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An overview of recent developments in CAD/CAM-produced restorations

Merve Sena Ekinci[1], **Beste Çetin**[2]

[1] Adıyaman University, Faculty of Dentistry, Department of Prosthodontics, Adıyaman, Türkiye
[2] Kahramanmaraş Sütçü İmam University, Faculty of Dentistry, Department of Prosthodontics, Kahramanmaraş, Türkiye

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Correspondence:

Dr. Merve Sena EKİNCİ
Adıyaman University, Faculty of Dentistry,
Department of Prosthodontics,
Adıyaman, Türkiye.
E-mail: mervesekinci@icloud.com

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Abstract

The evolution of computer-aided design and manufacturing (CAD/CAM) systems has enabled the development of new materials, treatment methods, and prosthesis manufacturing processes. As innovation in material development continues, the production of new-generation materials with better functions and superior features has become possible. With CAD/CAM technology, chair-side manufacture of esthetic full ceramic restorations that are perfectly compatible with abutments has become possible. In addition, this technology has replaced resin composites applied directly intraorally with resin composite blocks produced with a milling system and applied indirectly, which are mechanically more durable. In addition, digitally produced removable prostheses have also been used widely in recent years. Thus, since the time spent by the dentist for the patient at the clinic and the number of appointments decrease, the delivery time of the prosthesis to the patient is also significantly shortened. Subjective errors due to the technician are also eliminated with these systems, and more accurate manufacture of prostheses is achieved. Because newly developed CAD/CAM materials are manufactured industrially in a standard way and the manufacturing phases are strictly controlled, they can be considered more advantageous than materials used in conventional methods in terms of structural properties. The purpose of this review is to provide physicians with a different perspective on the selection of current materials to be used in the production of CAD/CAM restorations and to assist in material selection in clinical practice.

Keywords: CAD/CAM, glass-matrix ceramics, zirconia, zirconia-reinforced lithium disilicate, fiber-reinforced composites, PEEK

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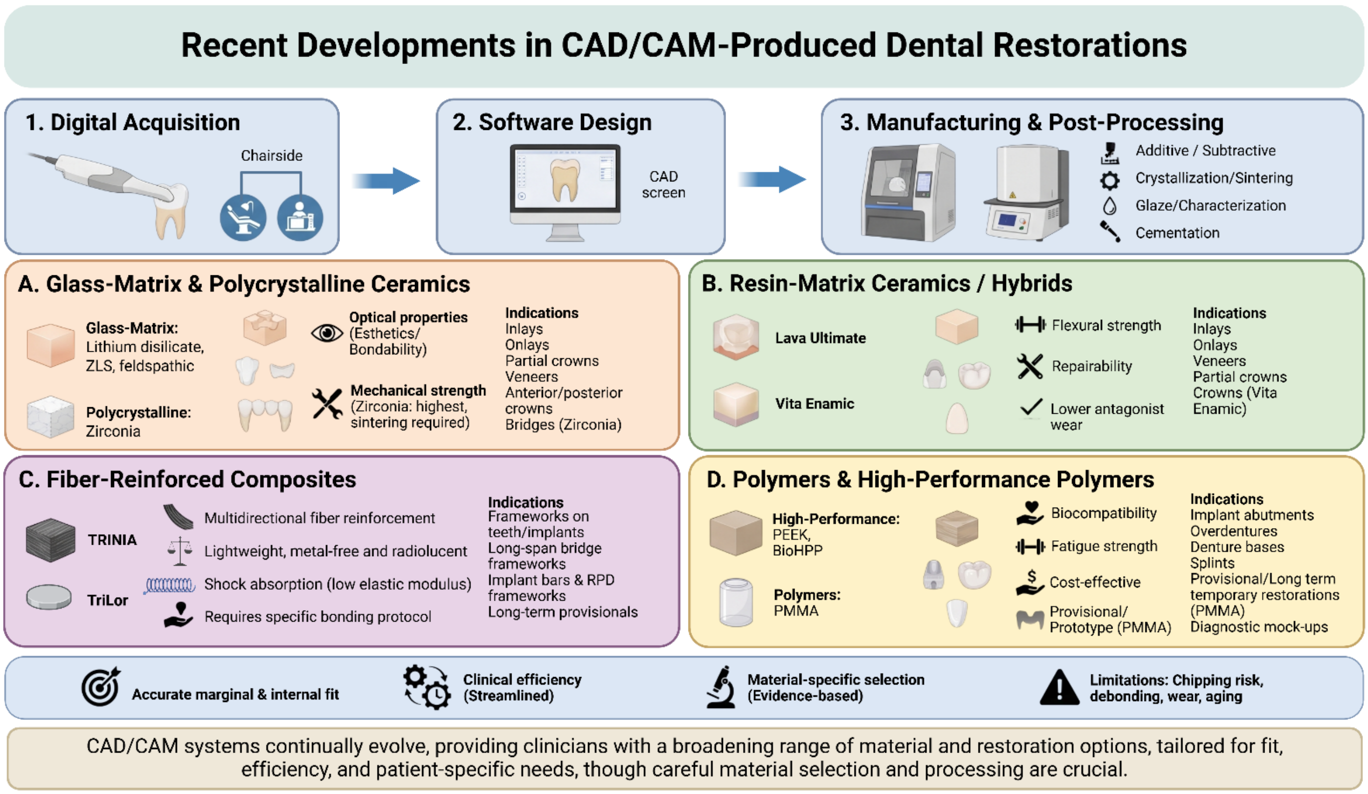
Graphical abstract



1. Introduction

Advances in computer-aided design (CAD)/computer-aided manufacturing (CAM) technologies and their ease of application have enabled the development of new treatment concepts for modern prosthetic dentistry. The variety of CAD/CAM restorative systems is constantly evolving to meet the increasing demand for highly esthetic, biocompatible, and durable permanent and temporary restorations.

Computer-Aided Design / Computer-Aided Manufacturing (CAD/CAM) technologies, which are widely used due to their advantages, such as predictable aesthetic designs, informing patients about final restorations at the beginning of treatment, shortening appointment and laboratory sessions, and eliminating production errors due to personal reasons, were developed in the 1960s for use in the industrial sector. Its introduction to dentistry dates back to the 1970s by François Duret (1).

Today, various materials, such as ceramics, composites, polymers, and metals, can be used for CAD/CAM-supported indirect dental restorations. However, two main materials stand out in these systems for esthetic purposes: glass-ceramics/ceramics and resin composites. Glass-ceramics/ceramic materials are generally superior to resin composites in terms of optical properties, durability, and transparency. However, resin composites are preferred because of their ease of production, relatively low cost, and intraoral repair (2). CAD/CAM materials are generally grouped into three different groups: all-ceramics, resin composites, and polymers.

A complete digital workflow comprises four consecutive stages: digital acquisition of the preparation by intraoral scanning or by desktop scanning of a conventional impression or cast; design of the restoration in CAD software; manufacture by a subtractive (milling) or additive (three-dimensional printing) route; and material-specific post-processing before cementation. The post-processing stage differs fundamentally between material classes and is described in the relevant sections below.

2. Full-ceramics

The criteria used to distinguish all-ceramic materials are based on the phase or phases present in their chemical composition. Thus, an all-ceramic material is classified according to whether a glass matrix phase is present or whether the material contains an organic matrix highly filled with ceramic particles (glass matrix ceramics, polycrystalline ceramics, and resin matrix ceramics) (3, 4).

2.1 Glass-matrix ceramics

Glass-matrix ceramics form the largest group of esthetic CAD/CAM materials and are subdivided according to the type and volume fraction of the crystalline phase dispersed within the glassy matrix (3). Feldspathic ceramics, which were the first blocks produced for chair-side milling, consist of a predominantly glassy matrix with a limited crystalline content. They closely reproduce the optical behavior of enamel and are minimally abrasive to the antagonist dentition, but their comparatively modest flexural strength limits them to conservative restorations such as inlays, onlays, and laminate veneers (1).

Leucite-reinforced glass ceramics increase the crystalline fraction, and therefore the strength of the material, while retaining acceptable translucency. Lithium disilicate glass ceramics contain a considerably higher volume of elongated crystals; the crack-deflection mechanism produced by this microstructure raises the flexural strength of the material and permits the fabrication of single crowns and short-span anterior fixed dental prostheses in addition to partial-coverage restorations (1). Because all glass-matrix ceramics contain a silica-based glassy phase, they can be conditioned with hydrofluoric acid etching followed by silane application, and adhesive cementation is therefore an integral part of their clinical protocol.

In a systematic review and meta-analysis of ceramic laminate veneers, pooled survival rates at a mean observation period of 10.4 years were 96.13% for feldspathic ceramics, 93.70% for leucite-reinforced glass ceramics and 96.81% for lithium disilicate, with no statistically significant difference between the materials. Lithium disilicate nevertheless demonstrated the lowest long-term technical, esthetic and biological complication rates (5).

2.2 Zirconia-reinforced lithium silicate ceramics

Manufacturers have combined the aesthetic and optical properties of lithium disilicate with the superior mechanical properties of zirconia to introduce an innovative material, zirconia-reinforced lithium silicate (ZLS) ceramics. This ceramic system is formed by adding 8-12% tetragonal zirconia to lithium silicate. Color options and durability have increased, allowing the production of aesthetic, anatomical, and monolithic crowns. Restorations can be produced using pressing and milling methods. The first ZLS blocks produced for CAD-CAM milling were Vita Suprinity PC (Vita Zahnfabrik, Bad Säckingen, Germany) and Celtra Duo (Dentsply Sirona, Hanau-Wolfgang, Germany).

Vita Suprinity is a contemporary glass-ceramic material. It is reinforced by adding 10% zirconia to the glass ceramic using an innovative production process. Thus, the first zirconia-reinforced lithium silicate ceramic (ZLS) was produced. This material combined the positive properties of glass ceramic and zirconia. Owing to the 10% zirconia content after crystallization, high mechanical properties and aesthetically pleasing results were achieved. ZLS blocks are produced in three stages. In the first stage, the components are melted at high temperatures. The molten material is then placed in a mold while still in the glass phase. At this stage, the material is brittle and unsuitable for milling. Therefore, thermal preheating is required. With thermal preheating, the nucleation reaction starts, and the crystals begin to form and grow. The resulting material exhibits ceramic-like properties and is suitable for milling. It reaches its real physical properties and aesthetic appearance after the final crystallization firing (6).

Celtra Duo is manufactured in crystallized form and defined by a particular, ultra-fine microstructure due to the homogeneous distribution of zirconium dioxide grains in the glassy, amorphous matrix of lithium silicate crystals, which are four to eight times smaller than lithium disilicate crystals. The internal configuration of the glass-ceramic matrix, along with the very fine structure of the lithium silicate crystals, provides the material with particular mechanical and optical properties (7, 8).

Zirconia-reinforced lithium silicate ceramics are indicated for a wide range of clinical applications, including inlays, onlays, partial crowns, veneers, anterior and posterior crowns, and single-tooth restorations on implant abutments (9).

The fracture strengths of Celtra Duo milled, Celtra Duo fired, and Suprinity restorations at different thicknesses were analyzed. Assuming a maximum chewing force of 600-800 N, all three materials survived the fatigue test in the group with a thickness of 1.5 mm. When the thickness was reduced to 0.5 and 1 mm, the highest survival rate was observed in Suprinity (10).

Mendonça et al. investigated the flexural strength and microporosity of posterior monolithic crowns fabricated using four different CAD/CAM materials. They reported that lithium disilicate and ZLS restorations demonstrated higher mechanical properties than hybrid high-performance polymer composite resin and hybrid polymer infiltrated ceramic (11).

In a study investigating the effect of multiple firings on translucency, 0.6- and 1-mm-thick lithium disilicate and ZLS ceramics were investigated. They reported that repeated firings affected the translucency of both materials, and the translucency decreased with increasing thickness (12).

2.3 Polycrystalline ceramics (zirconia)

Polycrystalline ceramics contain no glassy phase; their microstructure consists entirely of densely packed crystals, which accounts for their high flexural strength and fracture toughness but also for their comparatively opaque appearance (3). Yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP) was the first generation introduced into dentistry and derives its toughness from the stress-induced transformation of tetragonal grains into the monoclinic phase, which places the crack tip under compression and arrests propagation.

To meet increasing esthetic demands, partially stabilized formulations with a higher yttria content (4Y-PSZ and 5Y-PSZ) were subsequently developed. These contain a greater proportion of the cubic phase, which improves light transmission and permits monolithic anterior use, but reduces flexural strength and diminishes the transformation-toughening reserve. Translucency and strength therefore stand in inverse relation across the zirconia generations, and material selection must be matched to the span and the occlusal load of the planned restoration.

Unlike glass-matrix ceramics, zirconia is milled in a pre-sintered state and requires a final sintering firing, during which the framework undergoes a predictable volumetric shrinkage that is compensated by an enlargement factor in the design software. Because the same tetragonal-to-monoclinic transformation that confers toughness can also be triggered by moisture at low temperature, zirconia is susceptible to hydrothermal aging, also termed low-temperature degradation. This process produces progressive surface transformation, microcracking, increased surface roughness and a decrease in mechanical strength over time; its extent depends on yttria content, grain size and the sintering protocol employed (13). Zirconia is indicated for monolithic single crowns, multi-unit fixed dental prostheses including long-span designs, implant abutments and implant-supported frameworks. Since it lacks a silica phase, hydrofluoric acid etching is ineffective, and adhesive cementation requires airborne-particle abrasion combined with a phosphate-monomer-containing primer.

After sintering, the surface of a ceramic restoration is finished either by mechanical polishing or by a glaze firing, and the glaze cycle is also the stage at which extrinsic stains are applied for shade characterization. The two routes are not interchangeable. Surface roughness after finishing governs plaque accumulation, staining and abrasion of the opposing dentition, and chairside mechanical polishing has been shown to produce surface roughness and biaxial flexural behavior comparable to laboratory reglazing without requiring an additional firing appointment (14). Finishing and characterization should therefore be treated as an integral stage of the manufacturing workflow rather than as a cosmetic afterthought.

2.4 Resin matrix ceramics

Lava Ultimate (3M ESPE, Seefeld, Germany), which can be milled with a CAD/CAM system, was launched in 2011 by 3M ESPE. It is based on a polymerizable composite resin (Filtek Supreme Ultra, 3M). It contains 80% silica nanoparticles and zirconia nanoparticles embedded in a dimethacrylate resin. The flexural strength and elastic modulus of the resin were 200 MPa and 12 GPa, respectively. Resin nanoceramics can be used for veneers, inlays, and onlays. When used with resin luting cements, they should be bonded after roughening with air abrasion (6). Another ceramic system with a resin matrix is Vita Enamic (Vita Zahnfabrik, Bad Säckingen, Germany). The ceramic/polymer ratio was 86/14 by mass. The polymer part consisted of urethane dimethacrylate (UDMA) and triethylene glycol dimethacrylate (TEGDMA). The elastic modulus was 30 GPa, and the flexural strength was 150-160 MPa. Its elastic modulus is approximately 2.5 times that of Lava Ultimate. Indications include implant-supported posterior crowns, veneers, inlays, onlays, and anterior and posterior crowns. There are monochromatic or multichromatic types (HT, LT, T) (1).

Vafaee et al. investigated the flexural strength and fatigue resistance of IPS e.max CAD, Lava Ultimate, and Vita Enamic materials. They reported that IPS e.max CAD exhibited the highest flexural strength, followed by Lava Ultimate and Vita Enamic. The flexural strength of Lava Ultimate and Enamic was found to be good compared to dental resin composites, and fractures were observed at higher levels than the fracture load recommended for posterior restorations. Therefore, their use in posterior restorations appears promising. However, careful case selection is warranted in patients with bruxism or high masticatory forces (15).

In another comparative study, Vita Enamic and Lava Ultimate were found to cause less antagonist tooth wear than Lava Plus, Vita Suprinity, and IPS e.max CAD. Lava Plus had the highest hardness, followed by Vita Suprinity, IPS e.max CAD, Vita Enamic, and Lava Ultimate. Nanofil composite resin and polymer infiltrated ceramics were reported to be the most antagonist-friendly materials when sliding against enamel (16).

A practical advantage shared by the resin-matrix group is that no crystallization or sintering firing is required after milling; the restoration is finished by polishing, and intraoral repair with conventional composite resin is possible. Finishing protocol nevertheless influences long-term optical behavior, and the surface treatment selected after milling affects the color stability of CAD/CAM ceramics (8).

The manufacturer indication range of the polymer-infiltrated ceramic network additionally includes partial crowns alongside inlays, onlays, veneers and full crowns, and monolithic crowns milled from this material have demonstrated high resistance to sliding-contact fatigue fracture and wear under mouth-motion loading in vitro (17). Because the elastic modulus of the resin-matrix group lies closer to that of dentin than the modulus of glass-matrix or polycrystalline ceramics, these materials deform slightly under occlusal load and are correspondingly less abrasive towards the antagonist dentition (16).

3. Resin composites

A conventional resin composite material (CRCM) consists of a polymeric matrix reinforced with fillers, which are usually inorganic, organic, or composite. It also contains other components, such as polymerization initiators, stabilizers, and color pigments. Conventional resin composites are manually shaped at the application site and cured using a high-intensity light source. Resin composite blocks (RCB) designed for CAD/CAM are obtained by adding filler particles to a monomer mixture cured under high pressure and high temperature; therefore, they do not require an additional curing process. This production method results in material properties such as fewer defects, more homogeneous filler distribution, higher mechanical strength, and reduced water absorption. CAD-CAM RCBs also have lower porosity and contain urethane dimethacrylate (UDMA), which improves the color stability of the restorations (18, 19). Hussain et al. reported that the mechanical properties of RCBs were superior and that the RCBs eluted less residual monomer than the CRCMs. However, they reported less favorable cytotoxicity results for the RCBs than for the conventional composites (19).

TRINIA (Bicon LLC, Boston, MA, USA) is a lightweight, metal-free CAD/CAM material. Its discs and blocks consist of multilayered, multidirectionally interlaced fiberglass and resin, and the material has a flexural modulus of elasticity of 18.8 GPa (20). This value is relatively close to the reported elastic modulus of dentin (12-14 GPa) (21).

TRINIA is intended for permanent and transitional prosthetic restorations. TRINIA's fiber-reinforced composite (FRC) consists of approximately 60% glass fiber and 40% epoxy resin. Its most prominent features include a flexural strength of 393 MPa (N/mm^2) and a very low water absorption of 0.03%. TRINIA can be processed using conventional wet or dry milling machine systems with nano-diamond burs. It is a suitable material for making permanent and transitional anterior or posterior crown-bridges, copings, and substructures or frameworks on natural teeth or implant abutments. It can be used in cement-retained restorations as well as in screw-retained or telescopic crown systems. The material is available in ivory and pink colors. It can be processed efficiently while retaining high flexural and compressive strength (20).

Because fiber-reinforced composites contain no metallic component, they are radiolucent, which permits unobstructed radiographic assessment of the underlying abutment teeth and peri-implant bone. The absence of a metallic substructure also eliminates the greyish discoloration of the overlying soft tissues associated with cast alloy frameworks. Conversely, the glass fibers exposed at a milled surface make adhesive conditioning of the framework a material-specific step: a defined surface treatment and an appropriate resin-based luting or veneering protocol are required before the framework is joined to the veneering material or luted to the abutment.

Zaparolli et al. investigated the stress distribution of implant bars manufactured using different materials. They reported that the TRINIA bar showed more favorable stress distribution than the titanium and cobalt-chromium bars (22).

In rehabilitation with TRINIA prostheses compared with BioHPP, microstrain around implants with angled abutments was lower. Microstrain increased with increasing abutment angulation and was higher under oblique loading than under axial loading (23).

The flexural modulus of fiber-reinforced composites is substantially lower than that of metal or zirconia frameworks, so an FRC substructure deforms elastically under occlusal load instead of transmitting the force rigidly to the abutments. This shock-absorbing behavior is the mechanical basis of the two findings above: the more favorable stress distribution recorded for TRINIA implant bars relative to titanium and cobalt-chromium (22), and the lower peri-implant microstrain measured for TRINIA compared with the ceramic-reinforced polymer BioHPP (23).

TriLor (Bioloren, Saronno, Italy) is a further glass fiber-reinforced CAD/CAM technopolymer in which multidirectional glass fibers are integrated into an epoxy resin matrix. It is supplied as discs and as preformed arches and can be dry- or wet-milled to produce removable partial denture frameworks, full-arch implant superstructures and bridge frameworks, which are subsequently veneered with composite or acrylic resin. Owing to its capacity to flex under load, it has been proposed as a resilient substructure beneath zirconia, lithium disilicate, acrylic or composite superstructures in implant-supported rehabilitations (24).

4. Polymers

Polyetheretherketone (PEEK), a high-performance plastic polymer with semi-crystalline properties, is an important material in dentistry due to its good biocompatibility, high toughness and temperature resistance (melting point of 343 °C), high fatigue strength, color stability, relatively low wear rate (0.9 ± 1.1 mm^3/MC), ease of processing, and corrosion resistance. It is lighter than traditional materials. The modulus of elasticity is similar to human bone tissue, thus reducing the stress shielding of PEEK restorations. However, the strength of PEEK may not be sufficient for occlusal forces, thus increasing the risk of fracture. It can be blended with materials such as fibers and ceramics to increase its mechanical strength. Compared with ceramics, PEEK prostheses have poor aesthetics and do not provide acceptable aesthetic results unless coated with composite resins (25).

PEEK, which is widely used in dentistry, is used in the production of metal-free fixed dental prostheses, endocrowns, resin-bonded fixed dental prostheses, implant-supported fixed prostheses, implant-retained overdentures, removable dental prostheses, dental implants, implant abutments, healing abutments, and occlusal splints (26).

PEEK restorations can be produced using traditional injection molding, milling, and 3D additive manufacturing. Milling involves creating the designed object in CAD software by subtracting material from a PEEK block. CAD/CAM fabrication offers good durability, rapid production, and good marginal fit (27). Arnold et al. produced dental prostheses using indirect rapid prototyping, direct rapid prototyping, indirect milling, and direct milling methods. They examined the fit of prostheses. They reported that the direct milling group had better precision and fit (28).

Given its biocompatibility and low weight, PEEK use as an implant abutment alternative to titanium and zirconia has increased in recent years. To prevent peri-implantitis, the surface roughness of the abutment is important for the attachment and colonization of microorganisms. Wiessner et al. reported that zirconia had the lowest biofilm formation, followed by titanium, PEEK, and PEEK-BioHPP (29). When PEEK is used as a substrate, bond strength between the coating material and cement is important. Surface treatments such as laser application, sulfuric acid etching, monomer primer application, and air abrasion with alumina particles increase bond strength (27).

PEEK offers better stress modulation through plastic deformation, minimal abrasion, and good color stability, making it a promising alternative to zirconia crowns. Abhay et al. reported that zirconia was three times more abrasive than PEEK and exhibited greater color stability, whereas PEEK demonstrated greater displacement resistance (30).

BioHPP (bredent GmbH & Co. KG, Senden, Germany) is a partially crystalline PEEK reinforced with ceramics. The ceramic content improves the strength and wear properties. As a material that provides a balance between elasticity and stiffness and can cushion the distribution of occlusal forces at the bone level, BioHPP® has become widely used, especially in implant overdentures. BioHPP showed a relatively low fracture rate compared to zirconia inlays in posterior teeth during the one-year observation period. Compared with lithium disilicate endocrowns, the marginal and internal conformations of both materials were clinically acceptable. BioHPP may be a good alternative due to its retention, durability, and high marginal compatibility (31–33).

Polymethyl methacrylate (PMMA), an important biomaterial in dentistry since the 1940s, is a synthetic polymer obtained from methyl methacrylate monomer. Its ease of processing and manipulation, low density, adaptable physical and mechanical properties, aesthetics, and cost-effectiveness make it a suitable and popular biomaterial for dental applications. PMMA is used in the production of artificial teeth, denture bases, occlusal splints, obturators, orthodontic retainers, and temporary restorations. In digital workflows it is additionally employed for diagnostic mock-ups and prototype restorations, in which the planned contour is milled from a PMMA block and evaluated intraorally for function and esthetics before the definitive material is selected. Conventional PMMA is available in powder and liquid forms. The polymerization reaction is initiated and activated chemically or by energy sources such as heat, light, and microwave (34). Denture base materials can be produced by heat polymerization, autopolymerization, milling of CAD/CAM PMMA blocks, or three-dimensional additive manufacturing. Heat-polymerized PMMA resin has disadvantages such as a high residual monomer content and increased Candida albicans adhesion as surface roughness increases. It may cause mucosal ulcers and stomatitis in patients with long-term prosthesis use (35, 36). CAD/CAM PMMA blocks are polymerized under high temperature and pressure. This process produces blocks with improved mechanical properties, lower surface roughness, and reduced residual monomer content (37).

Al-Fouzan et al. investigated the adhesion rate of Candida albicans to PMMA denture bases produced using CAD/CAM and to those produced using the conventional method. More Candida albicans adhesion was observed on prosthesis bases produced using the conventional method. The CAD/CAM procedure for the fabrication of complete dentures was considered a promising approach for reducing the adhesion of Candida to the denture base surface (38).

Srinivasan et al. reported that conventional PMMA and CAD-CAM PMMA used in the production of removable dental prostheses are equally biocompatible. They reported that CAD-CAM PMMA prostheses produced with high pressure offered higher mechanical properties (37). A similar study reported that CAD/CAM PMMA specimens exhibited better flexural strength and flexural modulus than conventional heat-cured groups (39). Tushar et al. investigated the flexural and impact strengths of different polymers. They reported that PEEK and CAD/CAM PMMA showed similar results, but both had higher mechanical properties than conventional PMMA (40).

5. Clinical limitations and material-specific considerations

Although CAD/CAM restorations offer accurate marginal and internal fit, a broad indication range and a streamlined workflow, each material class carries characteristic modes of failure that should inform case selection. Technical complications reported for ceramic restorations include crack formation, chipping of the ceramic surface, bulk fracture, marginal gap formation and debonding; in a long-term meta-analysis of ceramic laminate veneers the pooled rates were 13.73% for marginal gap formation, 4.3% for crack formation, 3.53% for chipping, 2.51% for bulk fracture and 2.2% for debonding (5). Wear behavior differs markedly between classes, and polymer-infiltrated and nanofilled materials are the most favorable towards the antagonist dentition, whereas harder monolithic ceramics are more abrasive (16). For polycrystalline ceramics, hydrothermal aging constitutes an additional, time-dependent mode of strength loss that is not observed in glass-matrix or resin-matrix materials (13). Material selection should therefore be guided by the restoration type, the anticipated occlusal load, the remaining tooth structure, the available bonding substrate and the esthetic demand, rather than by the manufacturing technology alone.

6. Conclusion

CAD/CAM systems integrate digital acquisition of tooth preparations, design software, restorative material options, and milling processes. They offer advantages such as accurate results, a wide range of indications, streamlined workflows, and ease of use. The demand for aesthetic and durable restorations is increasing, and CAD-CAM systems continue to develop and expand. As these developments continue, clinicians will have a wider range of options to address diverse patient needs effectively.

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