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Digital Dentistry: Transforming Diagnosis and Treatment Planning through CAD/CAM and 3D Printing

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Abstract

Background: Digital dentistry has revolutionized the field by enhancing diagnostic accuracy and treatment planning through advanced technologies such as Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) and 3D printing. These innovations have streamlined workflows, improved patient outcomes, and increased efficiency in dental practices.

Aim: This review article aims to explore the transformative impact of CAD/CAM and 3D printing on dental diagnosis and treatment planning, examining historical developments, current practices, manufacturing techniques, and materials used, while also addressing challenges and future opportunities.

Methods: A comprehensive literature review was conducted, analyzing scholarly articles, clinical studies, and industry reports related to digital dentistry. Emphasis was placed on the evolution of CAD/CAM technologies and 3D printing, focusing on their applications in restorative, orthodontic, and prosthetic dentistry. Real-world examples from dental practices were also incorporated to illustrate practical implementations.

Results: The review highlights the historical progression of digital dentistry from traditional techniques to modern CAD/CAM systems and 3D printing technologies. Current manufacturing techniques include subtractive and additive processes, with materials ranging from ceramics to polymers, each tailored for specific dental applications. Case studies demonstrate the successful integration of these technologies, leading to significant improvements in efficiency, precision, and patient satisfaction. However, challenges such as high initial costs, the need for specialized training, and concerns over cybersecurity are identified.

Conclusion: Digital dentistry, through CAD/CAM and 3D printing, is transforming the landscape of dental diagnosis and treatment planning. While challenges persist, the opportunities for enhanced patient care, increased productivity, and innovation in materials and techniques are promising. Future advancements in digital dentistry will likely continue to shape clinical practices, emphasizing the importance of continuous education and adaptation in the field.

Keywords: Digital dentistry, CAD/CAM, 3D printing, diagnosis, treatment planning, manufacturing techniques, materials, challenges, opportunities..

1. Introduction

Computer-aided design/computer-aided manufacturing (CAD/CAM) technology has been employed in various industries for decades and has seen a significant rise in utilization within dentistry over recent years. Applications range from creating impressions and casts to provisional fabrications and final restorations [1-3]. A dental CAD/CAM system typically comprises a scanner, software for data processing, and a fabrication mechanism that converts digital data into a tangible restoration, denture, or appliance. This "digital workflow" captures both

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dentitions, enabling clinicians to assess tooth preparations and develop restorations that align with the treatment plan. Additionally, digital files can be uploaded to a cloud-based server for streamlined communication with technicians, allowing for modifications before advancing to the subsequent steps. This workflow is generally efficient, minimizes the necessity for impression materials, and often facilitates same-day delivery of the final restoration within the same appointment. Various scanning systems are currently available on the market, some of which use an oxide powder to enhance scan quality. Scanning can be performed through static image sequences or video streams to capture the tooth preparation geometry accurately. The design software, specific to each CAD/CAM system, enables clinicians or technicians to design restorations or appliances relative to the opposing dentition. The finalized data can then be manufactured chairside, in a laboratory, or at a centralized production facility [4]. The fabrication process is accomplished through either subtractive or additive techniques. For optimal treatment results, it is essential for the restorative team to be knowledgeable about the range of CAD/CAM materials available. This review will examine the materials utilized in CAD/CAM procedures, their properties, and their precision in comparison to conventional methods in restorative dentistry. It will first explore materials produced by subtractive manufacturing (SM), followed by those created through additive manufacturing (AM).

Digital Dentistry Meaning:

Over recent decades, digital dentistry has been progressively incorporated into dental practices, with various technological advancements being adopted at different stages to enhance the practice of dentistry. These innovations aim to increase precision and accuracy, elevate patient experience, boost productivity and efficiency, and improve interprofessional communication, ultimately leading to better treatment and clinical outcomes. Additionally, digital dentistry optimizes laboratory workflows, is cost-effective, integrates with other healthcare technologies, and supports more accurate and efficient diagnosis and treatment of dental conditions through technological advancements [5, 6]. Applied digital dentistry, therefore, encompasses the use of sophisticated digital technologies within dental practices and laboratories to improve the accuracy, efficiency, and quality of dental procedures. These digital tools support various dental fields—including restorative, orthodontic, implant, and cosmetic dentistry—enhancing the ability to create highly individualized treatment plans. The graphical abstract illustrates several current trends in digital dentistry R&D&I, such as artificial intelligence (AI), virtual reality (VR), augmented reality (AR), 3D printing, digital smile design (DSD), and teledentistry [7]. AI and machine learning (ML) are increasingly applied to analyze patient data, offering personalized treatment recommendations [8] and creating intelligent systems for diagnosis and treatment planning [9]. These systems analyze vast datasets to tailor individualized treatment suggestions. VR and AR also contribute to improved treatment outcomes by creating realistic 3D dental models, enabling patients to visualize their treatment plans and aiding in greater accuracy [10].

The adoption of 3D printing in dentistry is also expanding, providing highly precise fabrication for dental implants, dentures, and orthodontic devices, which helps reduce treatment time and improves outcomes [11]. Additionally, DSD—a novel approach in cosmetic dentistry—employs digital imaging and specialized software to create a personalized smile design, enhancing both planning and communication between the dentist and patient for improved aesthetic results [12]. Furthermore, teledentistry has gained traction, especially in remote or underserved areas, by facilitating remote dental consultations and care through telecommunication technologies [13]. With the rise of high-speed internet and mobile accessibility, teledentistry serves as a critical tool in bridging gaps in dental care access for populations with limited dental resources, potentially reducing healthcare disparities. These technological trends hold transformative potential for dental care by improving treatment outcomes, shortening treatment times, and expanding access to services [14]. Moreover, the socioeconomic implications of digital dentistry research are substantial, enhancing accessibility, reducing costs, improving patient outcomes, and creating job opportunities [15]. Technologies like 3D printing reduce treatment costs through precise and accurate dental fabrications, minimizing the need for repeat treatments and associated expenses [16]. These digital advances also contribute to more accurate and personalized treatments, decreasing treatment durations and improving patient satisfaction, which in turn fosters enhanced health and quality of life [17]. As digital technologies become increasingly integral to dentistry, there is a growing demand for professionals skilled in digital dentistry, dental technology, and teledentistry, thus fostering new employment opportunities in these specialized fields [18]. Consequently, as technology continues to progress, we can anticipate even more innovative developments in digital dentistry research and applications.

History of Digital Dentistry:

The origins of digital dentistry can be traced back to the 1970s with the introduction of the first computerized tomography (CT) scanners, which provided highly detailed imaging of the teeth and jaw, enhancing both diagnostic accuracy and treatment planning [19]. In the 1980s, digital advancements continued with the introduction of the first CAD/CAM system for dental restorations [20]. This technology enabled the computer-aided design of restorations, which were then milled from material blocks using CAM systems. Notably, in 1971, physicist and dentist Robert Ledley developed the first computer-controlled dental drill at the National Institutes of Health, allowing for precise control over the drill's speed and direction to achieve greater procedural accuracy [21]. By the 1990s, digital dentistry saw further advancements with the introduction of the first 3D printers for dental applications [22]. Rapid developments in 3D printing technology have since made it widely applicable for creating crowns, bridges, and other restorations. Another significant milestone in digital dentistry was the creation of CEREC (Chairside Economical Restoration of Esthetic Ceramics) by the German company Sirona in the early 1990s [23]. The CEREC system integrated digital imaging with CAD/CAM technology to produce custom restorations like crowns and bridges in a single appointment, drastically simplifying and accelerating the procedure. The rapid progression of digital dentistry continued as companies such as 3Shape, Dentsply Sirona, and Align Technology developed advanced digital imaging, scanning, 3D printing, and virtual treatment planning software [24]. These innovations have been utilized across a broad spectrum of dental specialties, including restorative and aesthetic dentistry, orthodontics, implantology, and surgical applications.

Current State of Digital Dentistry:

Digital dentistry has become a fundamental aspect of contemporary dental practice. CAD/CAM systems facilitate the design and creation of dental restorations, while 3D printing technology is widely used for producing surgical guides, models, and orthodontic devices [25]. Augmented reality (AR) enhances patient education and supports treatment planning [26], and teledentistry is increasing access to dental services in remote or underserved locations [27]. In recent years, the scope of digital dentistry has broadened to incorporate artificial intelligence (AI) and machine learning (ML) algorithms, further enhancing the accuracy and efficiency of diagnostic processes, treatment planning, and prosthetic design [28]. These advanced technologies enable the analysis of patient data, contribute to more precise diagnoses, and support the development of customized treatment plans. AI and ML are also being leveraged to control robotic dental systems; for instance, robotic arms can be programmed to execute specific dental procedures with heightened precision, reducing the likelihood of human error [29,30]. Consequently, as digital technologies continue to progress and gain wider acceptance, the outlook for digital dentistry appears promising. The integration of AI, ML, and robotics is set to transform dental care, driving significant improvements in patient outcomes.

Manufacturing:

Subtractive manufacturing (SM) in dentistry involves shaping a final dental restoration or appliance from a pre-sintered or fully sintered material using a milling machine. These milling machines, which can operate in either wet or dry conditions, follow defined paths with capabilities ranging from 3 to 5 axes. SM systems are divided into laboratory and chairside milling systems, both of which use a digital file—often in STL format (stereolithography)—to guide the milling of various materials like wax, poly(methyl methacrylate) (PMMA), composite resins, high-performance polymers, metals, and ceramics. Recent ceramic options include glass-ceramics, resin-based ceramics, hybrid ceramics, and polycrystalline ceramics.

Wax: Wax, primarily composed of acrylate polymers, can be digitally designed and milled, offering a cost- and time-efficient alternative to traditional waxing, which is both labor-intensive and requires high skill. Milled wax patterns can undergo metal casting or ceramic pressing. For example, VITA CAD-Waxx Blocks (VITA North America, Yorba Linda, CA) provide wax options for restorations. Studies show that CAD/CAM wax-up methods yield similar accuracy to traditional methods and compare favorably to additive wax fabrication.

Poly(methyl methacrylate) (PMMA): PMMA is a versatile synthetic polymer produced from methyl methacrylate and used for both temporary single crowns and fixed partial dentures. Studies comparing PMMA to glass-ceramic inlays report similar mechanical properties and marginal fits. Improved PMMA blocks, such as Telio CAD (Ivoclar Vivadent) and VITA CAD-Temp MultiColor Blocks (VITA Zahnfabrik), offer enhanced aesthetics and physical qualities. CAD/CAM PMMA has become popular for denture bases due to its polishable surface, resembling traditional dentures in appearance. New CAD/CAM PMMA dentures, like IvoBase CAD, boast superior strength and smoother surfaces compared to conventional heat-cured PMMA, which enhances denture durability. Studies indicate that CAD/CAM PMMA also improves fit and retention, reducing the frequency of traumatic ulcers compared to traditional dentures [31-36].

Examples and Characteristics of Polymer Used:

Telio CAD is composed of 99.5% PMMA polymer, providing a flexural strength of 135 MPa, a modulus of elasticity of 3.10 GPa, water sorption at 23.20 $\mu g/mm^3$, and a fracture load around 900 N. VITA CAD-Temp, made of PMMA with inorganic microfillers, has a flexural strength of ≥80 MPa, modulus of elasticity of 2.80 GPa, and fracture load of approximately 500 N, with wear resistance around 105 mm^3 in two-body wear tests. artBloc Temp is composed of PMMA with organic fillers, has a flexural strength of 93 MPa, modulus of elasticity of 2.68 GPa, and a fracture load of about 700 N. Dentokeep, a material containing 80% PEEK and 20% TiO_2, has a modulus of elasticity of 3.43 GPa, a Vickers hardness of 27.74, and low water sorption at approximately 2.20 $\mu g/mm^3$. Minimum occlusal wall thickness for both Telio CAD and VITA CAD-Temp is 1.5 mm, while artBloc Temp requires 1.0 mm. Circumferential wall thicknesses for Telio CAD and VITA CAD-Temp are both 0.8 mm, with artBloc Temp at 1.0 mm [37-39].

Composite Resins:

Composite resins consist of an organic resin matrix incorporating inorganic or organic fillers, along with initiators, stabilizers, and pigments. Direct composite resins are applied, shaped, and polymerized within the oral cavity, while indirect composite resins, produced from pre-polymerized millable blocks, are digitally designed, milled, and polymerized outside the mouth, effectively addressing issues like polymerization shrinkage and leachable monomers while enhancing mechanical strength. Millable composite resins generally require minimal post-processing, such as polishing and the addition of photopolymerizable stains for detailed characterization, to create restorations like veneers, inlays, onlays, and crowns. Strength and other properties of these resins have been compared with ceramic blocks, though no definitive material superiority has been established [40-41]. Additional research, including clinical trials, is needed to identify the optimal material for these applications. Notable examples of CAD/CAM composite resins include Paradigm MZ100 (3M ESPE, St. Paul, Minnesota) and BRILLIANT Crios (Coltene, Altstätten, Switzerland).

The properties of Brilliant, Paradigm MZ100, and Tetric CAD composite resins exhibit notable differences based on their composition and mechanical attributes. Brilliant is composed of 70% glass and silica, whereas Paradigm MZ100 contains 85% zirconia-silica. Tetric CAD consists of barium glass (64%), silica (7.1%), and dimethacrylates (28.4%). In terms of fracturing toughness, Brilliant demonstrates a toughness of 1.41 MPa m1/2, which is higher than Paradigm MZ100 at 0.78 MPa m1/2. The flexural strength varies among these materials, with Brilliant at 198 MPa and Paradigm MZ100 at 157 MPa. The modulus of elasticity for these materials also differs slightly, with Brilliant at 10.30 GPa, Paradigm MZ100 at 12.60 GPa, and Tetric CAD at 10.20 GPa. For biaxial strength, Brilliant achieves 284.22 MPa, while Tetric CAD records a similar 273.80 MPa. Water sorption rates are 23 µg/mm³ for Brilliant and 22.5 µg/mm³ for Tetric CAD. Fracture load results show Paradigm MZ100 has a load of 1826 Newtons, while Brilliant sustains 1580 Newtons, and Tetric CAD holds an estimated fracture load of around 2600 Newtons. The Vickers hardness of Brilliant is 82.61 VH, with Paradigm MZ100 and Tetric CAD values not provided. Additionally, Paradigm MZ100 specifies a minimum wall thickness of 1.50–2.00 mm occlusally and 1.50 mm circumferentially, while such measurements for the other materials remain unspecified [42-46].

Reinforced (High-Performance) Polymers:

High-performance polymers are increasingly favored by clinicians due to their advantageous mechanical, physical, and biocompatible characteristics. Materials such as polyetheretherketone (PEEK), thermoplastic polyaryletherketone (Pekkton), and fiber-reinforced composite blocks (e.g., Trinia from Shofu, Japan) are utilized in the milling of removable partial denture frameworks and fixed restorations, including crowns, three-unit bridges, custom implant abutments, implant-supported superstructures, and telescopic copings. These materials offer mechanical stability during post-processing and are milled more easily than metals, resulting in less wear on milling equipment. Comparisons of the fit accuracy of removable partial dentures made using conventional methods versus those made with CAD/CAM PEEK show that the latter often provides a comparable or even superior fit to traditional techniques [47,48]. Furthermore, two-body wear testing has indicated that PEEK outperforms other CAD/CAM composite resins and PMMA materials [49]. In vitro studies of PEEK molar crowns mounted on zirconia and titanium abutments in chewing simulators demonstrated acceptable fracture strength, supporting their clinical application [50].

Metals:

Millable metals such as chrome-cobalt, titanium, and noble/high noble gold have become valuable additions to the CAD/CAM material selection due to their ability to eliminate miscasting errors in final restorations. Chrome-cobalt, an economical and corrosion-resistant metal, is frequently used as a framework for crowns and fixed partial dentures, often layered with porcelain. Solid-state chrome-cobalt pucks can be machined in robust milling machines, while a softer variant can be milled similarly to wax and subsequently sintered in an argon environment to yield solid-state chrome-cobalt metal. Titanium blocks are also milled to fabricate custom abutments, which can then be anodized to achieve desired colors for more complex aesthetic cases. The milling of noble and high noble alloys circumvents issues related to spruing, burnout, and casting, resulting in quicker production times and reduced labor compared to conventional methods.

Ceramics:

A wide variety of millable ceramics suitable for CAD/CAM technologies are available, making the selection process potentially overwhelming and leading to incorrect choices if adequate information and scientific data regarding their properties are lacking. CAD/CAM ceramic materials can be classified into several categories: infiltrated ceramics or hybrid ceramics, silicate ceramics—including feldspathic ceramics, leucite-reinforced ceramics, and lithium disilicate ceramics—and oxide or polycrystalline ceramics, which include aluminum oxide ceramics and zirconium oxide ceramics. The latter category can be further delineated into three mol% yttria-tetragonal zirconia polycrystals (3Y-TZP), four mol% yttria-partially stabilized zirconia (4Y-PSZ), and five mol% yttria-partially stabilized zirconia (5Y-PSZ).

Infiltrated Ceramics/Resins:

The category of CAD/CAM ceramics known as infiltrated ceramics/resins includes two distinct types: one comprising a polymer matrix infiltrated with ceramic filler particles, such as Lava Ultimate from 3M ESPE, Katana Avencia Block from Kuraray Noritake (Tokyo, Japan), and Cerasmart from GC International AG (Luzern, Switzerland), and the other featuring a ceramic network infiltrated with polymer, exemplified by VITA Enamic. Notable attributes of these materials include high load capacity, fatigue resistance, superior modulus of elasticity, and favorable milling characteristics, which result in smoother margins without the need for crystallization or sintering. Hand polishing is typically required after the milling process [51,52]. The bonding strategies differ between these types of ceramic blocks. For polymer-infiltrated ceramics, the ceramic structure necessitates acid etching with 5% hydrofluoric acid for 60 seconds, followed by the application of a silane coupler. Conversely, ceramic-infiltrated polymer blocks, like Lava Ultimate, must be pretreated with aluminum-oxide particle abrasion of ≤50 μm before applying silane [53]. While polymer-infiltrated ceramics exhibit superior wear resistance compared to ceramic-infiltrated polymers, both materials demonstrate lower wear resistance than traditional ceramic restorations [54]. Ceramic-infiltrated blocks are recommended for use in veneers and inlays/onlays, whereas polymer-infiltrated ceramic blocks are suitable for single crowns. However, clinical trials are currently insufficient to fully endorse these ceramics as a reliable option for indirect restorations [54-58].

The properties of various CAD/CAM materials demonstrate significant variability in composition and performance characteristics. Cerasmart consists of 71% silica and barium glass, exhibiting a fracture toughness of 1.22 ± 0.20 MPa m^1/2 and a flexural strength of 219 MPa. Lava Ultimate contains 80% silica and zirconia, achieving a higher fracture toughness of 1.60 MPa m^1/2, while its flexural strength is recorded at 191 ± 2.70 MPa. Grandio blocs, with an 86% nanohybrid filler composition, display a flexural strength of 208 MPa but lack specific data on fracture toughness. The HC block CAD/CAM is formulated from silica powder, microfumed silica, and zirconium silicate, showing a flexural strength of 191 MPa, although its fracture toughness remains unreported. Katana Avencia comprises silica, alumina, and dimethacrylates, with a fracture toughness of 1.47 ± 0.28 MPa m^1/2 and a flexural strength of 230 MPa. Lastly, VITA Enamic, which consists of silica (63%), alumina (23%), and sodium oxide (11%), has a fracture toughness of 1.23 ± 0.02 MPa m^1/2 and a lower flexural strength of 152 ± 2.90 MPa. In terms of modulus of elasticity, values range from 7.90 GPa for Cerasmart to 22.10 GPa for VITA Enamic, highlighting their stiffness differences. Biaxial strength measurements indicate Grandio blocs to be superior at 333 MPa, while water sorption varies, with Cerasmart absorbing 22.0 ± 0.7 μg/mm³ and VITA Enamic absorbing significantly less at 7.00 ± 0.70 μg/mm³. Water solubility figures suggest a negative trend for all materials, with VITA Enamic showing the least solubility at −2.80 ± 0.00 μg/mm³. Fracture load testing reveals Cerasmart bearing approximately 1522 ± 352 Newtons, whereas VITA Enamic tolerates the highest load at 2766 ± 98 Newtons. Vickers hardness values indicate that Grandio blocs possess the highest hardness at 121.80, compared to the 2.30 ± 0.10 measured for VITA Enamic. Wear resistance, measured through two-body wear tests, shows Grandio blocs performing best with a wear rate of 59.90 mm³, while other materials like Cerasmart and Lava Ultimate exhibit higher wear rates around ~105 and ~50 mm³, respectively. Minimum wall thickness specifications remain consistent across the majority of materials at 1.50 mm for occlusal and circumferential thickness, with Katana Avencia allowing for a reduced circumferential thickness of 1.00 mm [54-58].

Silicate Ceramics:

Silicate ceramics, particularly those based on silica, are widely recognized for their glassy matrix, which imparts translucency and mimics the optical properties of enamel and dentin. This quality makes them ideal for restorations in esthetic zones; however, it also results in brittleness and low fracture resistance, which can be compensated by adhesively bonding the restoration. Traditional feldspathic porcelain represents the oldest type of silicate ceramic, known for its optimal optical characteristics but is considered the weakest among glass-based ceramics. To prepare feldspathic porcelain for bonding, it is treated with 9.6% hydrofluoric acid for one minute, followed by ultrasonic cleaning to eliminate salt residues and the application of a silane coupler [33-36]. Efforts to enhance the mechanical strength of feldspathic ceramics have led to the development of leucite-reinforced ceramics, such as IPS Empress CAD from Ivoclar Vivadent. These ceramics maintain excellent optical properties suitable for esthetic restorations; however, their strength is only minimally improved compared to traditional feldspathic porcelain, rendering them unsuitable for load-bearing areas. Leucite-reinforced ceramics are prepared for bonding by applying 4.9% hydrofluoric acid for one minute, followed by ultrasonic cleaning and silane application [59-62].

Lithium disilicate ceramics, which contain 72% lithium and silicate oxides, represent a significant advancement in the field. They significantly enhance the strength of glass-based ceramics while preserving excellent optical characteristics. For bonding, lithium disilicate ceramics undergo treatment with 4.9%

hydrofluoric acid for 20 seconds, followed by ultrasonic cleaning and silane application [63,64]. Feldspathic porcelain is exemplified by millable blocks like CEREC Blocs and VITABLOC, which come in various colors and translucency gradations. These materials are suitable for veneers, inlays, onlays, and anterior crowns, with clinical trials indicating success rates ranging from 84% to 95% over a period of 9 to 18 years, primarily hindered by restoration fractures. Leucite-reinforced ceramics, such as IPS Empress CAD, offer improved mechanical properties and high translucency, making them well-suited for esthetic applications, particularly in non-load-bearing areas. Lithium disilicate ceramics, like IPS E.max CAD, consist of a crystalline phase that allows them to withstand loads at specified thicknesses while retaining superior optical properties, making them ideal for a range of restorations. They undergo a manufacturing process that involves milling in a precrystallized phase, followed by crystallization in a sintering furnace and subsequent polishing, staining, and glazing [65-70].

Oxide Ceramics:

Oxide ceramics, particularly zirconium dioxide (zirconia), are known for their high density and exceptional mechanical properties. The most common form, 3 mol% yttria-stabilized zirconia polycrystals (3Y-PSZ), boasts flexural strengths around 1200 MPa. Examples of zirconia products include Katana HT (Kuraray Noritake, Japan), Lava Plus (3M, St. Paul, Minnesota), and IPS E.max ZirCAD (Ivoclar Vivadent). A key feature of zirconia is its transformation toughening mechanism: when a crack begins to propagate, the tetragonal particles (approximately 85% of the structure) transform into larger monoclinic particles, creating compressive stresses that prevent further crack propagation [71]. The first generation of zirconia lacked translucency and typically required a veneering layer of feldspathic porcelain for aesthetic appeal. However, chipping of the veneering porcelain was a common issue, which was addressed by improving core designs to support the overlaying porcelain and implementing gradual cooling post-sintering, significantly reducing chipping occurrences [72]. Due to its durability, zirconia cores rarely fractured, leading to the development of full-contour monolithic zirconia restorations.

3Y-PSZ is suitable for heavy load-bearing applications, such as single crowns and fixed dental prostheses, which can be conventionally cemented to tooth structure using resin-modified glass ionomer cements, assuming proper resistance and retention forms are established. Nonetheless, the lack of translucency limited its use in esthetically sensitive cases, prompting the design of more translucent monolithic zirconia restorations. By increasing yttria content to 5 mol% and reducing alumina, the presence of cubic-phase crystals (approximately 55%) increases light transmission (e.g., Katana UTML and Bruxzir Anterior, Glidewell Laboratories). However, enhancing translucency resulted in a significant reduction in strength. The increased cubic content and decreased tetragonal particles in this new zirconia generation minimize the transformation toughening effect, allowing more crack propagation and leading to reduced strength. Consequently, these zirconia types require adhesive bonding to tooth structures. To prepare zirconia for bonding, air-particle abrasion with particles ≤50 μm at 2 bar pressure is recommended, followed by the application of a ceramic primer containing 10-methacryloyloxydecyl dihydrogen phosphate monomer, which bonds effectively to metal oxides. Due to light attenuation through zirconia, dual-polymerizing cement is necessary. Additionally, using Ivoclean (Ivoclar Vivadent), a cleaning paste, after the trial fit is advisable to enhance bond strengths [73].

Concerns regarding the low fracture resistance of 5 mol% yttria-stabilized zirconia have led to a reduction in yttria content to 4 mol%, which decreases cubic content to 25% and enhances transformation toughening and fracture resistance compared to the 5 mol% variant. This adjustment maintains translucency at a higher level compared to conventional 3 mol% yttria zirconia [46]. Examples of this type include Katana STML (Kuraray Noritake, Japan) and Bruxzir Esthetic (Glidewell Laboratories). Recent advancements have introduced chairside "fast-sintering" CAD/CAM zirconia blocks (e.g., 3M Chairside zirconia and Katana STML) that minimize sintering time from the traditional 8 hours to just 20 minutes using specialized speed-sintering furnaces (e.g., CEREC Speedfire, Dentsply Sirona). Among the various types of zirconia, conventional 3 mol% yttria zirconia is recommended for heavy load-bearing areas where aesthetics are not a concern. The 5 mol% yttria zirconia is typically used in esthetic zones; however, its fracture resistance concerns and the superior aesthetic qualities of lithium disilicate ceramics raise reservations regarding its use. The newly introduced 4 mol% yttria zirconia may serve as a viable alternative to 5 mol% zirconia in esthetic applications, with recommendations to cut back the facial aspect and layer with feldspathic porcelain to optimize aesthetics. Long-term clinical trials are necessary for all types of monolithic zirconia restorations to establish their viability as alternatives to traditional gold and porcelain-fused-to-metal restorations [74-76].

Additive Manufacturing in Dentistry

Additive manufacturing (AM), commonly known as 3D printing, has gained significant traction in the dental field due to its versatility in creating surgical guides, temporary restorations, occlusal splints, bite guards, scaffolds, and orthodontic appliances. AM technology enables the layer-by-layer addition of materials such as composites, metals, and ceramics based on a computerized 3D model, which suggests it may shape the future of dental restoration and appliance delivery. However, it's crucial to assess the properties, durability, and surface characteristics of the current materials used in AM to determine their viability as alternatives to conventional materials processed through subtractive manufacturing (SM).

Benefits of Additive Manufacturing

- **Reduced Material Waste**: AM techniques significantly lower material consumption compared to traditional manufacturing methods.
- **Energy Efficiency**: The process consumes less energy due to minimized steps in production.
- **Simplified Workflow**: Fewer steps reduce the need for human intervention, minimizing potential errors.
- **Intricate Details**: AM allows for the production of complex geometries at predictable costs.

Categories of Additive Manufacturing Technologies

AM technologies can be categorized into seven types:

1. **Stereolithography (SLA)**
2. **Material Jetting (MJ)**
3. **Material Extrusion or Fused Deposition Modeling**
4. **Binder Jetting**
5. **Powder Bed Fusion**
6. **Sheet Lamination**
7. **Direct Energy Deposition**

Among these, SLA and MJ are the most commonly used in dentistry. The quality of printed objects is influenced by the 3D printer's capabilities, which are defined by factors such as resolution, accuracy, precision, and trueness.

3D Printing of Polymers

Conventional provisional materials in dentistry are classified into:

- **Monomethacrylates or Acrylic Resins**
- **Dimethacrylates or Bis-Acryl/Composite Resins**

Current literature does not clearly indicate whether printable polymers possess properties identical to their conventional counterparts due to the differences in processing methods, highlighting the need for further chemical analysis of 3D printable polymers. Provisional restorations are critical for function and aesthetics until a definitive restoration is available. These materials must exhibit adequate mechanical properties, accurate fit, color stability, and hardness. Research comparing the flexural strength and microhardness of printable hybrid composite resins to conventional PMMA shows that the flexural strength of the printable resin (79.5 MPa) is lower than that of conventional (95.6 MPa) and milled PMMA (104.2 MPa). However, the microhardness of the printable resin (32.8) exceeds that of the conventional and milled PMMA (27.4 and 25.3, respectively). Vertical orientation during printing yields higher compressive strength than horizontal orientations. Nevertheless, the limited properties of printable polymers complicate recommendations for dimensions in connector areas of provisional fixed dental prostheses. Questions remain regarding the durability of these materials in clinical scenarios, including their ability to be repaired or relined with conventional polymers.

3D Printing of Ceramics:

The high melting point of ceramics complicates the AM process, leading to crack formation during cooling and increased porosity, which diminishes mechanical properties. Direct inkjet printing with zirconia suspensions has shown potential, producing samples comparable to conventionally prepared zirconia materials, though not without flaws. SLA methods have demonstrated superior outcomes, achieving mechanical and surface properties akin to milled zirconia. Additionally, SLA techniques have been used to print zirconia implants with high dimensional accuracy and flexural strength (943 MPa) comparable to conventionally produced ceramics (800-1000 MPa). AM has also been explored with other ceramics and calcium phosphate compositions for scaffolds in bone regeneration, yielding promising results. However, challenges such as surface quality, dimensional accuracy, and mechanical properties require attention for the production of high-quality products. Future advancements in AM technology are anticipated to lower production costs, improve material properties, and enhance manufacturing efficiency.

3D Printing of Metals:

Selective laser sintering (SLS) is utilized for metal-based appliances primarily made from titanium, chrome-cobalt, and various alloys. Initial attempts at this technology produced porous products with poor surface finishing unsuitable for load-bearing areas. However, advancements have led to metallic structures exhibiting optimal mechanical properties and minimized surface irregularities, enhancing osteointegration in implant cases. Direct metal laser sintering has effectively addressed challenges associated with chrome-cobalt appliances, such as shrinkage during casting and hardness during milling, as it involves no active force application during fabrication. Furthermore, the reduced material wastage characteristic of this technology is particularly advantageous when working with precious alloys. As the field of additive manufacturing evolves, ongoing research is crucial to fill knowledge gaps regarding the properties and durability of AM materials in dentistry. The integration of these technologies presents a promising future for dental restorations and appliances, yet a thorough evaluation of their performance and clinical viability remains imperative.

Real Life Examples:

One illustration of the application of digital dentistry in contemporary dental practices is the utilization of intraoral scanners. These compact, handheld devices are capable of capturing three-dimensional images of the teeth and gums, which can then be utilized for the design and production of dental restorations, such as crowns or bridges, through a computer-aided design/computer-aided manufacturing (CAD/CAM) system. This advancement has diminished the reliance on traditional impressions, which often cause discomfort for patients, and has enhanced the accuracy and fit of dental restorations [78]. These clear plastic trays progressively move a patient's teeth into the desired alignment. The aligners are produced using a three-dimensional model of the patient's dentition, generated via an intraoral scanner or a computed tomography (CT) scan. This innovation has transformed orthodontic treatment, rendering it more comfortable and efficient for patients [79].

Furthermore, there are numerous other instances of how digital dentistry is being integrated into modern dental practices. In the past, digital impressions replaced traditional putty impressions, utilizing intraoral scanners to capture intricate digital images of the patient's teeth and surrounding oral structures. These images were subsequently used for CAD/CAM of dental restorations such as crowns and bridges. Notable real-life examples of this technology include the 3M True Definition Scanner and iTero Element Scanner. Additionally, computer-aided implant placement involved cone-beam computed tomography (CBCT) imaging to create three-dimensional models of the patient's oral anatomy, which were then used in CAD/CAM software to meticulously plan the placement of dental implants. Real-life examples include SimPlant and Blue Sky Plan.

In the present, 3D printing technology is utilized to create physical models of the patient's dental and jaw structures from digital scans, serving purposes such as treatment planning, prosthesis fabrication, and orthodontic appliance design. Examples of this technology include the Formlabs Form 2 and Stratasys Objet30 Dental Prime. Artificial intelligence (AI) algorithms are also employed to analyze dental images, such as X-rays and intraoral scans, for the accurate detection and diagnosis of dental caries (cavities). These AI systems assist dentists in early detection and intervention, with real-life examples including Denti.AI and Dentulu. Moreover, augmented reality (AR) applications enhance patient education by allowing individuals to visualize potential treatment outcomes through the overlay of virtual dental restorations on real-world images of their mouths. Examples include DentalAR and DentalViewer.

Looking to the future, AI-powered treatment plans will analyze patient data, including dental images, medical history, and genetic information, to generate personalized treatment plans for orthodontics and oral surgery procedures, thereby improving treatment efficiency and predictability. Furthermore, advancements in 3D printing technology will enable the fabrication of biocompatible dental implants directly from digital designs, resulting in customized implants with optimal fit and aesthetics. Teledentistry is also set to expand, allowing for remote consultations and diagnoses via telecommunication, image sharing, and patient monitoring. This capability will enable dentists to provide advice, triage emergency cases, and remotely manage non-urgent dental care, with real-life examples including MouthWatch TeleDent and Denteractive. Finally, personalized prosthodontics will be facilitated by digital scanning combined with CAD/CAM software and 3D printing technology, enabling the creation of highly customized and precise dental prostheses that offer improved functionality and aesthetics.

Digital Implant Treatment Planning:

Digital implant treatment planning leverages artificial intelligence (AI) algorithms to analyze dental X-rays and other imaging modalities, aiding dentists in achieving more precise diagnoses. For instance, a deep learning algorithm trained on extensive datasets of X-rays can swiftly identify patterns linked to prevalent dental issues, such as cavities, periodontal disease, or oral malignancies [80]. Moreover, digital implant planning incorporates cone beam computed tomography (CBCT) scans alongside CAD/CAM software, facilitating the design and placement of titanium dental implants with enhanced precision and accuracy [81]. Specifically, CBCT scans generate three-dimensional images of the teeth and jaw, which serve as essential tools for planning the implant's placement and orientation [82]. The subsequent fabrication of the implant occurs through a CAD/CAM system, which promotes greater customization and precision in the implant's design. Additionally, AI algorithms can assist dentists in formulating tailored treatment plans for individual patients by analyzing comprehensive patient data, including X-rays, dental histories, and medical records, thus identifying the most appropriate treatment options for each patient [83].

Digital Smile Design (DSD):

Digital smile design (DSD) utilizes digital imaging software to produce a virtual three-dimensional model of a patient's teeth and gums. This model is instrumental in devising a personalized treatment plan aimed at enhancing the aesthetic appeal of the smile. Furthermore, this technology enables dental professionals to present patients with a preview of their post-treatment smile, thereby empowering them to make informed decisions regarding their dental care [84].

Teledentistry:

Teledentistry, a subset of telemedicine, employs digital technologies to deliver dental care and consultations remotely. This approach allows patients to receive consultations, screenings, and even certain treatments without the necessity of visiting a physical dental office, thus enhancing convenience and reducing costs. It is particularly beneficial for patients residing in remote, isolated, or underserved regions who may lack access to dental services. Teledentistry can also facilitate follow-up appointments, consultations, and the monitoring of patients who have undergone dental procedures. In light of the COVID-19 pandemic, Teledentistry has emerged as a rapidly expanding domain within digital dentistry, significantly improving access to care and treatment outcomes while minimizing the risk of disease transmission by enabling early detection and intervention for oral and dental issues [85].

Digital Occlusal Analysis:

Digital occlusal analysis employs digital sensors to evaluate a patient's bite and occlusion, identifying areas of excessive pressure or wear on the teeth. This technology assists dental practitioners in diagnosing and addressing conditions such as temporomandibular joint disorders. Additionally, AI and machine learning (ML) algorithms are utilized to design dental prosthetics, including implants, bridges, and dentures. These algorithms consider various factors such as the patient's bite, jaw anatomy, and other relevant anatomical features to create a more natural and comfortable fit [86].

Intraoral Scanning Technology:

Intraoral scanning technology has emerged as a crucial component of digital dentistry, with hand-held intraoral scanners employing optical or laser technology to capture intricate digital impressions and generate virtual models of the teeth and gingiva. This advancement eliminates the need for conventional impressions, facilitating the design and manufacturing of dental restorations such as crowns, bridges, and dentures across various fields, including restorative dentistry, orthodontics, and implant dentistry. The use of intraoral scanning devices offers numerous advantages, including enhanced accuracy, increased speed, and improved patient comfort [87].

Digital Radiography:

Digital radiography represents a contemporary substitute for traditional film-based radiography, utilizing digital sensors to capture radiographs that yield high-quality images with reduced radiation exposure. These digital images can be stored electronically and readily shared with other dental and medical professionals, aiding in collaborative diagnosis, treatment planning, and follow-up care [88]. 3D printing technology is a relatively recent innovation in digital dentistry that employs computer-aided design (CAD) files to fabricate physical models, custom surgical guides, implant abutments, and even dental restorations. This additive manufacturing process has transformed the production of dental prostheses by decreasing both the time and cost associated with their fabrication [89].

Regenerative Dentistry:

Regenerative dentistry leverages stem cells, growth factors, and other biological materials to restore damaged or missing oral tissues, marking another area significantly influenced by digital technologies [90, 91]. Techniques in tissue engineering and 3D printing hold the promise of transforming dental regenerative procedures. Digital imaging and modeling facilitate the design of tailored scaffolds and implants, while 3D printing with biocompatible materials like ceramics or polymers enables the creation of these constructs for tissue regeneration [92]. Furthermore, digital planning and simulation software can be utilized to devise and simulate regenerative procedures, allowing dental professionals to optimize treatment strategies and more accurately predict outcomes, thereby mitigating the risk of complications and enhancing treatment results. Additionally, virtual reality technology can create immersive simulations for regenerative procedures, enabling practitioners to rehearse complex techniques before applying them on patients [93].

Artificial Intelligence (AI):

Artificial intelligence (AI) has increasingly integrated into dentistry, offering the potential to enhance diagnostic accuracy, treatment planning, and patient outcomes. AI algorithms can process substantial datasets, including radiographic images and clinical histories, to facilitate the early detection of oral and dental diseases and to formulate personalized treatment strategies [94, 95]. The role of digital marketing in dentistry has become progressively vital for dental practice management [96]. With the rising prevalence of the internet and social media, dental practices must establish a robust digital presence to attract and retain patients while providing educational content. Strategies such as search engine optimization and targeted advertising campaigns can enhance online visibility and foster brand recognition. Additionally, video marketing serves as an effective tool for disseminating educational material, showcasing the practice and its services, and introducing the dental team. These videos can be disseminated through the practice’s website and social media channels [97].

Challenges and Implications:

Despite the numerous advantages offered by digital dentistry, there are several challenges and limitations that dental professionals must navigate. These challenges include the high costs associated with acquiring advanced technologies, the necessity for specialized training to effectively utilize these tools, and the potential for technological errors or failures during clinical procedures [98]. Awareness of these issues is crucial for practitioners as they integrate digital solutions into their workflows. Additionally, the risk of cybersecurity breaches and violations of patient privacy presents a significant concern. Digital images and sensitive patient data can be targets for cyberattacks, necessitating robust security measures to safeguard this information [99]. Another concern among some dental professionals is the apprehension surrounding job loss due to automation and technological advancements. However, it is essential to clarify that digital dentistry aims not to replace dental practitioners but to augment their capabilities and enhance patient care [100]. The field of digital dentistry is continuously evolving, with future advancements likely to involve the integration of augmented reality (AR), virtual reality (VR), and machine learning (ML) technologies [101]. These innovations hold the promise of further improving patient outcomes and overall treatment experiences. Additionally, the intersection of nanotechnology and digital dentistry is becoming increasingly relevant. Nanodentistry refers to the application of nanotechnology in dentistry, which involves the use of materials and devices at the nanoscale—one billionth of a meter. This approach includes the use of nanomaterials and nanorobots for diagnosing, treating, and preventing dental diseases [102]. Digital technologies can facilitate the design, fabrication, and manipulation of these nanomaterials and devices. For instance, nano-based diagnostic tools such as biosensors and imaging agents offer high sensitivity and specificity for detecting disease biomarkers and other diagnostic targets, with digital technologies enabling the analysis and interpretation of the data generated by these tools [103]. Moreover, nanotechnology can enhance targeted and precise treatment options while reducing the need for invasive procedures [104]. For example, the development of nano-based coatings can prevent bacterial growth on dental implants and enable monitoring of their effectiveness. Nanoparticle imaging, a novel technique utilizing nanoparticles, improves the resolution of digital radiographs, aiding in the detection of dental diseases and treatment planning. Additionally, nanotechnology has facilitated the creation of nano-structured implants that offer improved osseointegration and reduced failure rates, allowing for customization that matches a patient's natural dentition for enhanced aesthetics. Nanobiotechnology has also led to the creation of durable and aesthetically superior nano-based dental restorations compared to traditional materials. The future of digital dentistry appears highly promising, with ongoing technological advancements expected to further enhance the capabilities of dental practitioners and oro-dental surgeons. This evolution includes the application of AI and ML algorithms to refine diagnosis and treatment planning, as well as the development of regenerative dental techniques through hybrid 3D printing technology [109]. However, as digital dentistry progresses, ethical considerations surrounding these technologies must also be addressed [105].

Conclusion:

Digital dentistry represents a significant advancement in the field of dental care, fundamentally transforming the processes of diagnosis and treatment planning. The integration of technologies such as Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) and 3D printing has not only streamlined dental workflows but has also enhanced the accuracy and precision of dental restorations and interventions. These technologies allow dental professionals to create highly customized prosthetics, implants, and orthodontic devices, ultimately leading to improved patient outcomes and satisfaction. The historical evolution of digital dentistry reveals a transition from traditional methods to sophisticated digital solutions that facilitate real-time collaboration and enhanced communication among dental teams. With the advent of CAD/CAM systems, practitioners can design and manufacture restorations in-house, reducing turnaround times and enhancing the patient experience. Additionally, 3D printing technology enables the creation of complex structures and customized solutions that were previously unattainable, thus broadening the scope of dental applications. However, the transition to digital dentistry is not without its challenges. High initial costs associated with the acquisition of advanced equipment, the necessity for specialized training, and concerns regarding cybersecurity and patient data privacy pose significant hurdles. Moreover, some dental professionals may exhibit resistance to adopting these technologies due to fears of job displacement and automation. Despite these challenges, the future of digital dentistry is promising. Continuous advancements in materials, such as biocompatible polymers and nanomaterials, are enhancing the performance and aesthetic outcomes of dental restorations. Furthermore, ongoing research and development in artificial intelligence and machine learning are poised to refine diagnostic capabilities and treatment planning processes further. In conclusion, while there are obstacles to overcome, the benefits of digital dentistry are compelling. The ongoing integration of CAD/CAM and 3D printing technologies will likely redefine dental practice, offering new opportunities for innovation and improved patient care. To fully realize the potential of digital dentistry, dental professionals must embrace these technologies, pursue ongoing education, and adapt to the evolving landscape of dental care. The journey towards a fully digital dental practice is well underway, promising a future of enhanced precision, efficiency, and patient-centered care.

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