*ERURJ* **2025**, *4*, 2, 2595-2629

*(Review)*

# A Review on the Evolution of CAD-CAM Materials in Fixed Prosthodontics Regarding Mechanical Properties, Aesthetic Outcomes, and Clinical Indications

Menna ElGendy [1], Noran ElSharkawi [1]

[1] *Fixed Prosthodontics Department, Faculty of Oral and Dental Medicine, Egyptian Russian University, Badr City, Cairo-Suez Road, Cairo 11829, Egypt.*

*Corresponding authors: Menna Ahmed Emad ElGendy, Noran Mohamed ElSharkawi,
e-mail: mennaallha-ahmed@eru.edu.eg, Nuran-Muhammad-mustafa@eru.edu.eg

*Received: 18th November 2024, Revised 25th November 2024, Accepted 28th November 2024*
*DOI: 10.21608/erurj.2025.331419.1196*

**ABSTRACT**

In recent years, the dental field has witnessed a transformative shift with the advent of Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) technology. It integrates advanced digital technology into the traditional dental workflow, allowing for more precise, efficient, and personalized patient care. CAD/CAM materials have become increasingly popular in fixed prosthodontics due to their aesthetic appeal, biocompatibility, and durability. This review examines the mechanical properties, aesthetic outcomes, and clinical applications of key CAD-CAM materials, including glass-ceramics (leucite-reinforced and lithium disilicate derivatives), zirconia, and alumina. It highlights the notable inverse relationship between translucency and strength, factors influencing material selection, and practical clinical indications such as crowns, bridges, and implant-supported restorations. By comparing the advantages, disadvantages, limitations, and emerging trends in these materials, this paper offers insights into optimizing restorative outcomes. Dental professionals can benefit from this comprehensive review by making informed treatment decisions that enhance both functionality and aesthetics.

*Keywords:* Mechanical properties*; Restorations; glass ceramics; Zirconia.*

## 1- Introduction

The evolution of Computer-Aided Design and Computer-Aided Manufacturing (CAD-CAM) materials in fixed prosthodontics has significantly transformed dental restoration practices over the past few decades. Initially introduced in the 1980s, CAD-CAM technology has advanced from rudimentary systems to sophisticated digital workflows that enhance the precision and efficiency of dental restorations. This review aims to explore the development of CAD-CAM materials, focusing on their mechanical properties, aesthetic outcomes, and clinical indications.

The mechanical properties of CAD-CAM materials are crucial for their performance in clinical applications. Materials such as zirconia, lithium disilicate, and polymethylmethacrylate (PMMA) have been extensively studied for their strength, durability, and fracture resistance. Zirconia, known for its high flexural strength (up to 1400 MPa), is widely used in load-bearing applications such as posterior crowns and bridges. In contrast, lithium disilicate offers a balance between aesthetics and mechanical strength, making it suitable for anterior restorations where translucency is paramount. The introduction of PMMA-based materials has also expanded options for provisional restorations due to their improved mechanical properties compared to conventional PMMA. [1]

Aesthetic considerations are essential in fixed prosthodontics, particularly for anterior restorations where visual appeal is critical. CAD-CAM materials have evolved to include tooth-colored options that mimic natural dentition closely. The optical properties of these materials, including translucency and color stability, are vital for achieving lifelike results. Recent advancements have led to the development of materials with enhanced aesthetic outcomes, such as multi-layered zirconia and composite resins that provide both strength and a natural appearance. The ability to customize color and translucency through digital design further enhances aesthetic outcomes. [2]

The clinical applications of CAD-CAM materials are diverse, ranging from single crowns to complex multi-unit bridges. The choice of material often depends on specific clinical scenarios, including the location of the restoration, patient preferences, and functional requirements. For example, zirconia is preferred for posterior restorations due to its strength, while lithium disilicate is favored for anterior applications due to its superior aesthetics. Additionally, recent studies indicate that CAD-CAM materials can effectively reduce plaque accumulation and periodontal complications compared to traditional materials. [3]

The evolution of CAD-CAM materials in fixed prosthodontics represents a significant advancement in dental technology. With ongoing research focusing on enhancing mechanical properties, aesthetic outcomes, and clinical applicability, these materials continue to reshape restorative dentistry. Future developments will likely focus on optimizing material performance while addressing patient-specific needs in aesthetic dentistry. This review highlights the importance of understanding these advancements to leverage CAD-CAM technology effectively in clinical practice.

## 2- CAD/CAM Technology

The inception of CAD-CAM in dentistry can be traced back to the pioneering work of Dr. François Duret, who patented the first system capable of producing fixed dental prostheses (FDPs) in 1984. This innovation aimed to address challenges in creating durable and aesthetically pleasing restorations efficiently. [4,5] Over the decades, CAD-CAM systems have evolved from single-unit restorations to comprehensive rehabilitations completed within a single appointment. [4,6] The integration of digital impressions and milling technologies has allowed for the production of restorations with marginal gaps comparable to those achieved through traditional methods, thus enhancing clinical acceptability. [3]

The CAD-CAM system comprises three primary steps: digital scanning, digital design, and manufacturing. Intraoral scanners capture dental records, generating digital data that is subsequently processed by software programs to visualize and design dental restorations. These designs are then fabricated using either subtractive (milling) or additive manufacturing as shown in Figure (1).[7]

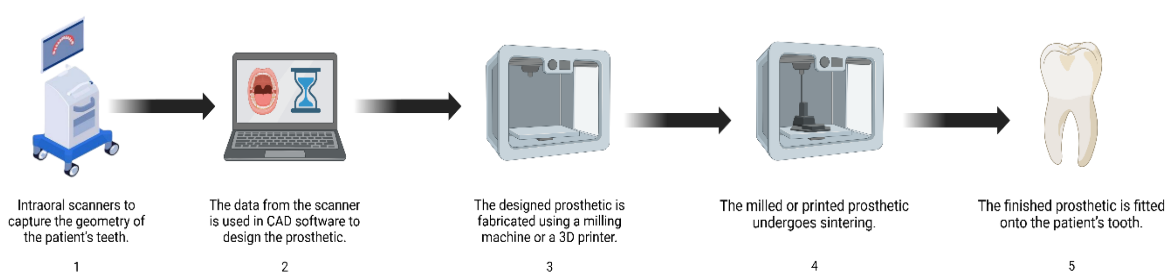


**Figure 1.** CAD/CAM system follows a streamlined process for the fabrication of prosthetic restorations.

CAD/CAM technology has revolutionized the field of dentistry by offering several distinct advantages over traditional methods. One of the most significant benefits is the increased accuracy and precision achieved through digital modeling and computer-controlled machining. This translates to improved marginal fit and reduced risk of marginal leakage in restorations, crucial factors for long-term success. In addition to enhanced precision, CAD/CAM workflows significantly improve efficiency. By automating and streamlining the fabrication process, CAD/CAM technology enables faster turnaround times for prosthetic restorations compared to manual techniques. This benefits both dentists and patients by reducing chair time and accelerating treatment processes. Furthermore, CAD/CAM technology empowers dentists to explore complex designs and utilize biocompatible materials, expanding the possibilities for restorative dentistry. This opens up new avenues for creating innovative and functional restorations that meet the diverse needs of patients.[8,9]

Previous studies have consistently highlighted the efficiency and comfort of digital scanning compared to conventional impression-taking methods. CAD-CAM restorations offer a harmonious blend of aesthetics, durability, and functionality. They exhibit superior marginal adaptation, reduce plaque accumulation, and minimize the risk of periodontal inflammation and caries. Moreover, intraoral scanners expedite procedures, enhance patient comfort, and achieve high levels of precision.

However, the implementation of CAD-CAM technology presents certain challenges, including its relatively high cost and the requirement for specialized training. The learning curve for dental professionals can vary from days to months. Furthermore, the survival rate of CAD-CAM restorations may differ depending on the materials used, making direct comparisons with conventionally fabricated restorations difficult.

### 3- A. Chronological Overview of CAD/CAM in Dental Restorations

The introduction of computer-aided design/computer-aided manufacturing (CAD/CAM) technology in dentistry marked a significant development in the fabrication of dental restorations. This innovative approach, pioneered in the 1980s, revolutionized the way dentists could design and produce customized restorations chairside. [10]

One of the earliest milestones in the history of CAD/CAM dentistry was the introduction of the CEREC 1 system in 1985. This pioneering system, developed at the University of Zurich Dental School, enabled dentists to design and mill ceramic restorations directly in their practices.

The initial ceramic material used in CEREC 1 was Vitablocs Mark, a feldspar-based ceramic that could be compressed into blocks and machined into dental restorations.[6,11]

Over the subsequent years, significant advancements were made in both ceramic materials and CAD/CAM technology. In 1987, Vitablocs Mark II was introduced, offering a finer-grained, high-glass-content feldspar-based ceramic that provided improved aesthetics and strength. This material remained the primary choice for CEREC restorations until the late 1990s. [6]

In 1997, a major breakthrough occurred with the introduction of Paradigm MZ100 blocks. These blocks, developed by 3M ESPE, were composed of a highly filled silica ceramic particle embedded in a resin matrix. This innovative material offered several advantages, including increased density, uniformity, and reduced polymerization shrinkage. Additionally, Paradigm MZ100 blocks could be shaped anatomically in a milling machine, providing greater flexibility in restoration design.

The early 2000s saw further advancements in ceramic materials. In 2003, 3M ESPE introduced Paradigm C, a leucite block that offered enhanced strength and translucency. Subsequently, in 2006, Ivoclar Vivadent introduced IPS e.max CAD, a lithium disilicate ceramic that combined the properties of a structural and aesthetic ceramic. This material provided exceptional strength and lifelike aesthetics, making it a popular choice for CAD/CAM restorations.[12]

In 2007, Sirona Dental Systems launched the CEREC Block, a material that is comparable to Vitablocs Mark II but features a distinct shading system. The introduction of CEREC blocks in multiple shades and varying levels of color saturation—specifically translucent, medium, and opaque—enabled more accurate matching to the natural colors of teeth.([0,12]

In parallel with these material advancements, significant technological improvements were also taking place. The transition from two-dimensional to three-dimensional design programs was facilitated by advancements in computer speed and memory. This shift enabled dentists to create more accurate and realistic restorations.[11]

The evolution of CAD/CAM in dental restorations has been marked by a series of significant advancements in both ceramic materials and design technology. These innovations have led to the development of more durable, aesthetically pleasing, and efficient restorations, revolutionizing the field of dentistry and improving the quality of care for patients. [6]

## 4- Classification of CAD-CAM Materials

The literature describes various classifications for CAD-CAM materials, considering factors such as material composition, processing route, and manufacturing type as summarized in Table (2). Common classifications include:

- Material-based: The categories of materials encompass metals, polymer-infiltrated ceramic networks (PICN), polyether ether ketone (PEEK), polymethyl methacrylate (PMMA), composite resins, silicate ceramics, and oxide ceramics.
- Processing route-based: Laboratory-side and chairside.
- Manufacturing type-based: Additive or subtractive.

The range of CAD-CAM materials is extensive, encompassing a wide variety of compositions. Each material possesses distinct processing parameters, necessitating adaptation of the entire system to its specific characteristics. The composition of CAD-CAM materials directly influences their mechanical and physical properties, guiding dental practitioners in selecting the most suitable material for individual applications as shown in figure (2).

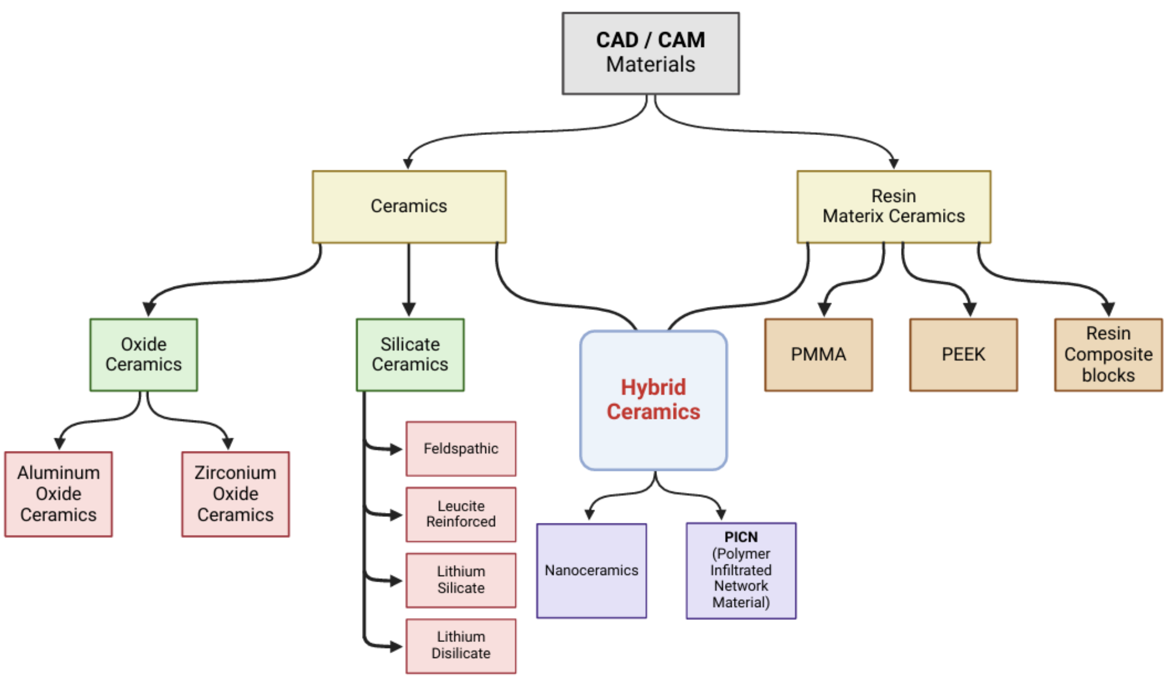


**Figure 2.** Categorization of CAD/CAM dental materials by chemical composition

**4-1. Silicate Ceramics or Glass Ceramics**

Silica-based ceramics are non-metallic materials characterized by a glassy matrix. The presence of this glassy component imparts certain properties, including brittleness, reduced fracture strength, and resistance to specific substances. Despite these characteristics, these ceramics exhibit translucency, owing to their inherent natural appearance, which allows for exceptional optical properties.

To augment micromechanical retention and adhesive bonding, silica-based ceramics require etching with hydrofluoric acid (HF). This process dissolves the amorphous matrix, revealing a crystalline phase that provides a suitable surface for resin cement interdigitation. Within the family of silicate ceramics, prominent types include traditional feldspathic ceramics, lithium silicate, lithium disilicate, and leucite-reinforced ceramics.

**4-1.1. Feldespathic and The Role of Aesthetic Ceramics in CAD/CAM Restorations**

Aesthetic ceramics, a cornerstone of modern dentistry, are well-known for their exceptional translucency, glass phase composition, and moderate strength. These properties allow for biocompatibility and aesthetic appeal, resulting in restorations that closely resemble the color, translucency, and surface texture of natural teeth. The glass phase within aesthetic ceramics enables etching with hydrofluoric acid, creating a micro-retentive surface for improved bonding to tooth structure.This bonding technique enhances the retention and longevity of the restoration, minimizing the risk of debonding or fracture. [13]

Feldspathic ceramics were the first silicate ceramics used in CAD-CAM systems, especially for chairside applications. Chemically, they are composed of clay, quartz, and feldspar. Potassium feldspar contributes to leucite crystal formation, enhancing the restoration's strength.[14]

Two prominent types of feldspathic glass ceramics used in CAD/CAM restorations are Vita blocs Mark II and TriLuxe blocks. These materials incorporate three distinct shade layers to recreate the natural gradient of color, translucency, and fluorescence observed in teeth from the cervical to incisal regions. TriLuxe blocks, in particular, feature a gradual increase in fluorescence and chroma towards the cervical area, further enhancing the lifelike appearance of the restoration.[15]

The etching time and concentration required for aesthetic ceramics depend on their crystalline content. Traditional feldspathic ceramics are typically etched with 9.8% HF acid for 2 minutes to expose a micro-retentive surface for resin cement bonding. Leucite-reinforced feldspathic ceramics, due to their higher crystalline phase content, can be etched with the same concentration for a shorter duration of 1 minute. Lithium disilicate ceramics, with their unique glass-ceramic composition, require a lower concentration of 4.6% HF and a significantly shorter etching time of 20 seconds to prevent excessive surface dissolution. [10]

Following etching, a silane coupling agent is applied to the ceramic surface to promote adhesion between the ceramic and the resin luting agent. Ultrasonic cleaning is essential to remove any precipitates from the etched surface prior to silane application.[16]

Despite their relatively low physical properties compared to other ceramic materials, feldspathic ceramics have demonstrated excellent clinical success in numerous studies. A survival rate of 95% has been reported for chairside CAD/CAM feldspathic ceramic restorations, such as those fabricated with VITABLOCS Mark II. Several factors, including restoration design, occlusal loading, and oral hygiene practices, can influence the long-term success of feldspathic ceramic restorations. Premolars, with their simpler occlusal anatomy and reduced occlusal forces, tend to have higher success rates than molars. Vital teeth, with their intact pulp and periodontal tissues, generally exhibit better outcomes than non-vital teeth. Feldspathic ceramics are well-suited for a variety of restorations, including inlays, onlays, anterior and posterior crowns, and veneers, including those on metal substructures with a coefficient of thermal expansion of approximately 10% or less to minimize stress at the interface. Examples of feldspathic ceramic blocks includeVita Zahnfabrik's Vitabloc Mark II, Real-Life, and TriLuxe, and Dentsply Sirona's Cerec blocs. [17]

**4-1.2. Leucite-Reinforced**

Leucite-reinforced ceramics are a type of particle-filled glass, characterized by their synthetic composition, typically containing up to 45% leucite depending on the manufacturer. Reinforcing the matrix with leucite offers several advantages, including improved flexural strength (up to 104 MPa) and a high thermal contraction coefficient. [18,19] Additionally, leucite-reinforced ceramics exhibit excellent translucency properties due to their refractive index, which is similar to that of feldspathic glasses. The leucite reinforcement also allows for selective etching, enhancing micromechanical bonding. [20] Given their high translucency and exceptional optical properties, leucite-reinforced materials are particularly suitable for aesthetic areas compared to non-load-bearing regions.

Leucite-reinforced glass restoration ceramics, such as Duraceram and Dentsply Degussa, have been evaluated for their long-term clinical performance. While these materials offer acceptable aesthetic qualities and wear resistance comparable to other glass ceramics, their lower mechanical properties make them less suitable for crowns in the posterior segment.[21,22]

Examples of commercially available leucite-reinforced CAD/CAM ceramics include IPS Empress CAD, IPS Classic, and Ivoclar Vivadent. These materials are indicated for veneers, inlays, onlays, and single crowns. For leucite-reinforced CAD/CAM ceramics, etching with 5% HF for 20 seconds is recommended to optimize surface preparation. [23,24]

In recent years, lithium silicate ceramics have emerged as a preferred alternative due to their superior physical properties and comparable optical characteristics. This transition reflects the ongoing advancements in dental materials and the drive for improved clinical outcomes.[21,22]

**4-1.3. Lithium Silicate**

Lithium silicate ceramics represent a modern advancement within the domain of silicate ceramics, often considered a progression from traditional silicate materials. Chemically, they consist of a crystalline phase of lithium disilicate and lithium orthophosphate. The homogeneous dispersion of this crystalline phase contributes to increased mechanical strength.[25]

Lithium silicate ceramics, such as VITA Suprinity PC produced by VITA Zahnfabrik and Celtra Duo from Dentsply Sirona, represent advanced materials in dental applications. These ceramics are primarily utilized for creating single crowns, particularly in the anterior regions, as well as for veneers, inlays, and onlays. Additionally, they are employed in leucite-reinforced CAD/CAM ceramics, which enhance aesthetic outcomes and mechanical properties in restorative dentistry.

The versatility of lithium silicate ceramics can be attributed to their superior mechanical strength and aesthetic qualities, making them suitable for various dental restorations. Their composition allows for excellent translucency and color matching with natural teeth, which is crucial in anterior restorations where aesthetics are paramount. Furthermore, these materials exhibit favorable bonding characteristics with dental adhesives, enhancing the longevity and durability of the restorations.

In clinical practice, the application of silicate ceramics is generally confined to specific restorative procedures due to their mechanical properties and stress distribution capabilities. For instance, while they are ideal for anterior crowns where esthetics is critical, their use in posterior restorations may be limited unless reinforced with additional materials to withstand occlusal forces.[23,24]

The incorporation of approximately 10% zirconium dioxide significantly improves the mechanical properties of lithium silicate ceramics while preserving their outstanding optical qualities. These materials display a flexural strength of approximately 400 MPa and offer enhanced color stability in comparison to high-translucency zirconia and nanoceramics. [26]

**4-1.4. Lithium Disilicate**

Lithium disilicate (Li2Si2O5) is a glass-ceramic material that consists of roughly 65% lithium disilicate crystals set within an amorphous glass matrix. The chemical makeup of Li2Si2O5 plays a crucial role in its impressive mechanical properties, which include elevated flexural strength, fracture toughness, high heat extrusion temperature, a specific thermal expansion coefficient, and outstanding translucency.[27]

Launched in 1998, lithium disilicate ceramic (IPS Empress 2) is renowned for its exceptional combination of high fracture toughness and superior translucency. This material's advantageous properties arise from its unique chemical composition, which includes lithium disilicate and lithium orthophosphate. The incorporation of these compounds not only enhances the mechanical strength of the ceramic but also contributes to its aesthetic qualities, making it an ideal choice for various dental restorations. [28]

Research has shown that IPS Empress 2 exhibits significantly improved mechanical properties compared to its predecessor, IPS Empress, allowing for broader applications in restorative dentistry. Its ability to be processed using CAD/CAM technology further enhances its versatility, facilitating precise and efficient restoration fabrication. As a result, lithium disilicate ceramics like IPS Empress 2 have become a standard choice in modern dental practice for achieving both functional and aesthetic outcomes in restorative procedures.

Clinical studies have demonstrated the long-term success of lithium silicate ceramics, with a failure-free rate of up to 93%. [29] Additionally, research has indicated their superior color stability compared to other materials, such as high-translucency zirconia, nanoceramic, or hybrid ceramic, when exposed to staining solutions like coffee or cola.[30]

The remarkable translucency of lithium disilicate ceramics makes them particularly suitable for cases that demand high aesthetic standards. However, the flexural strength of CAD-CAM blocks can differ significantly among manufacturers. These ceramic materials have shown considerable clinical success in non-load-bearing applications, while their robust mechanical properties enable broader usage in various restorations, including veneers, inlays/onlays, single crowns, and small bridges. [28]

A leading example of lithium disilicate CAD-CAM ceramics is IPS e.max CAD from Ivoclar Vivadent, which boasts an impressive flexural strength of approximately 360 MPa. Other notable products in this category include VITA Suprinity PC, Celtra Duo, and Obsidian. These materials are recognized for their superior mechanical characteristics, with flexural strengths reaching around 410 MPa. [28]

Lithium disilicate ceramics are favored in restorative dentistry not only for their aesthetic qualities but also for their durability and resistance to fracture. The combination of high strength and translucency allows these materials to closely mimic the appearance of natural teeth, making them ideal for anterior restorations where visual appeal is critical. Furthermore, advancements in CAD-CAM technology have facilitated the precise fabrication of these ceramics, enhancing their clinical applicability and success rates in various dental procedures. [28] This makes them among the strongest silicate ceramics available [31] For lithium disilicate CAD/CAM ceramics, the recommended etching procedure involves 5% hydrofluoric acid (HF) for 20 seconds.

**4-2. Oxide Ceramics**

Oxide ceramics, which consist of metallic or metalloid elements bonded with oxygen, are known for their outstanding mechanical properties, resistance to corrosion, and long-lasting durability. The elevated oxidation state of these materials contributes to their impressive stability under challenging industrial conditions and applications. Studies have demonstrated that oxide-based ceramics possess biocompatibility, rendering them appropriate for various dental uses.

Alumina (Al2O3) emerged as a prominent ceramic biomaterial in the late 1970s due to its robustness and biocompatibility. Zirconium dioxide later emerged as a promising alternative, offering relatively high fracture strength.[32]

Although oxide ceramics are known for their excellent mechanical properties, they may fall short in aesthetic qualities compared to silicate ceramics, which can restrict their use in certain applications. Nonetheless, oxide ceramics are highly suitable for various dental applications, including crowns, implant components, and Fixed Dental Prostheses (FDPs), applicable to both anterior and posterior regions. Additionally, they can be utilized in the fabrication of dental implants, abutments, and orthodontic brackets. The choice of a specific oxide ceramic for a dental application is influenced by factors such as the required mechanical characteristics, aesthetic considerations, and individual patient needs. [26]

Oxide ceramics used in dentistry include alumina ($Al_2O_3$), zirconia ($ZrO_2$), and titanium dioxide ($TiO_2$). These materials exhibit high flexural strength, fracture toughness, and wear resistance, making them ideal for demanding dental applications. Additionally, oxide ceramics have been shown to be biocompatible with human tissues, minimizing the risk of adverse reactions. Oxide ceramics are typically processed using sintering techniques, which involve heating the ceramic powder to a high temperature to densify it. This process results in a strong and durable material that can be shaped into various dental restorations.[32]

**4-2.1. Zirconium Oxide Ceramics**

Zirconia, a metal oxide known for its polymorphic and allotropic nature, is classified as an all-ceramic material in the field of dentistry. This material exhibits three distinct crystallographic phases: monoclinic, tetragonal, and cubic, each contributing to its varied mechanical and optical properties. The stability of these phases under different temperature conditions allows zirconia to maintain its structural integrity and performance in various applications. [33]

At elevated temperatures, zirconium oxide transitions between these crystallographic structures:

- **Cubic:** Above 2370 °C
- **Tetragonal:** Between 2300 °C and 1200 °C
- **Monoclinic:** Below 1200 °C

Upon cooling to room temperature, zirconia typically adopts a monoclinic phase, which has limited resistance to cyclic mechanical stress. To improve its mechanical performance, zirconia is processed into Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP). The incorporation of yttrium oxide in concentrations ranging from 3% to 5% significantly affects its mechanical properties.

Y-TZP is recognized for its outstanding mechanical characteristics, including exceptional fracture toughness and flexural strength. These properties make it particularly suitable for various dental applications, allowing for the fabrication of durable and resilient restorations. The tetragonal phase of Y-TZP not only enhances its strength but also contributes to its ability to undergo transformation toughening, which further improves its resistance to fracture under stress.[34]

Y-TZP demonstrates exceptional mechanical properties, including :

- **Fracture resistance:** 5-10 MPa m½
- **Flexural strength:** 800-1400 MPa

In addition to its mechanical strength, zirconia's optical characteristics enable it to closely resemble natural tooth enamel, making it particularly advantageous for aesthetic dental restorations. The tetragonal phase, which can be stabilized at room temperature through the addition of dopants like yttria, enhances its toughness and reduces the likelihood of fracture. This makes zirconia an excellent choice for dental implants, crowns, and other prosthetic devices, where both strength and appearance are crucial.Furthermore, ongoing research continues to explore the potential of zirconia in dental applications, highlighting its biocompatibility and resistance to bacterial colonization, which are essential factors in ensuring long-term success in oral health solutions.

Commercial examples of Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) include Nobelprocera Zirconia from Nobel Biocare and Lava Plus from 3M ESPE. These materials have shown high survival rates for fixed dental prostheses (FDPs) over extended periods, demonstrating their reliability and effectiveness in clinical applications. Studies indicate that Y-TZP's mechanical properties, such as fracture resistance and flexural strength, contribute significantly to its performance in various dental restorations, making it a preferred choice among dental professionals.[35]

Due to their superior mechanical features and optical properties, Y-TZP CAD-CAM materials are suitable for a wide range of applications, including single crowns, comprehensive rehabilitations involving multiple units (bridges in both anterior and posterior regions), and full-arch rehabilitations involving implants or natural teeth.[36]

Zirconia has evolved through four distinct generations, each characterized by advancements in chemical composition, crystal structure, and manufacturing processes. These generations represent a progression of improvements, with the emergence of a new multilayer generation addressing limitations and achieving enhanced properties as shown in Table (1).

**Table 1.** Generations of zirconia based on Yttria and Alumina Contents

| Generation | Yttria Content (mol%) | Alumina Content (mol%) | Crystal Structure | Strength (MPa) | Translucency | Commercial Examples | Ref |
|---|---|---|---|---|---|---|---|
| **First Generation (3Y-TZP 0.25$Al_2O_3$)** | 3 | 0.25 | Tetragonal | ~1200 | Opaque | Vita YZ (Vita Zahnfabrik), IPS e.max Zir (Ivoclar Vivadent) | (37) |
| **Second Generation (3Y-TZP 0.05$Al_2O_3$)** | 3 | 0.05 | Tetragonal | 800-1000 | Improved | InCeram Zirconia (Vita Zahnfabrik), Zenostar (Sirona) | (37) |
| **Third Generation (5Y-TZP 0.05$Al_2O_3$)** | 5 | 0.05 | Cubic | ~600 | High | Lava Plus (3M ESPE), Katana Zirconia (Kuraray Noritake Dental Science) | (37) |
| **Fourth Generation (4Y-TZP 0.05$Al_2O_3$)** | 4 | 0.05 | Tetragonal | ~750 | Improved | ZirCAD (Dentsply Sirona), Everest Zirconia (GC America) | (38) |

While zirconia offers exceptional mechanical strength, its inherent brittleness and limited translucency can be drawbacks. Gradient technology, a technique that involves creating a functionally graded material, presents a potential solution. Gradient zirconia, a type of functionally graded zirconia, addresses the limitations of traditional zirconia by incorporating a multilayer structure within a single disc. This structure typically consists of a core layer made from 3Y-TZP (3 mol% yttria-stabilized tetragonal zirconia polycrystal), known for its superior strength. The core layer is then followed by a gradual transition to a more translucent outer layer composed of materials such as 5Y-TZP (5 mol% yttria-stabilized tetragonal zirconia polycrystal) or zirconia with even lower yttria content. [39]

Gradient structure allows for a natural-looking restoration with improved light transmission, closely mimicking the aesthetics of natural teeth. The gradual change in composition also creates a built-in stress gradient, potentially reducing the risk of fracture. Manufacturing techniques like multi-layer deposition and slip casting are employed to achieve this graded structure. Some commercial examples of multilayer zirconia include IPS e.max ZirCAD Prime from Ivoclar Vivadent and Katana Zirconia Multilayer from Kuraray Noritake Dental Science. [40]

### 4-2.2. Aluminum Oxide Ceramics

Glass-infiltrated alumina ceramics feature a core made of densely packed sintered Al2O3 (alumina), comprising 80% to 82% by weight, which is subsequently infused with molten glass.

[41] This unique construction results in a favorable combination of strength and aesthetic appeal. With a flexural strength of around 500-600 MPa, these ceramics are particularly recommended for anterior three-unit fixed dental prostheses and crowns, making them suitable for use in posterior restorations as well [42]. A well-known commercial product in this category is InCeram Alumina from VITA Zahnfabrik. Studies have shown that alumina crowns achieve impressive long-term survival rates, with reports indicating up to 100% survival over seven years. This durability and dependability contribute to their popularity in dental restorations. However, despite their satisfactory long-term performance, they have largely been supplanted by zirconia ceramics, which provide enhanced physical properties. [43,44]

**4-3. Hybrid Ceramics**

The advancement of CAD/CAM dentistry has led to the introduction of innovative materials such as hybrid ceramics. These materials serve as a bridge between conventional ceramics and resin composites, providing a distinctive blend of aesthetic appeal and functional performance in dental restorations. The key benefits of hybrid ceramics include their ability to deliver exceptional aesthetics alongside enhanced mechanical properties compared to traditional resin composites. Hybrid ceramics typically incorporate nano-scale filler particles designed to replicate the light scattering properties of natural teeth, resulting in superior aesthetic outcomes. This allows for excellent color matching and a high degree of translucency, which contributes to the creation of restorations that closely resemble natural dentition. Clinical studies have demonstrated that hybrid ceramics, such as Vita Enamic and Lava Ultimate, exhibit notable aesthetic results, making them suitable for both anterior and posterior restorations.[45,46]

Furthermore, the integration of a polymeric network within Polymer-Infiltrated Ceramic Networks (PICNs) or the refined grain structure found in nanoceramics enhances their flexural strength beyond that of traditional resin composites. This increased strength enables their use in posterior restorations that endure moderate occlusal forces, thereby broadening their application beyond anterior regions. Research indicates that hybrid ceramics can achieve flexural strengths comparable to or exceeding those of conventional ceramics, making them viable options for various clinical scenarios. [47,48]

In addition to their mechanical advantages, hybrid ceramics may allow for less tooth reduction due to their effective bonding properties with tooth structures. This characteristic supports a more conservative approach to restorative procedures, aligning with contemporary trends towards minimally invasive dentistry. Studies have shown that restorations made from hybrid ceramics can maintain adequate bonding strength and longevity under clinical conditions. [4]

However, despite their advantages, hybrid ceramics present certain limitations that warrant careful consideration during material selection. While they offer improved wear resistance over traditional composites, their wear resistance may still fall short compared to that of fully ceramic materials. This limitation can lead to an earlier need for restoration replacement, particularly in high-wear areas. Additionally, some hybrid ceramics may exhibit a marginally higher fracture risk compared to established ceramic materials, necessitating thorough evaluation of occlusal loads and functional demands before choosing a hybrid ceramic for specific applications[45-47]

Hybrid ceramics are increasingly available from various manufacturers in pre-fabricated blocks or discs designed for milling in CAD/CAM systems. These materials come in a range of shades and translucencies, including pre-characterized options that facilitate the creation of natural-looking restorations that integrate seamlessly with surrounding teeth. [48]

**4-3.1. Polymer-Infiltrated Ceramic Network (PICN):**

The Polymer-infiltrated Ceramic Network (PICN) is a hybrid material that integrates the beneficial properties of both ceramics and polymers. The manufacturing process for PICN involves creating a pre-sintered porous ceramic framework, which is then infiltrated with a polymer through capillary action. This structure provides enhanced wear resistance compared to traditional composite resins, along with flexural strength and elasticity comparable to that of dentin. The robust ceramic network contributes to excellent wear resistance, while the interpenetration of ceramic and polymer components helps to inhibit crack propagation within the material. [49]

As a relatively recent development in dental materials, long-term studies assessing the performance of PICN restorations are still limited. Currently, the color options available for PICN materials are somewhat restricted, and there is insufficient data on their durability in cervical regions and their susceptibility to discoloration. [50]

PICN is indicated for various applications, including veneers, inlays/onlays, single crowns (both anterior and posterior), and implant prostheses. [49,50] However, due to its relatively lower aesthetic appeal, it is generally more suitable for posterior restorations. An example of a commercially available PICN composite is VITA ENAMIC, which features a silicate glass ceramic framework infused with acrylic resin. [51]

Previous studies have shown that PICN composites like VITA ENAMIC can effectively mimic the mechanical properties of human enamel. While this hybrid material presents promising advantages for dental restorations, further research is necessary to fully explore its long-term performance and clinical applications. [52]

**4-3.2. Nanoceramics**

Nanotechnology presents a broad spectrum of applications in both medicine and dentistry by integrating nanomaterials to enhance the properties of various substances. The incorporation of appropriate nanoparticles can significantly improve the optical, chemical, electrical, and mechanical characteristics of these materials. [53]

In resin-based composites, nanosized filler particles (typically less than 100 nm) are utilized to occupy the spaces between larger filler particles, resulting in a reduction of resin content by approximately 15%. This modification can lead to enhanced mechanical properties and decreased shrinkage during polymerization. [54]

Nanoparticles possess a considerably larger surface area compared to their larger counterparts, which can amplify their chemical reactivity by as much as 1000 times. This increased surface area can significantly affect the material's properties and its interactions with biological tissues. [55]

Among the materials used in CAD/CAM technology, nanoceramics—a specific type of resin matrix ceramic—have gained significant attention. These materials combine the aesthetic and mechanical benefits of both ceramics and composites. Notable examples include Cerasmart from GC Dental Products and Lava Ultimate, which utilize nanotechnology to integrate nanoceramic particles into a resin matrix. [54]

Nanoceramics are particularly advantageous for aesthetic restorations due to their high translucency, which is attributed to the incorporation of nanosized zirconia and silica particles. The addition of these nanoparticles enhances tensile and compressive strengths by approximately 20% and 30%, respectively, thereby minimizing secondary caries by reducing microleakage. [56]

While nanotechnology offers numerous opportunities for modifying material properties, it is crucial for researchers and clinicians to assess its long-term effects and potential toxicity. Although the use of nanoparticles is generally regarded as safe, both the positive and negative implications of nanotechnology in dentistry warrant comprehensive evaluation.

Nanoceramics, which consist of a polymeric matrix combined with ceramic nanoparticles, provide a unique set of properties. Their microstructure resembles that of resin composites; however, they feature a significantly higher filler-to-polymer ratio (approximately 80%) and smaller particle sizes (less than 100 nm). This composition enhances their mechanical properties, making them comparable to natural teeth in terms of flexural strength (around 200 MPa), compressive strength (up to 400 MPa), and abrasion resistance (2-10 microns annually). Their elastic modulus is approximately 15-20 GPa. [57]

These characteristics make nanoceramics suitable for single-tooth restorations or short bridges, particularly in posterior regions. However, it is important to note that the polymer matrix within nanoceramics may be more susceptible to wear than the ceramic component, potentially increasing abrasion on opposing teeth.

Nanoceramics have applications across various dental procedures, including veneers, inlays/onlays, and single crowns or bridges for both anterior and posterior segments. A prominent example is Lava Ultimate from 3M ESPE, specifically designed for compatibility with CAD/CAM systems. The robust chemical bonds within the nanoceramic structure contribute to its high fracture strength, while its elastic modulus (approximately 30 GPa) closely resembles that of dentin. This makes it particularly suitable for posterior restorations. [58]

Overall, while nanoceramics like Lava Ultimate demonstrate significant potential in restorative dentistry due to their mechanical properties and compatibility with CAD/CAM technology, ongoing research is essential to fully understand their long-term performance and clinical implications.

### 4-4. Resin Matrix Ceramics

#### 4-4.1. PMMA

Poly(methyl methacrylate) (PMMA) is a synthetic polymer produced through the free radical addition polymerization of methyl methacrylate. It is extensively utilized in dentistry due to its advantageous properties, which include low density, aesthetic appeal, cost-effectiveness, ease of manipulation, and versatility. [59] The increasing demand for PMMA restorations has spurred the development of PMMA blocks with improved optical and physical characteristics. Notable examples include Telio CAD, Shlan, and VITA CAD-Temp MultiColor Blocks. Additionally, heat-cured PMMA restorations can be polished to enhance their aesthetic qualities. [60]

PMMA finds application in various prosthodontic procedures, such as the fabrication of synthetic teeth, denture bases, complete dentures, obturators, orthodontic retainers, provisional crowns, and repairs for dental prostheses [61]. While CAD/CAM PMMA shares the same chemical composition as traditionally heat-cured PMMA, it exhibits superior hardness, flexural strength, flexural modulus, and impact resistance. These enhanced mechanical properties make CAD/CAM PMMA suitable for long-term provisional restorations lasting up to one year. Furthermore, CAD/CAM PMMA is more hydrophobic than conventional PMMA, which helps to reduce plaque accumulation and lower the adhesion of Candida albicans. [62]

The advancements in PMMA technology also include the introduction of nanocomposites that incorporate nanoparticles to further enhance its mechanical and physical properties. For instance, studies have shown that adding nanoparticles can improve the strength and durability of PMMA-based materials. [62]

Despite its many advantages, researchers must consider potential long-term effects and toxicity associated with PMMA use in dentistry. Although the addition of nanoparticles is generally deemed safe, it is crucial to evaluate both the benefits and potential drawbacks of integrating nanotechnology into dental materials. [61]

**4-4.2. PEEK**

Polyetheretherketone (PEEK) is a semi-crystalline thermoplastic polymer that serves as a versatile alternative to metal frameworks in dentistry. It is applicable for various dental restorations, including removable and fixed dental prostheses, implant-supported prostheses, overdentures, endo-crowns, and resin-bonded fixed dental prostheses. PEEK exhibits excellent wear resistance, minimal plaque retention, and strong adhesion properties with veneering composites and luting cements. Its low modulus of elasticity (approximately 4 GPa) provides a cushioning effect that reduces stress on abutment teeth. [63]

Comparative studies indicate that CAD/CAM-fabricated PEEK dentures can achieve a fit that is comparable to or even superior to those produced using traditional techniques. Furthermore, PEEK has demonstrated favorable performance in wear tests against other CAD/CAM materials, such as composite resins and PMMA. In vitro studies simulating chewing stresses have revealed satisfactory fracture strength for PEEK molar crowns, suggesting their clinical viability. [63]

Despite its promising characteristics, PEEK is not yet widely adopted in clinical practice due to a lack of extensive long-term studies. Additionally, PEEK displays notable abrasive properties that are similar to those of metallic alloys regarding abrasion resistance; however, there have been no clinical comparisons of PEEK crowns with other materials concerning their impact on tooth wear. [63]

Given its advantageous abrasion resistance, mechanical properties, and robust bonding capabilities with composites and dental tissues, PEEK fixed partial dentures are expected to have a satisfactory survival rate. Leading manufacturers of CAD/CAM PEEK include Juvora Dental PEEK CAD/CAM-Rohling from Straumann and BioHPP™ from Bredent. These materials are suitable for milling frameworks for dentures or fixed dental prostheses (FDPs), with BioHPP™ specifically approved for use in three to four-unit FDPs, telescopic restorations, implant abutments, and secondary structures in bar-supported prostheses. [63]

Research has shown that ceramic-reinforced PEEK exhibits significantly higher flexural strength (around 180 MPa) compared to both milled PMMA (approximately 90 MPa) and heat-compressed PMMA (about 68MPa). Additionally, ceramic-reinforced PEEK displays a higher average roughness (Ra) value on unpolished surfaces compared to the other materials; however, polishing all materials leads to a significant reduction in average roughness values. No significant differences were found in the adhesion of Candida albicans across the different material groups. [63]

#### 4-4.3. Resin Composite Blocks (RCBs)

Resin composite blocks (RCBs) specifically designed for CAD/CAM applications are produced by integrating filler particles into a blend of monomers, which are subsequently cured under high temperature and pressure conditions [64]. This polymerization method results in a material that is more uniform than traditional resin composites, leading to fewer defects and voids [65]. Additionally, this process achieves a higher degree of conversion, which minimizes water absorption and enhances mechanical properties such as fracture resistance, bending strength, and wear resistance. [66]

Most CAD/CAM RCBs utilize urethane dimethacrylate (UDMA) as the polymer matrix, which offers lower solubility and reduced water absorption, thereby improving the color stability of the restorations. Recent advancements in dimethacrylate formulations have introduced addition-fragmentation monomers that enhance translucency while also increasing both the degree of conversion (DC) and Vickers hardness (VH) during the polishing process. This contributes to optimal clinical performance. [67]

For instance, Paradigm MZ100 (3M Oral Care, Seefeld, Germany) was the first CAD/CAM composite to achieve a flexural strength of 160 MPa, which is comparable to that of feldspathic ceramics. (68) Other notable RCBs include Tetric CAD from Ivoclar Vivadent, exhibiting a flexural strength of 274 MPa and an elastic modulus of 10 GPa (69); LuxaCam Composite from DMG with a flexural strength of 165 MPa and an elastic modulus of 10GPa; (64) and Grandio Blocks from VOCO GmbH, which demonstrate a flexural strength of 330 MPa and an elastic modulus of 29 GPa. [70]

Clinical studies have indicated that CAD/CAM RCBs provide superior color stability compared to both direct and indirect resin composites, although they are less stable than ceramic materials. Factors influencing color stability include the composition of the material as well as the techniques used for finishing and polishing. According to manufacturer guidelines, these composites are suitable for a variety of restorative procedures including inlays, onlays, veneers, partial crowns, crowns, and multi-unit bridges (up to three units), thanks to their two translucency levels—high translucency (HT) and low translucency (LT)—which enhance their optical properties to closely resemble natural teeth. [71,72]

A randomized controlled trial conducted by Elmoselhy et al. evaluated the two-year clinical performance of indirect restorations made from CAD/CAM nano-hybrid composites versus lithium disilicate in patients with severely damaged vital teeth. The study found no significant differences in clinical outcomes between the two materials after two years, suggesting that CAD/CAM nano-hybrid composites can serve as reliable alternatives to traditional ceramics for various applications. [73]

Additionally, a systematic review by Rexhepi et al. highlighted that CAD/CAM materials exhibit improved mechanical properties and clinical performance across different types of restorations. The research emphasized that CAD/CAM restorations provide excellent marginal adaptation and lower plaque accumulation compared to conventional methods, contributing to reduced incidences of periodontal inflammation. [5]

While CAD/CAM composites demonstrate higher color stability than direct or indirect resin composites, they exhibit lower stability compared to ceramic materials. The color stability is influenced by both material composition and finishing/polishing techniques. Overall, the advancements in RCB technology continue to enhance their applicability in dental restorations while addressing concerns related to durability and aesthetic performance. [74]

**Table 2.** Overview of CAD/CAM Materials and their mechanical properties with their clinical applications

| Material Category | Material Type | Flexural Strength (MPa) | Manufacturers | Indications/Applications |
|---|---|---|---|---|
| **Silicate Ceramics** | Feldspathic | 97-133 | CEREC Blocs (VITABLOC, Germany) | **Best for *veneers* and *anterior crowns*** due to its excellent aesthetic properties. Commonly used in cases where **high translucency** and lifelike appearance are **critical.** |
| | Leucite-reinforced | 106-160 | IPS Empress CAD (Ivoclar Vivadent, Liechtenstein) | Suitable for ***inlays, onlays***, and ***anterior crowns.*** Provides **higher strength than feldspathic**, making it ideal for moderate-load-bearing situations. |
| | Lithium silicate | 400 | Suprinity PC (Vita Zahnfabrik, Germany), Celtra Duo (Dentsply Sirona, Verona, Italy) | Often used for ***anterior crowns*** and ***small posterior crowns***, as well as ***veneers.*** Excellent for **single-unit restorations** with a need for superior aesthetics. |
| | Lithium disilicate | 130 | IPS E.max CAD (Ivoclar Vivadent, Liechtenstein) | **Ideal for *veneers, crowns*** (anterior and posterior), ***inlays/onlays*, and *3-unit bridges*** *(up to the second premolar)*. Known for its balance of strength and aesthetics, allowing its use in moderate-load posterior regions. |
| **Oxide Ceramics** | Zirconium | 500-1200 | Nobelprocera Zirconia (Nobel Biocare, Switzerland), Lava Plus (3M ESPE, Milano, Italy) | **Highly recommended for** *posterior crowns*, *multi-unit bridges*, and *implant abutments*. Its high flexural strength makes it perfect for load-bearing areas, especially for *full-arch bridges* and *molar crowns*. |
| | Aluminum | 500 | InCeram Alumina (Vita Zahnfabrik, Germany) | **Mostly used for** *anterior crowns* and *short-span bridges*. Preferred when **high aesthetic demands are present** but in non-stress-bearing zones, as it is **less strong than zirconia**. |
| **Hybrid Ceramics** | Polymer-infiltrated ceramic network (PICN) | 107.8-153.7 | VITA ENAMIC (Vita Zahnfabrik, Germany) | **Useful for *veneers, inlays/onlays***, and ***single-unit crowns***. Suitable for restorations requiring both **flexibility** and **aesthetic appeal**, often in *anterior teeth*. |
| | Nanoceramics | 200 | Lava Ultimate (3M ESPE, Milano, Italy) | **Indicated for *veneers, inlays/onlays, anterior and posterior crowns***, and ***anterior bridges.*** High **polish-ability** makes them great for **aesthetic cases**, while they retain enough strength for moderate function. |
| **Resin Matrix Ceramics** | Polymethyl Methacrylate (PMMA) | 80-135 | Telio CAD, VITA CAD-Temp Multicolor (Vita Zahnfabrik, Germany) | **Primarily used for *long-term provisional restorations*** (up to 1 year). **Suitable for *temporary crowns*, bridges**, and **removable prostheses**, offering flexibility and ease of adjustment. |
| | Polyether Ether Ketone (PEEK) | 165-185 | Juvora Dental PEEK CAD (CAD/Rohling, Straumann) | **Ideal for** ***frameworks for dentures*** and *FDPs* (Fixed Dental Prostheses). Used in ***implant abutments*** and ***secondary structures*** due to its **high biocompatibility and flexibility**. |
| | Resin Block Composites | 80 | Grandio Blocks (VOCO GmbH, Germany), LuxaCam Composite (DMG, Cheshire, UK) | **Indicated for *veneers, inlays/onlays***, and ***partial crowns.*** **Great for *multi-unit bridges*** (up to three units) **in non-load-bearing zones** due to moderate strength and good aesthetic properties. |

## 5- Chair- Side and Laboratory CAD/CAM

### 5-1 Chair-side CAD/CAM systems

Chair-side CAD/CAM systems enable dentists to design and fabricate restorations during a single patient visit. This method significantly enhances patient convenience and reduces the need for multiple appointments. The first generation of chairside CAD/CAM systems appeared in the 1980s, with limited capabilities for designing and producing ceramic inlays. However, contemporary leading chairside systems, such as PlanScan, Carestream, and CEREC, have evolved to offer a "full-digital workflow," enabling the fabrication of a wide range of prosthetic devices, including inlays/onlays, veneers, endocrowns, bridge crowns, and implant abutments.[75,76]

This streamlined workflow often allows for same-day restoration delivery, providing significant benefits to both dentists and patients. Chairside CAD/CAM eliminates the need for multiple appointments and laboratory procedures, resulting in reduced chair time and improved patient comfort. [77]

A clinical trial by elmoshely et al. evaluated the two-year performance of CAD/CAM nano-hybrid composite versus lithium disilicate restorations in posterior teeth. The study found that both materials exhibited similar clinical performance, with success rates of 91.4% and 87.2%, respectively, demonstrating that chair-side CAD/CAM composites can be as reliable as traditional ceramics for indirect restorations. [73]

Another study focused on the outcomes of chair-side CAD/CAM all-ceramic restorations placed on endodontically treated posterior teeth over a three-year follow-up period. The results indicated a success rate of 92%, with oral parafunction identified as a significant risk factor affecting restoration longevity. This highlights the effectiveness of chair-side CAD/CAM systems in providing durable restorations while emphasizing the importance of patient-specific factors in treatment planning.[78]

### 5-2 Laboratory CAD/CAM Systems

Laboratory CAD/CAM systems involve a more extensive fabrication process, often utilizing advanced materials that may not be available for chair-side use. These systems are typically employed for complex cases requiring high precision and durability, such as full-arch restorations or multi-unit bridges. A systematic review by Fasbinder (2018) noted that laboratory-fabricated restorations have shown promising long-term outcomes, with survival probabilities reported at 95% after five years and around 84.9% after 16.7 years. [12] This indicates that laboratory CAD/CAM systems can provide reliable solutions for extensive restorative needs. The material composition plays a crucial role in the success of laboratory CAD/CAM restorations. For instance, studies have demonstrated that zirconia-based restorations offer superior strength and fracture resistance compared to resin composites, making them suitable for high-stress applications such as posterior crowns. Furthermore, laboratory systems allow for the use of advanced materials like lithium disilicate ceramics, which combine aesthetic appeal with excellent mechanical properties.[79]

Comparative studies between chair-side and laboratory CAD/CAM systems have shown varying outcomes based on specific clinical scenarios. For example, research has indicated that while chair-side systems offer convenience and immediate results, laboratory systems may provide enhanced aesthetic qualities and strength due to the ability to utilize superior materials and techniques. [73,78]

In a clinical evaluation conducted by Vervack et al., it was found that both chair-side and laboratory-fabricated restorations performed well in terms of marginal integrity and patient satisfaction; however, laboratory-fabricated restorations showed slightly better results in terms of longevity and mechanical properties. [79] This suggests that while chair-side options are increasingly viable, laboratory options may still hold an edge in specific high-demand situations. [80]

## 6- Additive and Subtractive Manufacturing Techniques

Subtractive and additive manufacturing are two significant techniques utilized in modern dental practices, each offering unique advantages and applications in the fabrication of dental restorations.

### 6-1 Subtractive Manufacturing

Subtractive manufacturing involves the removal of material from a solid block to create a desired shape or form. In dentistry, this method is commonly used for creating crowns, bridges, and other restorations from materials such as ceramics and metals. The process typically begins with a digital impression or scan of the patient's dental anatomy, which is then converted into a computer-aided design (CAD) model. The CAD model guides a milling machine that precisely carves the restoration from a solid block of material. A significant advantage of subtractive manufacturing is the high precision it offers. For instance, a study by Javaid et al. demonstrated that subtractive CAD/CAM restorations exhibited excellent marginal integrity and fit when compared to traditional methods, with a clinical success rate of 91.4% over two years [81] This precision minimizes the risk of complications such as secondary caries or debonding, which can arise from poorly fitting restorations. However, subtractive manufacturing also has limitations. The process can generate significant material waste, particularly when creating complex shapes from solid blocks. Additionally, the range of materials available for milling is often limited compared to those used in additive manufacturing. [81]

**6-2 Additive Manufacturing**

Additive manufacturing, commonly referred to as 3D printing, involves building objects layer by layer based on digital models. This technique has gained traction in dentistry due to its ability to create complex geometries that may be challenging or impossible to achieve with subtractive methods. Materials used in additive manufacturing can include polymers, ceramics, and even metals. [82,83]

Research indicates that additive manufacturing can yield restorations with comparable mechanical properties to those produced by traditional methods. For example, a study published by BMC Oral Health found that CAD/CAM nano-hybrid composite restorations fabricated using additive techniques achieved similar clinical performance to lithium disilicate ceramics over a two-year follow-up period. [84]

One of the key benefits of additive manufacturing is its ability to customize restorations for individual patients quickly and efficiently. This capability allows for the production of patient-specific implants and prosthetics tailored to unique anatomical features. Furthermore, because additive processes typically generate less waste than subtractive techniques, they can be more environmentally friendly. [85]

However, challenges remain regarding the regulatory landscape surrounding additive manufacturing in dentistry. The FDA has identified gaps in testing and validation processes for these technologies, which can hinder widespread adoption ensuring the safety and efficacy of 3D-printed dental devices is paramount as clinicians seek to integrate these innovations into their practices.(86)

Several clinical studies have evaluated the effectiveness of both subtractive and additive manufacturing techniques in dentistry: Javaid et al. conducted a randomized controlled trial comparing CAD/CAM nano-hybrid composite restorations with lithium disilicate ceramics. The results showed no significant differences between the two materials regarding marginal integrity and clinical performance after two years. [81] Celik et al. reviewed various studies on chair-side CAD/CAM systems and noted that while these systems provide convenience and immediate results, laboratory-fabricated restorations often demonstrate superior aesthetic qualities due to advanced materials used. [87] Salmi et al. reported on the clinical performance of CAD/CAM resin composite restorations over an extended period, noting complications such as debonding but overall high success rates. [85]

## 7- Challenges and future prospective

The evolution of CAD-CAM materials in fixed prosthodontics has significantly transformed clinical practices, enhancing mechanical properties, aesthetic outcomes, and the range of clinical indications. However, several challenges persist that must be addressed to fully employ the potential of these materials. One of the primary challenges is the inherent limitations of current materials. While advancements have introduced hybrid ceramics and improved resin composites, issues related to their mechanical properties and wear resistance remain. For example, studies have indicated that although materials like Lava Ultimate demonstrate favorable mechanical performance, they may not consistently match the durability of traditional ceramics under specific conditions. [5]

Another significant challenge is the variability in clinical performance associated with CAD-CAM materials. Factors such as operator skill, material selection, and the specific clinical scenario can lead to differing outcomes. while CAD-CAM materials generally show improved mechanical properties, their success rates can fluctuate based on the type of restoration and its location within the dental arch. This variability underscores the need for standardized protocols and comprehensive training for clinicians to optimize patient outcomes.[19]

The are several promising future perspectives for CAD-CAM materials in fixed prosthodontics. One key area for future research is the development of new materials that are cost-effective, durable, and biocompatible for CAD-CAM applications. This includes exploring hybrid materials that combine beneficial properties of ceramics and resins as well as investigating nanomaterials that could enhance both mechanical strength and aesthetic qualities. Ongoing studies are examining new resin composites with improved wear resistance and color stability to address current limitations. The enhancement of digital workflows presents another exciting opportunity for future advancements in CAD-CAM technology. Integrating artificial intelligence (AI) and machine learning into CAD-CAM processes could streamline design workflows and improve accuracy in restoration fabrication. Enhanced digital imaging techniques may facilitate better patient-specific customization, leading to improved fit and function of restorations.

Additionally, research into automated post-processing techniques could reduce labor costs and time associated with finishing restorations. As knowledge about CAD-CAM materials continues to expand, there is potential for their applications to extend beyond traditional fixed prosthodontics into areas such as orthodontics, endodontics, and oral surgery. Future studies should explore innovative uses of CAD-CAM technologies in these fields to address specific clinical needs; for instance, 3D printing technologies could be employed to create customized surgical guides or orthodontic appliances customized to individual patient anatomy.[6]

Finally, there is a significant need for long-term clinical studies to evaluate the performance of emerging CAD-CAM materials over extended periods. Such studies will provide valuable data on survival rates, wear resistance, and patient satisfaction associated with different types of restorations. Comprehensive clinical trials will help establish evidence-based guidelines for material selection in various restorative scenarios.

## 8- Conclusion

In conclusion, while the evolution of CAD-CAM materials in fixed prosthodontics presents both challenges and opportunities for enhancing dental care, addressing current limitations while exploring innovative solutions will be crucial for advancing this field. By focusing on material development, optimizing digital workflows, expanding clinical applications, and conducting long-term studies, the future of CAD-CAM technology holds promise for improving patient outcomes in restorative dentistry.

- **Conflict of Interest**

A declaration of conflict of interest.

## 9- References

[1]Rexhepi I, Santilli M, D'Addazio G, Tafuri G, Manciocchi E, Caputi S, et al. Clinical applications and mechanical properties of CAD-CAM materials in restorative and prosthetic dentistry: A systematic review. J Funct Biomater. 2023;14(8):431.

[2]Calle Barros MC, Abril Ochoa DG. Fracture resistance analysis of CAD/CAM interim fixed prosthodontic materials: pmma, graphene, acetal resin and polysulfone. 2023;

[3]Sadid-Zadeh R. Clinical Applications of Digital Technology in Fixed Prosthodontics. Clinical Applications of Digital Dental Technology. 2023;122–53.

[4]Paulson B. Evolution Of CAD/CAM Materials In Prosthodontics: A Review. IOSR Journal of Dental and Medical Sciences . 2023;22(9):35–42.

[5]Rexhepi I, Santilli M, D'Addazio G, Tafuri G, Manciocchi E, Caputi S, et al. Clinical applications and mechanical properties of CAD-CAM materials in restorative and prosthetic dentistry: A systematic review. J Funct Biomater. 2023;14(8):431.

[6]Zarina R, Jaini J, Raj RS. Evolution of the Software and Hardware in CAD/CAM Systems used in Dentistry. Int J Prev Clin Dent Res. 2017;4(4):284–91.

[7]Vogler JA, Billen L, Walther KA, Wöstmann B. Conventional cast vs. CAD/CAM post and core in a fully digital chairside workflow–An in vivo comparative study of accuracy of fit and feasibility of impression taking. Journal of Dentistry. 2023;136:104638.

[8]Alhamoudi FH. Comparing the accuracy of crown fitting between milling and 3D printing techniques using CAD/CAM technologies. Technology and Health Care. 2024 May 18(Preprint):1-4.

[9]Grant GT. Direct digital manufacturing. Clinical Applications of Digital Dental Technology. 2023 Feb 1:46-59.

[10] Moörmann WH. The evolution of the CEREC system. The Journal of the American Dental Association. 2006;137:7S-13S.

[11] Christensen GJ. In-office CAD/CAM milling of restorations: the future? The Journal of the american dental association. 2008;139(1):83–5.

[12] Fasbinder DJ. Materials for chairside CAD/CAM restorations. Compendium of Continuing Education in Dentistry (15488578). 2010;31(9).

[13] Fuertes V, Reinosa JJ, Fernández JF, Enríquez E. Engineered feldspar-based ceramics: A review of their potential in ceramic industry. Journal of the European Ceramic Society. 2022 Feb 1;42(2):307-26.

[14] Arango Santander S, Pelaez Vargas A, Saldarriaga Escobar J, Monteiro FJ, Restrepo Tamayo LF. Ceramics for dental restorations-An Introduction. Dyna. 2010 Sep;77(163):26-36.

[15] Poticny DJ. Adhesive Cementation Redefined.

[16] Conejo J, Ozer F, Mante F, Atria PJ, Blatz MB. Effect of surface treatment and cleaning on the bond strength to polymer-infiltrated ceramic network CAD-CAM material. J Prosthet Dent. 2021;126(5):698–702.

[17] Stamenković DD, Tango RN, Todorović A, Karasan D, Sailer I, Paravina RD. Staining and aging-dependent changes in color of CAD-CAM materials. J Prosthet Dent. 2021;126(5):672–8.

[18] Ahmed H. Craig’s restorative dental materials. Nature Publishing Group UK London; 2019.

[19] Lambert H, Durand JC, Jacquot B, Fages M. Dental biomaterials for chairside CAD/CAM: State of the art. J Adv Prosthodont. 2017;9(6):486–95.

[20] Gracis S, Thompson VP, Ferencz JL, Silva NRFA, Bonfante EA. A new classification system for all-ceramic and ceramic-like restorative materials. International Journal of prosthodontics. 2015;28(3).

[21] Brochu JF, El-Mowafy O. Longevity and clinical performance of IPS-Empress ceramic restorations-a literature review. Journal-Canadian Dental Association. 2002;68(4):233–8.

[22] Mayinger F, Lümkemann N, Musik M, Eichberger M, Stawarczyk B. Comparison of mechanical properties of different reinforced glass-ceramics. J Prosthet Dent. 2022;127(1):146–53.

[23] Veríssimo AH, Moura DMD, Tribst JPM, Araújo AMM de, Leite FPP. Effect of hydrofluoric acid concentration and etching time on resin-bond strength to different glass ceramics. Braz Oral Res. 2019;33:e041.

[24] Avram LT, Galațanu SV, Opriș C, Pop C, Jivănescu A. Effect of different etching times with hydrofluoric acid on the bond strength of CAD/CAM ceramic material. Materials. 2022;15(20):7071.

[25] Hinz S, Bensel T, Bömicke W, Henningsen A, Rudolph J, Boeckler AF. Impact of the veneering technique and framework material on the failure loads of all-ceramic computer-aided design/computer-aided manufacturing fixed partial dentures. Materials. 2022;15(3):756.

[26] D'Addazio G, Santilli M, Rollo ML, Cardelli P, Rexhepi I, Murmura G, et al. Fracture resistance of Zirconia-reinforced lithium silicate ceramic crowns cemented with conventional or adhesive systems: An in vitro study. Materials. 2020;13(9):2012.

[27] Mavriqi L, Valente F, Murmura G, Sinjari B, Macrì M, Trubiani O, et al. Lithium disilicate and zirconia reinforced lithium silicate glass-ceramics for CAD/CAM dental restorations: biocompatibility, mechanical and microstructural properties after crystallization. J Dent. 2022;119:104054.

[28] Blatz MB, Conejo J. The current state of chairside digital dentistry and materials. Dental Clinics. 2019;63(2):175–97.

[29] Reich S, Endres L, Weber C, Wiedhahn K, Neumann P, Schneider O, et al. Three-unit CAD/CAM-generated lithium disilicate FDPs after a mean observation time of 46 months. Clin Oral Investig. 2014;18:2171–8.

[30] Eldwakhly E, Ahmed DRM, Soliman M, Abbas MM, Badrawy W. Color and translucency stability of novel restorative CAD/CAM materials. Dent Med Probl. 2019;56(4):349–56.

[31] Gardell E, Larsson C, von Steyern PV. Translucent zirconium dioxide and lithium disilicate: a 3-year follow-up of a prospective, practice-based randomized controlled trial on posterior monolithic crowns. Int J Prosthodont. 2021;34(2):163–72.

[32] Mirdamadi ES, Nazarpak MH, Solati-Hashjin M. Metal oxide-based ceramics. In: Structural Biomaterials. Elsevier; 2021. p. 301–31.

[33] Monaco C, Caldari M, Scotti R. Clinical evaluation of tooth-supported zirconia-based fixed dental prostheses: a retrospective cohort study from the AIOP clinical research group. International Journal of Prosthodontics. 2015;28(3).

[34] Fonzar RF, Carrabba M, Sedda M, Ferrari M, Goracci C, Vichi A. Flexural resistance of heat-pressed and CAD-CAM lithium disilicate with different translucencies. Dental Materials. 2017;33(1):63–70.

[35] Guazzato M, Albakry M, Ringer SP, Swain M V. Strength, fracture toughness and microstructure of a selection of all-ceramic materials. Part II. Zirconia-based dental ceramics. Dental materials. 2004;20(5):449–56.

[36] Pihlaja J, Näpänkangas R, Raustia A. Outcome of zirconia partial fixed dental prostheses made by predoctoral dental students: A clinical retrospective study after 3 to 7 years of clinical service. J Prosthet Dent. 2016;116(1):40–6.

[37] Malallah AD, Hasan NH. Classification and Generations of Dental Zirconia. InZirconia-New Advances, Structure, Fabrication and Applications 2023 Nov 8. IntechOpen.

[38] Skorulska A, Piszko P, Rybak Z, Szymonowicz M, Dobrzyński M. Review on polymer, ceramic and composite materials for cad/cam indirect restorations in dentistry—Application, mechanical characteristics and comparison. Materials. 2021;14(7):1592.

[39] Edelhoff D, Schubert O, Stimmelmayr M, Schweiger J. CAD/CAM full-mouth rehabilitation of an elderly patient: One-piece digital complete denture meets multilayered zirconia with gradient technology. Journal of Esthetic and Restorative Dentistry. 2024 Jan;36(1):174-85.

[40] Alves MF, Abreu LG, Klippel GG, Santos C, Strecker K. Mechanical properties and translucency of a multi-layered zirconia with color gradient for dental applications. Ceramics International. 2021 Jan 1;47(1):301-9.

[41] Joda T, Gintaute A, Brägger U, Ferrari M, Weber K, Zitzmann NU. Time-efficiency and cost-analysis comparing three digital workflows for treatment with monolithic zirconia implant fixed dental prostheses: A double-blinded RCT. J Dent. 2021;113:103779.

[42] Conejo J, Nueesch R, Vonderheide M, Blatz MB. Clinical performance of all-ceramic dental restorations. Curr Oral Health Rep. 2017;4:112–23.

[43] Schlenz MA, Skroch M, Schmidt A, Rehmann P, Wöstmann B. Monitoring fatigue damage in different CAD/CAM materials: A new approach with optical coherence tomography. J Prosthodont Res. 2021;65(1):31–8.

[44] Ozer F, Mante FK, Chiche G, Saleh N, Takeichi T, Blatz MB. A retrospective survey on long-term survival of posterior zirconia and porcelain-fused-to-metal crowns in private practice. Quintessence Int. 2014;45(1):31–8.

[45] Hereher MEE, Aly El-Gabrouny M, Abdel-Aziz Shebl A. Fracture Strength And Marginal Gap of Two Different Types Of Hybrid Ceramic Crowns. Dental Science Updates. 2023;4(1):185–94.

[46] Chen Y, Sun C, Cao J, Wu Y, Cui B, Ma J, et al. Mechanical properties and in vitro biocompatibility of hybrid polymer-HA/BAG ceramic dental materials. Polymers (Basel). 2022;14(18):3774.

[47] Bajraktarova-Valjakova E, Korunoska-Stevkovska V, Kapusevska B, Gigovski N, Bajraktarova-Misevska C, Grozdanov A. Contemporary dental ceramic materials, a review: chemical composition, physical and mechanical properties, indications for use. Open Access Maced J Med Sci. 2018;6(9):1742.

[48] Palacios T, Tarancón S, Pastor JY. On the mechanical properties of hybrid dental materials for CAD/CAM restorations. Polymers (Basel). 2022;14(16):3252.

[49] Enamic V. Multichromatic and highly translucent hybrid ceramic Vita Enamic. Int J Comput Dent. 2018;21:239–50.

[50] Yano HT, Ikeda H, Nagamatsu Y, Masaki C, Hosokawa R, Shimizu H. Correlation between microstructure of CAD/CAM composites and the silanization effect on adhesive bonding. J Mech Behav Biomed Mater. 2020;101:103441.

[51] Kang L, Zhou Y, Lan J, Yu Y, Cai Q, Yang X. Effect of resin composition on performance of polymer-infiltrated feldspar-network composites for dental restoration. Dent Mater J. 2020;39(5):900–8.

[52] Kawajiri Y, Ikeda H, Nagamatsu Y, Masaki C, Hosokawa R, Shimizu H. PICN nanocomposite as dental CAD/CAM block comparable to human tooth in terms of hardness and flexural modulus. Materials. 2021;14(5):1182.

[53] Eldwakhly E, Ahmed DRM, Soliman M, Abbas MM, Badrawy W. Color and translucency stability of novel restorative CAD/CAM materials. Dent Med Probl. 2019;56(4):349–56.

[54] Bapat RA, Joshi CP, Bapat P, Chaubal T V, Pandurangappa R, Jnanendrappa N, et al. The use of nanoparticles as biomaterials in dentistry. Drug Discov Today. 2019;24(1):85–98.

[55] Schmalz G, Hickel R, van Landuyt KL, Reichl FX. Nanoparticles in dentistry. Dental Materials. 2017;33(11):1298–314.

[56] Mitra SB, Wu D, Holmes BN. An application of nanotechnology in advanced dental materials. The Journal of the American Dental Association. 2003;134(10):1382–90.

[57] Demirel A, Bezgin T, Akaltan F, Sarı Ş. Resin Nanoceramic CAD/CAM Restoration of the Primary Molar: 3-Year Follow-Up Study. Case Rep Dent. 2017;2017(1):3517187.

[58] Heck K, Paterno H, Lederer A, Litzenburger F, Hickel R, Kunzelmann KH. Fatigue resistance of ultrathin CAD/CAM ceramic and nanoceramic composite occlusal veneers. Dental Materials. 2019;35(10):1370–7.

[59] Bidra AS, Taylor TD, Agar JR. Computer-aided technology for fabricating complete dentures: systematic review of historical background, current status, and future perspectives. J Prosthet Dent. 2013;109(6):361–6.

[60] Zafar MS. Prosthodontic applications of polymethyl methacrylate (PMMA): An update. Polymers (Basel). 2020;12(10):2299.

[61] Arslan M, Murat S, Alp G, Zaimoglu A. Evaluation of flexural strength and surface properties of prepolymerized CAD/CAM PMMA-based polymers used for digital 3D complete dentures. Int J Comput Dent. 2018;21(1).

[62] Murat S, Alp G, Alatalı C, Uzun M. In vitro evaluation of adhesion of Candida albicans on CAD/CAM PMMA-based polymers. Journal of Prosthodontics. 2019;28(2):e873–9.

[63] Almogbel L, Sadid-Zadeh R, Örgev A, Çakmak G, Li R. Flexural strength, surface roughness, and biofilm formation of ceramic-reinforced PEEK: An in vitro comparative study. Journal of Prosthodontics. 2023;

[64] Vichi A, Balestra D, Scotti N, Louca C, Paolone G. Translucency of CAD/CAM and 3D printable composite materials for permanent dental restorations. Polymers. 2023 Mar 15;15(6):1443.

[65] Marchesi G, Camurri Piloni A, Nicolin V, Turco G, Di Lenarda R. Chairside CAD/CAM materials: current trends of clinical uses. Biology (Basel). 2021;10(11):1170.

[66] Alamoush RA, Silikas N, Salim NA, Al-Nasrawi S, Satterthwaite JD. Effect of the composition of CAD/CAM composite blocks on mechanical properties. Biomed Res Int. 2018;2018(1):4893143.

[67] Alharbi A, Ardu S, Bortolotto T, Krejci I. Stain susceptibility of composite and ceramic CAD/CAM blocks versus direct resin composites with different resinous matrices. Odontology. 2017;105:162–9.

[68] Liebermann A, Wimmer T, Schmidlin PR, Scherer H, Löffler P, Roos M, et al. Physicomechanical characterization of polyetheretherketone and current esthetic dental CAD/CAM polymers after aging in different storage media. J Prosthet Dent. 2016;115(3):321–8.

[69] Paolone G, Mandurino M, De Palma F, Mazzitelli C, Scotti N, Breschi L, et al. Color stability of polymer-based composite CAD/CAM blocks: a systematic review. Polymers (Basel). 2023;15(2):464.

[70] Wendler M, Stenger A, Ripper J, Priewich E, Belli R, Lohbauer U. Mechanical degradation of contemporary CAD/CAM resin composite materials after water ageing. Dental Materials. 2021;37(7):1156–67.

[71] Vichi A, Goracci C, Carrabba M, Tozzi G, Louca C. Flexural resistance of CAD-CAM blocks. Part 3: Polymer-based restorative materials for permanent restorations. Am J Dent. 2020;33:243–7.

[72] Schlenz MA, Skroch M, Schmidt A, Rehmann P, Wöstmann B. Influence of Different Luting Systems on Microleakage of CAD/CAM Composite Crowns: A Pilot Study. Int J Prosthodont. 2019;32(6):530–2.

[73] Elmoselhy HAS, Hassanien OELS, Haridy MF, Salam El Baz MA El, Saber S. Two year clinical performance of indirect restorations fabricated from CAD/CAM nano hybrid composite versus lithium disilicate in mutilated vital teeth. A randomized controlled trial. BMC Oral Health. 2024;24(1):101.

[74] Mainjot AK, Dupont NM, Oudkerk JC, Dewael TY, Sadoun MJ. From artisanal to CAD-CAM blocks: state of the art of indirect composites. Journal of dental research. 2016 May;95(5):487-95.

[75] Vichi A, Sedda M, Del Siena F, Louca C, Ferrari M. Flexural resistance of Cerec CAD/CAM system ceramic blocks. Part 1: Chairside materials. Am J Dent. 2013 Oct 1;26(5):255-9.\

[76] WH M. The origin of the Cerec method: a personal review of the first 5 years. Int J Comput Dent. 2004;7(1):11-24.

[77] Kollmuss M, Kist S, Goeke JE, Hickel R, Huth KC. Comparison of chairside and laboratory CAD/CAM to conventional produced all-ceramic crowns regarding morphology, occlusion, and aesthetics. Clinical Oral Investigations. 2016 May;20:791-7.

[78] Hu SN, Li JW, Zhang XX, Wei R, Liang YH. Outcome of chairside CAD/CAM ceramic restorations on endodontically treated posterior teeth: a prospective study. BMC Oral Health. 2024;24(1):51.

[79] Vervack V, De Coster P, Vandeweghe S. Clinical evaluation of resin composite CAD/CAM restorations placed by undergraduate students. J Clin Med. 2021;10(15):3269.

[80] Sannino G, Germano F, Arcuri L, Bigelli E, Arcuri C, Barlattani A. Cerec CAD/CAM chairside system. ORAL & implantology. 2014 Jul;7(3):57.

[81] Javaid M, Haleem A. Current status and applications of additive manufacturing in dentistry: A literature-based review. J Oral Biol Craniofac Res. 2019;9(3):179–85.

[82] Caligiana G, Francia D, Liverani A. CAD-CAM integration for 3D hybrid manufacturing. InAdvances on Mechanics, Design Engineering and Manufacturing: Proceedings of the International Joint Conference on Mechanics, Design Engineering & Advanced Manufacturing (JCM 2016), 14-16 September, 2016, Catania, Italy 2017 (pp. 329-337). Springer International Publishing.

[83] Mikolajczyk T, Malinowski T, Moldovan L, Fuwen H, Paczkowski T, Ciobanu I. CAD CAM system for manufacturing innovative hybrid design using 3D printing. Procedia Manufacturing. 2019 Jan 1;32:22-8.

[84] Alanazi KK, Alzaid AA, Alotaibi A, Almehisni N, Alzahrani G, Gufran K. Assessment of knowledge and practices of additive manufacturing in dentistry among university teaching faculty in Saudi Arabia. BMC Oral Health. 2024;24(1):271.

[85] Salmi M. Additive manufacturing processes in medical applications. Materials. 2021;14(1):191.

[86] Özberk T, Karakaya İ. The Use of Additive Manufacturing Technologies in Restorative Dentistry. 2024;

[87] Celik HK, Koc S, Kustarci A, Caglayan N, Rennie AEW. The state of additive manufacturing in dental research–a systematic scoping review of 2012–2022, Heliyon 9 (2023), e17462.