios, Grandio Blocks,	3M, Coltene/Whaledent, Voco, DMG Fabrik, Ivoclar Vivadent, 3M, GC

	faster production times. - Lower wear resistance compared to ceramics	LuxaCam composite, Tetric CAD, Lava Plus, Everest	
Hybrid Ceramic	***Nanoceramic*** - Combines properties of ceramic and resin for improved aesthetics and strength.	Lava Ultimate, Cerasmart Block HC, Cerasmart, Mazic Duro, Avencia Block, Vita AMBIC	3M, GC, Shofu, GC America, Vericom co., Vita Zahnfabrik
	Polymer Infiltrated Ceramic Network (PICN) - Novel material with high strength and aesthetics	Enamic, Vita ENVY	Vita Zahnfabrik, Vita Zahnfabrik
Zirconia	***Tetragonal Zirconia*** - Excellent wear resistance and biocompatibility.	CEREC Zirconia, e.max ZirCAD, Katana Zirconia Block, Mazic Zir, LuxaCam Zircon HT Plus, Vita YZ, Lava Zirconia, Zotion	Dentsply Sirona, Ivoclar Vivadent, Kuraray Noritake Dental, Vericom co., DMG Fabrik, Vita Zahnfabrik, 3M, Zotion Dental
	Cubic Zirconia - Can be used for zirconia frameworks	Lava Plus	3M
	Multi-layered Zirconia	Katana Zirconia Multilayer, Zotion Multilayer Zirconia	Kuraray Noritake Dental, Zotion Dental
PMMA	Polymethyl Methacrylate	Lucitone, Vertex, TriLux	Dentsply Sirona, Ivoclar Vivadent, Triton
PEEK	Polyetheretherketone	Victrex PEEK, Ketac M, Celtra PEEK	Victrex plc, 3M ESPE, Dentsply Sirona
Co-Cr	Cobalt-Chromium	CoCr Sin, Vita VMK Master, Jelenko Cobalt Chrome	Amann Girrbach, VITA Zahnfabrik, Jelenko Dental
Titanium		Ti Grade 4, OsseoSpeed Titanium, Straumann SLActive	Various, Astra Tech, Straumann

7. Challenges and future prospective

CAD/CAM technology has significantly impacted dentistry, allowing for the creation of diverse dental restorations with remarkable precision. However, this field faces challenges that push the boundaries of future advancements.

A major obstacle is the limitations of current materials. There are many options available, but each has inherent drawbacks. For example, zirconia, known for its strength, might lack the natural translucency of teeth, compromising aesthetics. Conversely, composite resins excel aesthetically but may not be as wear-resistant as ceramics.(5)

Another challenge is the limited long-term clinical data on these materials. While short-term results are promising, extensive studies are needed to definitively assess their efficacy and durability in various situations. Additionally, current functionalities primarily focus on replicating the form and function of natural teeth. Future advancements should strive towards integrating more complex features, such as temperature or pressure sensing. This could potentially enable real-time monitoring of oral health or even drug delivery mechanisms. (44)

Furthermore, there is a balancing act between efficiency and precision. Chairside CAD/CAM systems prioritize speed and convenience, but this can sometimes come at the expense of achieving the intricate details possible with laboratory-based systems. Optimizing workflows to achieve a balance between the two remains an ongoing pursuit.(4)

Finally, cost considerations are a factor. The sophisticated technology and materials employed in CAD/CAM dentistry can translate to higher treatment costs compared to traditional methods. Developing more cost-effective materials and streamlining workflows can improve accessibility to this technology for a wider range of patients.

The development of biomimetic materials that closely resemble the natural structure and properties of teeth holds immense promise. These materials could offer superior aesthetics, functionality, and biocompatibility, pushing the boundaries of dental restoration.

The integration of artificial intelligence (AI) is another transformative prospect. AI has the potential to revolutionize CAD/CAM dentistry by automating design processes, optimizing settings for different materials, and even predicting long-term outcomes based on patient data. This integration can enhance efficiency, precision, and personalization of dental restorations.(45)

By addressing these challenges and highlighting the potential of future advancements, CAD/CAM technology and material science have the power to reshape the landscape of dentistry, offering patients a wider range of highly esthetic, functional, and durable restorative options.

8. Conclusion

In conclusion, this review has explored the remarkable synergy between computer-aided design and computer-aided manufacturing (CAD/CAM) technology and the continuous development of biocompatible materials in modern restorative dentistry. This integration has significantly transformed the field, offering numerous advantages over traditional methods.

Conflict of Interest

A declaration of conflict of interest.

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