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# DIGITAL RESTORATIVE PROCEDURES IN DENTISTRY

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***REVIEW***

## ABSTRACT

The integration of digital technologies in restorative dentistry has significantly transformed clinical workflows, enhancing precision, efficiency, and patient outcomes. This article explores the pivotal role of various digital procedures in modern dental practices. Digital imaging techniques have revolutionized diagnostic capabilities, providing high-resolution, detailed visualizations essential for accurate treatment planning. Digital cone beam computed tomography (CBCT) has further refined diagnostic accuracy, enabling three-dimensional assessment of dental structures, which is crucial for implantology and complex restorative cases. Digital caries detection methods offer enhanced early detection of carious lesions, improving preventative care and treatment outcomes. The advent of digital impression systems has streamlined the process of capturing accurate dental impressions, reducing patient discomfort and enhancing the precision of prosthetic restorations. Additionally, digital design-manufacturing (CAD/CAM) systems have facilitated the rapid production of high-quality dental restorations, allowing for same-day procedures and greater customization. Collectively, these digital advancements are reshaping the landscape of restorative dentistry, offering unprecedented opportunities for improving the accuracy, efficiency, and overall success of dental restorations. This review aims to provide an in-depth understanding of the current state of digital restorative procedures in dentistry, with a focus on the latest technological advancements and their clinical implications.

**Keywords:** Dentistry, digital technology, CAD/CAM, CBCT.

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## INTRODUCTION

The rapid progress in information technologies has significantly accelerated digital transformation in healthcare, revolutionizing both administrative and clinical processes. Artificial intelligence (AI) has swiftly integrated into healthcare systems, driving enhancements in service delivery, cost reduction, and the accuracy of diagnostic and therapeutic procedures. In the realm of dentistry, digital transformation has supplanted traditional techniques with cutting-edge technologies such as CAD/CAM systems, 3D printing, and digital impressions. These innovations have substantially improved the predictability, precision, and efficiency of dental treatments, particularly in the field of restorative dentistry (1-4).

Digital imaging technologies, including Cone Beam Computed Tomography (CBCT), have notably enhanced diagnostic accuracy, enabling clinicians to obtain detailed anatomical insights that inform more precise treatment planning. Moreover, the integration of digital systems in workflow management has streamlined clinical operations, resulting in increased efficiency and heightened patient satisfaction. As the field of digital dentistry continues to advance, its impact on restorative practices is expected to grow, offering increasingly cost-effective, accurate, and timely treatment options. These advancements are particularly vital in the context of a global rise in dental health challenges, where the demand for high-quality dental care is escalating. The adoption of digital technologies in restorative dentistry not only addresses these demands but also contributes to the delivery of superior outcomes, minimizing the risk of human error and reducing treatment times. As the industry moves forward, the role of digital dentistry will be indispensable in meeting the growing needs of patients while setting new standards for clinical excellence (1-5).

## DIGITAL IMAGING

In digital radiology, the process begins when X-rays penetrate a target object and are subsequently captured by advanced sensors, which are designed to convert the received radiation into electrical signals. These signals, representative of the varying intensities of the X-rays that have passed through different tissues, are then processed by sophisticated computer algorithms. The processed signals are converted into numerical data that is digitized to produce an image displayed on a computer screen. Each element of this image is termed a "pixel," which constitutes the smallest controllable unit of the sensor array. The accuracy of the image is determined by the number and quality of these pixels. Each pixel receives data regarding the intensity of light—specifically information about color and brightness—thereby contributing to the overall fidelity of the image. The higher the pixel density, the greater the resolution and quality of the image, which closely approximates the actual anatomical structures. Additionally, the precision with which each pixel renders color information plays a critical role in producing an ideal image that accurately reflects the nuances of the anatomical area being examined (4-7).

Digital radiography, a cornerstone of modern imaging in dentistry, is categorized into three primary types based on the technology used for image capture and processing: indirect, direct, and semi-direct digital radiography. Each type employs different mechanisms for converting X-ray energy into digital data, offering various benefits and limitations depending on clinical needs. These modalities have significantly advanced the field of dental imaging, allowing for more detailed and accurate diagnostic capabilities compared to traditional film-based radiography (6-9).

## Indirect Digital Imaging

Indirect digital imaging is a method that involves converting traditional radiographic films into a digital format using specialized cameras or scanners. Once digitized, these images are processed and displayed on a computer screen through various software applications designed for image manipulation and analysis. The digitization process preserves the original radiographic information, including any inherent limitations, such as noise or artifacts present in the initial film. Although this method facilitates easy access, image enhancement, and digital storage, it does so by reproducing the original radiographic image, often resulting in lower resolution compared to direct digital imaging techniques. This reduction in resolution is due to the secondary conversion process, which inherently limits the clarity and detail of the final digital image. Despite this, indirect digital imaging remains a valuable tool, particularly for archiving and accessing historical radiographic records where high resolution may not be as critical (5-9).

## Semi-Digital Direct Imaging

Semi-direct digital imaging represents an intermediate approach in digital radiography, utilizing wireless phosphor plate systems to bridge the gap between conventional and fully digital imaging methods. The first system of this kind was introduced by FUJI in 1981, followed by the development of the Soredex Digora phosphor plate system for intraoral imaging in 1994. Unlike direct digital sensors, phosphor plates are not physically tethered to a computer, providing greater flexibility and ease of use in clinical settings. During the imaging process, a latent image is formed on the phosphor plates after exposure to X-rays. This image is then scanned using a laser light within a specialized device, which converts the latent image into a digital format that can be viewed on a computer screen. Phosphor plates function by absorbing and storing X-ray energy, which is subsequently released as fluorescent light when scanned with specific laser wavelengths. The intensity of this emitted light is directly proportional to the amount of absorbed X-ray radiation. This light signal is then converted into an electrical signal, which is digitized and transferred to the computer for further analysis. Prior to reuse, phosphor plates must undergo a clearing process to remove residual electrons, ensuring they are ready for the next imaging procedure (7-10).

The flexibility and wireless nature of phosphor plates make them more user-friendly compared to other digital sensor systems, particularly in terms of patient comfort and ease of handling. Additionally, these systems typically require lower radiation doses and offer a broader dynamic range, allowing for more detailed imaging across a wider spectrum of exposure levels. However, the process of capturing, scanning, and generating the final image is generally more time-consuming than other digital methods. Furthermore, phosphor plates are relatively fragile, prone to physical damage, and require periodic replacement, adding to the maintenance demands of this technology. Despite these challenges, semi-direct digital imaging remains a viable option, particularly in situations where flexibility and reduced radiation exposure are prioritized (8-11).

### Direct Digital Imaging

Direct digital imaging, also known as wired systems, combines the image capture and digitization processes. X-rays that pass through the object are captured by a sensor, and the resulting signal is transmitted to a computer via a fiber optic cable. Within seconds, the irradiated image appears on the screen. Direct digital imaging systems typically use one of three sensor types: CCD, CMOS, or flat panel detectors (11-14).

***Charge-Coupled Device (CCD):*** As the first intraoral digital image receptor, the CCD sensor uses a thin silicon wafer to capture images. When x-ray photons strike, they break covalent bonds, creating an electrical charge proportional to the number of electrons. This charge produces an analog signal, which is transferred to a data amplifier and converted to voltage by an analog-to-digital converter (ADC). The voltage at each pixel is then converted into a numerical value representing a gray level, ultimately forming a digital image on the computer.

***Complementary Metal-Oxide Semiconductor (CMOS):*** CMOS sensors differ from CCD sensors in that each pixel is connected to a transistor. When x-rays are absorbed, they generate an electrical charge within the pixel, which is transferred to the transistor, stored, read, and displayed as a digital gray value. CMOS sensors are advantageous due to their lower energy consumption and reduced image degradation from charge leakage.

***Flat Panel Detectors:*** These sensors are used for larger medical imaging matrices, capable of digitally imaging extensive areas of the body. However, they are typically more expensive and have limited applications in specialized imaging modalities (11-14).

## DIGITAL CONE BEAM COMPUTED TOMOGRAPHY (CBCT)

Digital Cone Beam Computed Tomography (CBCT) has emerged as a transformative advancement in dental imaging, providing an unprecedented level of precision and versatility in diagnostic and treatment planning processes. Unlike traditional computed tomography (CT) scans, which utilize a fan-shaped X-ray beam to capture sequential slices of the target area, CBCT employs a cone-shaped X-ray beam. This configuration enables the acquisition of a comprehensive volume of data in a single rotational sweep, resulting in highly detailed three-dimensional reconstructions of the dental and maxillofacial structures. The comprehensive imaging capabilities of CBCT provide clinicians with an extensive view of the osseous structures, teeth, and adjacent soft tissues, which markedly enhances the accuracy of diagnostic assessments and treatment planning. This technology is particularly invaluable in the context of complex dental procedures, such as implant placement, where precise localization of anatomical landmarks is critical. CBCT's high-resolution images allow for meticulous evaluation of bone quality, density, and morphology, which are essential parameters in determining the feasibility and success of implant therapy. Additionally, CBCT proves indispensable in orthodontic assessments, where it provides a detailed visualization of craniofacial structures, aiding in the formulation of comprehensive treatment strategies. Its role extends to the evaluation of temporomandibular joint (TMJ) disorders, where the detailed imaging facilitates the accurate diagnosis of joint pathologies and informs effective therapeutic interventions (15-17).

One of the notable advantages of digital CBCT is its ability to deliver high-resolution images while significantly reducing the radiation dose compared to conventional CT scans, thereby enhancing patient safety. The rapid acquisition time associated with CBCT not only minimizes the duration of exposure but also contributes to improved patient comfort, making it a favorable option in clinical practice. Moreover, the integration of CBCT data with advanced digital treatment planning software represents a significant leap forward in precision medicine. This synergy allows clinicians to conduct virtual simulations of surgical procedures, enabling meticulous planning and execution that minimizes the risk of intraoperative complications. By providing a detailed roadmap for surgical interventions, CBCT technology contributes to improved procedural outcomes, offering patients a higher standard of care (15-17).

## DIGITAL CARIES DETECTION METHODS

Radiography plays a crucial role in the diagnosis of dental caries, serving as a valuable adjunct to the visual examination. Its primary function is to assess teeth suspected of having carious lesions, offering a more in-depth analysis that visual inspection alone may not provide. Radiographs are particularly useful in estimating the depth of carious lesions by detecting areas of mineral loss, as X-rays have the capability to penetrate both enamel and dentin, revealing changes that may not be immediately apparent to the naked eye. However, radiography does have its limitations in precisely delineating the boundaries of carious lesions. For example, a lesion that appears to be confined to the enamel on a radiograph may, upon histological examination, be found to have already extended into the dentin. This discrepancy highlights the potential for underestimating the extent of caries when relying solely on radiographic evidence. Consequently, to achieve a more accurate diagnosis, especially in the case of incipient occlusal caries, it is recommended to combine radiographic evaluation with a thorough visual inspection. This dual approach allows for a more comprehensive assessment, reducing the likelihood of misdiagnosis or underdiagnosis. It is also important to note that a significant degree of mineral loss is required for carious lesions to become visible on radiographs. Typically, a 30-40% reduction in enamel mineral content is necessary before a lesion can be detected radiographically. This threshold underscores the importance of utilizing radiographs in conjunction with other diagnostic methods to ensure early and accurate detection of caries, thereby enabling timely and appropriate intervention (18-22).

***Laser Fluorescence Method (Diagnodent):*** DiagnoDent (Kavo, Germany) detects caries by applying red light at 655 nm to the tooth, which is reflected as fluorescence and converted into a numerical value (0-99) on the device's display. Caries-induced changes in tooth tissue affect fluorescence values, with healthy teeth showing minimal fluorescence and decayed teeth exhibiting fluorescence proportional to the decay level. Values between 0-10 generally indicate healthy tissue, while values above 30 may suggest the need for restorative treatment. The fluorescence changes are attributed to proto-porphyrin, a pigment found in carious tissues due to bacterial activity (20,21).

***Quantitative Light-Induced Fluorescence (QLF) Method:*** This diagnostic technique detects changes in the fluorescence of dental hard tissues due to demineralization, showing high sensitivity in identifying enamel lesions. The method employs an optical filter system generating blue light at 404 nm or an argon laser at 488 nm. The data is processed into a digital image, where fluorescence differences between healthy and decayed tissues are analyzed. Decayed areas appear darker, and the method has been used to predict lesion progression and activity (22,23).

***Fiber Optic Transillumination (FOTI):*** FOTI uses a high-intensity white light beam to illuminate the tooth, revealing dark shadows in areas with demineralized enamel due to altered light scattering and absorption. This technique is applied to the buccal and lingual surfaces of the tooth, with lesions identified as dark areas when viewed occlusally. DI-FOTI, an enhanced digital version, utilizes a high-resolution CCD sensor to capture simultaneous images of the occlusal, buccal, and lingual surfaces. In these images, carious lesions appear as black areas, which can be digitally evaluated. However, DIFOTI cannot distinguish carious lesions from developmental defects like fluorosis or determine caries activity (24,25).

***Fluorescence-Aided Caries Excavation (FACE):*** The FACE method, a recent development, uses blue-violet light to induce autofluorescence in dental tissues. Healthy hard tissues appear green, while carious tissue appears orange-red, likely due to porphyrin, a byproduct of oral microorganisms. Special glasses with filters that block blue-violet light enhance the visibility of fluorescence for the clinician. Studies have found the FACE system superior to conventional methods in selectively removing infected dentin, reducing unnecessary cavity expansion and preserving dental hard tissue (26,27).

***Electronic Caries Monitor (ECM):*** ECM detects caries by measuring the difference in electrical conductivity between healthy and decayed tooth tissues. While healthy enamel is a poor conductor, demineralized areas show increased conductivity, which further rises with progression. Dentin, with its numerous tubules, conducts electricity better than enamel, so an increase in conductivity indicates demineralization reaching the enamel-dentin junction (28,29).

***Near-Infrared Imaging Technology:*** This technology uses high-wavelength rays that store varying amounts of energy on tissue, aiding in digital caries detection as an additional feature of digital scanners (30).

## DIGITAL IMPRESSION SYSTEMS

The process of creating an accurate negative replica of the oral soft and hard tissues, or maxillofacial structures, is known as making an impression. This step is fundamental to the success of both fixed and removable prosthetic treatments, as the quality and fit of the final restoration are highly dependent on the precision of the initial impression. The chosen impression technique and materials play a critical role in capturing all the necessary anatomical details. A precise impression ensures that the restoration will fit well with the supporting teeth or soft tissues, which is essential for the longevity and functionality of the prosthesis. Any inaccuracies in the impression process can lead to poorly fitting restorations, which may ultimately result in treatment failure. Dissatisfaction with the outcomes of restorations based on traditional impression methods, combined with some patients' inability to tolerate conventional impression techniques, has fueled the evolution and adoption of digital impression systems in dentistry. Traditional impressions often face challenges related to the accuracy of casting and the preservation of models, as well as the cumbersome process involved. These limitations, coupled with the streamlined and efficient workflow offered by digital impression systems, have accelerated the shift toward digital solutions in modern prosthetic treatments. Digital impression technology seeks to minimize the potential for errors that are commonly associated with conventional impression materials and techniques. By leveraging digital impressions, clinicians can offer faster treatment processes and reduce the number of patient visits required, enhancing overall patient experience and satisfaction. The primary objective of digital impressions in dentistry is to generate a highly accurate 3D model of the oral cavity. This digital model can then be seamlessly integrated into CAD/CAM software programs used for designing and fabricating restorations. As digital scanning technology continues to advance, it increasingly overcomes the limitations inherent in traditional impression materials, improving the quality and efficiency of dental treatments (31-35).

In CAD/CAM systems, data can be gathered by directly scanning the oral environment intraorally or by scanning a physical model obtained from a conventional impression. This flexibility allows for immediate evaluation of the captured data, enabling dentists to assess the relationship of the prepared area with the opposing arch and make necessary adjustments in real-time. Features such as enlargement and reduction in the digital environment allow for precise modifications, eliminating the need for multiple impressions that are often required with conventional methods to achieve the desired outcome. CAD/CAM technology is a cornerstone in the design and fabrication of dental restorations. This technology comprises three main components: (1) scanning, where the prepared teeth or the entire mouth are digitized either intraorally or extraorally to collect detailed data; (2) design, where the restoration is created in a 3D virtual environment using CAD software; and (3) manufacturing, where the digitally designed restoration is fabricated using CAM machinery. This integrated process not only enhances the accuracy and quality of dental restorations but also significantly reduces the time from diagnosis to delivery, improving both clinical outcomes and patient satisfaction (35-38).

Data collection methods in dentistry, particularly in restorative treatments, can be broadly categorized into direct and indirect techniques. Digital restorative treatments are designed to mitigate many of the common errors that arise due to the inherent sensitivity and variability of traditional impression materials. Unlike conventional methods, digital impressions provide a more efficient workflow, enabling faster treatment times and reducing the number of clinical sessions required to achieve optimal outcomes. The primary objective of digital impression systems is to accurately capture a 3D model of the oral cavity, which can then be converted into a data format compatible with CAD/CAM software. This digital data serves as the foundation for the design and production of prosthetics using CAD/CAM devices, ensuring a high degree of precision and customization in the final restoration. As digital technology continues to evolve, the role of digital impressions will become increasingly pivotal in addressing the limitations associated with conventional impression materials. These advancements will enhance the accuracy, efficiency, and predictability of restorative treatments, further improving the quality of care delivered to patients (31-38).

## Direct Digital Impression Method

The direct digital impression method revolutionizes traditional dental impression techniques by eliminating the need for conventional impression materials and methods. Instead, this approach utilizes advanced intraoral scanners to directly capture detailed images of the oral cavity, including the prepared teeth. The data collected from these scans is immediately transferred to a computer, where it can be processed and used in real-time. In this method, the entire CAD/CAM system is integrated within the clinic, allowing for the seamless design and fabrication of dental restorations from the digital impression. This integration streamlines the workflow significantly, as the restoration can be designed, milled, and applied to the patient within a single clinical session. The ability to complete the entire process in one visit not only improves efficiency but also enhances patient convenience and satisfaction, reducing the overall treatment time and eliminating the need for multiple appointments. This method represents a significant advancement in restorative dentistry, offering precise, timely, and patient-friendly solutions (35-38).

Numerous intraoral scanners are available in dentistry, including Lava, BegoMedifacturing, Ce Novation, Pro 50.waxpro, DCS Precident, Decim, Cercon Smart Ceramics, Perfactory, Etkon, GN-1, Digident, ZFN Verfahren, Xawex dental system, Everest, Celay, Procera, Triclone, Trios, Cerec, Fussen, ZfxTM IntraScan, Dental Wings**,** EDC, Wol Ceram, and Atlantis (39-44).

## Indirect Digital Impression Method

The indirect digital impression method bridges traditional and digital techniques by incorporating conventional impression-taking steps followed by digital processing. Initially, a traditional impression is taken, and a physical plaster model of the patient's oral cavity is created. This plaster model is then scanned using optical or mechanical systems to produce a digital representation. Alternatively, the impression itself can be scanned directly to generate a virtual model that serves as the basis for further digital design. Intraoral digital scanning systems, which typically comprise a portable camera, a computer, and specialized software, are employed to capture the three-dimensional geometry of the object. These systems utilize advanced techniques such as laser scanning and optical photography to create highly accurate digital models. Some of the widely used systems for digital impressions include CEREC, E4D, iTero, Lava C.O.S, and Trios. These tools have become integral in modern dental practices for their ability to provide detailed and precise digital impressions. However, unlike the direct digital method, the indirect approach still involves the use of traditional impression materials and methods, which can introduce potential challenges. Issues such as dimensional stability of the materials, the conditions under which the impressions or models are stored, and patient discomfort during the impression process can all affect the accuracy and precision of the final digital model. These factors must be carefully managed to ensure the fidelity of the impression, as any deviations can compromise the overall quality of the restoration. Despite these challenges, the indirect digital impression method remains a valuable option, particularly in situations where direct digital capture may not be feasible (31-36).

## DIGITAL WORKFLOW

### Conventional Digital Workflow

The Conventional Digital workflow integrates both traditional and digital techniques. Initially, a conventional impression is taken by the dentist using a measuring spoon and impression material. This physical impression is then sent to a dental laboratory, where a plaster model is created. The plaster model is subsequently scanned with an extraoral scanner to generate a 3D digital model. The digital model is used to design the prosthesis using CAD software, and the design is then produced by the CAM system. Once completed, the prosthesis is returned to the dentist, who fits it in the patient's mouth and makes any necessary occlusion adjustments. Alternatively, a 3D digital model can be created directly by scanning the impression, bypassing the need for a plaster model (45-48).

### Digital Workflow

The Digital Workflow starts with the capture of a digital intraoral impression using an intraoral scanner. This digital impression data is sent to a laboratory, where the digital file is loaded into CAD software. The technician marks the margins and creates a stereolithographic (SLA) model using a 3D printer. Restoration construction can then proceed either analogically, using traditional techniques, or entirely digitally, through CAD/CAM systems. Once the restoration is completed, it is sent back to the dentist, who fits it to the patient’s mouth and makes any necessary occlusion adjustments (46-49).

### Fast Digital Workflow

The Fast Digital Workflow is a streamlined approach that completes the entire process within a single clinical session. The clinician uses an intraoral scanner to capture the digital impression and then designs the restoration using CAD software. The design data is sent to an in-clinic milling machine (CAM device) for immediate production. The final restoration is prepared and applied to the patient's mouth during the same appointment, with any necessary adjustments made on the spot. This method significantly reduces the overall treatment time, enhancing patient convenience and satisfaction (45-49).

## Open and Closed Systems in Digital Workflow

In the realm of digital dentistry, CAD (Computer-Aided Design) software plays a critical role in the design and fabrication of dental restorations. The software used for this purpose can be categorized into two main types: Closed Systems and Open Systems. Each system has distinct characteristics that influence the workflow, data handling, and overall flexibility in the digital restorative process (49-53).

***Closed Systems:*** Closed system CAD software is proprietary to the manufacturer of the intraoral scanner used in the workflow. In this model, the scanning data obtained from the intraoral scanner is saved in a specialized format that is exclusively compatible with the manufacturer's CAD software. Consequently, the intraoral scanner and the CAD/CAM (Computer-Aided Design/Computer-Aided Manufacturing) units are integrated within the same ecosystem, often housed in the same location. This integration limits the ability to select different CAM systems or production centers, as the system is designed to function as a single, cohesive unit. One of the key advantages of closed systems is the elimination of data conversion steps. Since the digital model produced by the intraoral scanner is directly compatible with the CAD software, there is no need for format conversion, which reduces the risk of data loss and preserves measurement accuracy. This seamless integration positively impacts the precision of the digital workflow, ensuring reliable and consistent outcomes (50,51).

***Workflow in Closed System CAD Software (50,51):***

***Data Acquisition:*** Scanning data is obtained using an intraoral digital scanner.

***Data Transfer:*** The raw scanning data is transferred directly to the CAD software without format alteration.

***Design:*** The digital model is designed within the proprietary CAD software.

***Fabrication:*** The designed model is sent to the CAM unit for fabrication.

***Restoration Placement:*** The completed restoration is placed in the patient's mouth.

***Open Systems:*** Open system CAD software, in contrast, supports data in the STL (Standard Tessellation Language) format, which is a widely accepted file format for 3D models. To utilize open system CAD software, scanners that either directly output data in STL format or those that require conversion to STL format are employed. This flexibility allows for interoperability between different scanners, CAD software, and CAM systems. Open systems provide greater versatility and choice, enabling practitioners to select from a variety of hardware and production centers. However, the necessity for data conversion can introduce potential data loss or inaccuracies. The process of converting scanning data into STL format and then importing it into the CAD software can sometimes compromise the precision of the measurements, although advancements in technology continue to mitigate these issues (52,53).

***Workflow in Open System CAD Software (52,53):***

***Data Acquisition:*** Scanning data is obtained using an intraoral scanner that outputs in STL format, or the data is converted to STL format if necessary.

***Data Transfer:*** The STL file is imported into open system CAD software.

***Design***: The digital model is designed using the CAD software.

***Fabrication:*** The designed model is sent to the CAM unit for production.

***Restoration Placement:*** The completed restoration is placed in the patient's mouth.

## DIGITAL DESIGN-MANUFACTURING (CAD/CAM) SYSTEMS

Computer-aided design (CAD) and computer-aided manufacturing (CAM) systems are advanced technologies that use computer systems to design and produce a wide range of dental products (126-130). In dentistry, CAD/CAM systems are pivotal for improving efficiency and quality. They eliminate traditional measurement methods and their associated drawbacks, allowing for the 3D design and production of restorations in a single session, enhancing mechanical properties, edge compatibility, aesthetics, and durability (54-57).

CAD/CAM systems consist of three main components:

1. Data Acquisition: Scanning the prepared tooth intraorally or extraorally.

2. CAD: Designing the restoration in 3D on a computer.

3. CAM: Fabricating the designed restoration from materials like ceramic, composite, or metal.

Initially, CAD/CAM systems used the "subtraction method," which involved milling prefabricated blocks, leading to significant material waste. Modern systems use "additive" methods, where material is built up layer by layer, reducing waste. Some systems combine both methods to optimize production (54-57).

Current CAD/CAM systems are categorized into (54-57):

***In-office (chair-side) systems***: Digital scans are taken, and restorations are fabricated and delivered in the same session.

***In-lab systems***: Digital scans or plaster models are processed in a laboratory to create restorations.

***Centralized production***: Digital data is sent from the clinic to a central laboratory for restoration production.

CAD/CAM systems use digital formats such as open or locked STL. "Closed Systems" use proprietary formats that restrict data use to a specific software, while "Open Systems" allow data interoperability between different manufacturers' software and hardware. Overall, CAD/CAM systems enhance restoration design and production by eliminating traditional methods, improving accuracy, and increasing efficiency (56,57).

## Advantages of CAD/CAM Systems

There are some advantages in CAD/CAM systems (57-60):

***Precision and Symmetry:*** These systems enable the creation of symmetrical restorations through techniques like the biogeneric reference technique, and they accurately replicate the original tooth form using correlation techniques. This precision ensures high-quality results and consistency in restorations.

***Quality Control and Standardization:*** The standardization achieved with CAD/CAM systems facilitates stringent quality control in the laboratory, ensuring that each restoration meets high standards. This results in improved overall quality and reliability.

***Efficiency and Time Savings:*** CAD/CAM systems streamline the entire restoration process, allowing all procedures to be completed in a single session. This eliminates the need for multiple visits, reduces patient waiting times, and removes the traditional steps of plaster casting and temporary crown preparation, leading to time and cost savings for both patients and dentists.

***Biocompatibility and Aesthetics:*** These systems enable the production of biologically compatible, tooth-colored aesthetic restorations. The ability to design and manufacture restorations digitally enhances the aesthetic outcomes and ensures a better match to natural tooth color.

***Reduced Error and Contamination:*** CAD/CAM technology significantly reduces the potential for errors and minimizes the risk of cross-contamination that may occur with indirect restoration methods. This contributes to a safer and more reliable restorative process.

***Simplified Technician Workflows:*** The use of CAD software simplifies the design of infrastructures and restorations, making the work of dental technicians more straightforward and enhancing the quality of their output.

***Reduced Processing Steps:*** The system reduces the need for traditional ceramic material processing steps such as condensation, melting, and fusing, thereby simplifying the production process and improving efficiency.

***Enhanced Patient Involvement and Satisfaction:*** Digital design allows for greater patient involvement in the restoration process, increasing patient satisfaction by aligning the final product more closely with their preferences and expectations.

## Disadvantages of CAD/CAM Systems

There are some disadvantages in CAD/CAM systems (56-60)

***High Cost:*** CAD/CAM systems are associated with significant upfront and maintenance costs, making them a substantial investment for dental practices.

***Challenges with Subgingival Margins:*** Transferring teeth with deep subgingival margins to the digital environment can be challenging. Effective gingival retraction, akin to traditional fixed denture construction, is essential to capture accurate data.

***Interference from Biological Factors:*** Blood and saliva can interfere with the intraoral scanner's ability to record accurate data, complicating the scanning process.

***Difficulties in Certain Clinical Situations:*** Scanning can be particularly difficult in the posterior regions of the mouth or in patients with restricted mouth openings. Anatomical obstacles can impact both the ease of measurement and the quality of the data captured.

***Resolution Limitations***: The resolution of intraoral cameras or extraoral scanners may be limited, affecting the precision of the scans and the overall quality of the restoration.

***Aesthetic Limitations with Monochromatic Blocks:*** The use of monochromatic blocks may not always meet ideal aesthetic expectations. However, advancements in multi-colored blocks are gradually addressing this issue.

***Requirement for Skilled Operators:*** Proficient use of CAD/CAM systems requires experienced personnel. Training and expertise are necessary to effectively operate the technology and achieve optimal results.

## Parts of a CAD/CAM System

A CAD/CAM system comprises three key components, each integral to the design and manufacturing of dental restorations (51-58):

***Scanner:*** The scanner captures detailed information about the tooth preparation, adjacent teeth, and occlusal geometry, either intraorally or extraorally. It converts these physical impressions into three-dimensional virtual models. Scanners are generally categorized into mechanical and optical types. Mechanical scanners use a stylus to trace the contours of the tooth, while optical scanners capture data using light or laser.

***Design Software (CAD):*** CAD software is used to create and plan the restoration in a virtual environment. This software allows for detailed 3D design and planning, utilizing templates or custom modifications by the user. Typically, CAD software is proprietary to specific CAD/CAM systems, making it incompatible with others. Once the design is completed, the software generates a file of the virtual model, which is then transferred to the CAM unit for production. This software facilitates various designs and restorations, depending on the needs of the case.

***Production Device Hardware (CAM):*** The CAM unit utilizes computer-controlled milling or erosion machines to manufacture the designed restoration. Production methods are broadly classified into subtractive and additive systems. Subtractive systems, often referred to as milling systems, remove material from a prefabricated block using burs, diamond discs, or other cutting tools. In contrast, additive systems, such as selective laser sintering, build up the restoration layer by layer from ceramic or metal powders, minimizing material waste.

***Computer Aided Manufacturing (CAM):*** CAM is the stage where the designed restoration is produced based on the CAD blueprint. In subtractive methods, material is removed from a block to achieve the desired shape, often resulting in material wastage. Conversely, additive methods, such as rapid prototyping, add material layer by layer, eliminating waste and offering precise control over the final product. Once produced, restorations are finished through additional processes such as glazing or adding superstructure ceramics, preparing them for cementation and final placement in the patient's mouth.

## Materials Used in CAD/CAM Systems

Materials in CAD/CAM systems for dental restorations are categorized as follows (51-58):

### *Adhesive Ceramics:*

*Historical Context:* First introduced in the 1980s.

*Examples:* CEREC Blocks, VITABLOCs Mark II, VITABLOCS RealLife Ceramics Blocks, VITABLOC TriLux Forte.

*Properties:* These ceramics offer high translucency and aesthetic appeal but have relatively lower bending strength. While their use has decreased with the advent of lithium disilicate materials, they remain suitable for crowns and partial crowns.

### *Flexible Ceramics, Composite, and Temporary Materials:*

*Materials:* Includes polymeric CAD/CAM materials such as composite blocks (e.g., Paradigm MZ100) and flexible ceramics (e.g., LAVA Ultimate).

*Characteristics:* Also known as nanoceramics or hybrid ceramics, these materials have a resin matrix combined with inorganic refractory compounds. They exhibit lower physical properties compared to traditional ceramics but offer more uniformly milled margins and do not require firing. Improved ligation protocols have enhanced their survival rates, and some options are designed for long-term use.

***High Strength Ceramics:***

*Examples*: Lithium disilicate (e.g., IPS e.max CAD, Celtra Duo, CEREC Tessera) and advanced lithium disilicate formulations.

*Properties:* Known for their high flexural strength (400-700 MPa) and translucency, making them ideal for posterior crowns. These materials require a two-stage firing process and are popular for chairside CAD/CAM restorations due to their durability and aesthetic qualities.

*Zirconia:*

*Examples:* CEREC Zirconia, Katana Zirconia, 3M Chair Head Zirconia.

*Properties:* Zirconia provides high flexural strength (700-900 MPa) and minimal requirements for occlusal reduction. Despite its strength, long-term clinical performance data for chairside zirconia restorations are still being evaluated.

## DIGITAL COLOR MEASUREMENT IN DENTISTRY

Digital cameras and specialized devices have become essential tools in color measurement and enhancing communication between clinicians and laboratories. Known as RGB (Red, Green, Blue) devices, these digital cameras are among the simplest yet effective technological solutions for color assessment under standardized lighting conditions. Unlike dedicated measuring instruments, digital cameras capture images that are analyzed on a computer to aid in color selection. Digital cameras use sensors, specifically Charge-Coupled Devices (CCDs), which consist of millions of light-sensitive elements called photocytes. Each photocyte responds to incoming light, and through a process involving filters, the camera captures and records the three primary colors—red, green, and blue—at each pixel. This method allows for a comprehensive representation of color in the captured images. The quality and accuracy of digital photographs can be influenced by various factors, including the type of camera, camera settings, ambient lighting conditions, image size, and the positioning of the tooth and color key. While digital photography provides a visual record of the area of interest and facilitates communication between clinicians and technicians, it can be subjective and may not always deliver the precision required for accurate color matching. Nonetheless, the ability to capture the entire area of interest makes digital photography a valuable tool for enhancing collaboration, even when clinicians and technicians are not physically present together (61-64).

Spectrophotometers measure color by comparing the light reflected from an object to that from a white reference surface. This principle is integrated into various devices to improve color detection. Examples include the Crystaleye, SpectroShade Micro, Shadepilot, Zfx Shade, and VITA Easyshade V. For instance, the SpectroShade system employs dual digital cameras in conjunction with a spectrophotometer and uses halogen lighting to assess the entire surface of a tooth. Portable versions, such as the SpectroShade Micro and SpectroShade Mobile, offer flexibility for in-office use (65,66).

Colorimeters, which measure color using tristimulus values, feature three sensors that analyze reflected light in the red, green, and blue spectra without mathematical adjustments. Devices like the ShadeScan utilize a handheld design with an LCD display, combining digital imaging with colorimetric analysis. The ShadeScan uses a halogen light source to illuminate the tooth surface and records images directly onto a memory card, which is then transferred to a computer for detailed analysis. This method supports color and translucency mapping, which can be shared with laboratories via email or printed (63,66,67).

The VITA Easyshade V is a prominent digital spectrophotometer known for its quick, reliable, and consistent color detection capabilities for natural teeth and ceramic restorations. Utilizing LED technology, the VITA Easyshade V is unaffected by environmental conditions and features a touch screen with user-friendly software. Additionally, the VITA mobileAssist app facilitates seamless communication between technicians and dentists by integrating color measurements with digital photographs and offering additional image editing tools. This integration streamlines the workflow and enhances the precision of color matching in dental restorations (68,69).

## Digital Dental Photography

Dental photography serves various purposes, including diagnosis, treatment planning, oral cavity documentation, case presentations, color matching, evidence for malpractice cases, forensic identification, and decision-making between patients and clinicians. Camera Selection and Accessories: For optimal dental photography, digital single-lens reflex (DSLR) cameras are recommended due to their interchangeable lenses. Commonly used lenses for dental photography include 60 mm, 85 mm, and 105 mm. Additionally, twin and ring flashes designed for macro photography are used, with twin flashes preferred for detailed aesthetic applications in the anterior region and ring flashes suitable for less detailed applications in the posterior region. Before photographing, it's essential to prepare the patient by explaining the purpose of the photographs and obtaining consent for their scientific use. Once patient, clinician, and camera preparations are complete, full-face, profile, and intraoral photographs can be captured (70,71).

## DIGITAL SMILE DESIGN

Digital Smile Design (DSD) represents a transformative approach in aesthetic dentistry, enabling the creation and visualization of a patient's smile within a digital environment. This innovative technique enhances patient engagement from the initial stages of planning and significantly improves communication between the patient and the clinician. The DSD process begins with a comprehensive analysis of the patient's facial and dental proportions, adhering to established aesthetic guidelines to achieve an ideal smile. This analysis includes (72-74):

***Facial and Dental Proportions:*** Detailed evaluations of the patient's facial features and dental structures are performed to ensure that the smile design aligns with both aesthetic norms and individual characteristics.

***Dentogingival Analysis:*** The health and morphology of the gums are critically assessed, as they play a pivotal role in the overall aesthetic outcome. This analysis includes evaluating gum health, shape, and alignment, which are essential for creating a harmonious smile.

***Reference Parameters:*** To achieve a balanced and symmetrical smile, reference parameters for facial symmetry and segmentation are utilized, considering both frontal and profile views. These parameters guide the design of restorations and align them with the patient's facial features.

Before proceeding with the smile design, a thorough dental analysis is conducted to determine the appropriate shape, size, and color of the proposed restorations. High-quality photographs and adherence to fundamental aesthetic principles are crucial for effective digital smile design. These photographs provide a detailed and accurate representation of the patient's current smile and assist in visualizing the proposed changes. Traditional methods, such as plaster models, wax-ups, and silicone keys, often involve laborious processes and may not always achieve the desired results. In contrast, DSD programs address these limitations by offering digital simulations that consider the current condition of the teeth and soft tissues. This digital approach allows both the clinician and the patient to preview the potential outcome of the smile design, ensuring that it aligns with patient expectations and clinical objectives. Complex cases with high aesthetic demands frequently require a multidisciplinary approach, integrating input from various specialists to achieve the best results. DSD programs facilitate this process by providing a clear visual representation of the proposed changes, which helps in coordinating efforts among different dental professionals (72-74).

### Digital Smile Design Programs

Several programs are commonly used in digital smile design (75-78):

***3Shape Smile Design (3Shape Company, Denmark):*** Allows smile design directly from a 2D photo. The designs, once approved by the patient, are imported into 3Shape Dental System software, combined with 3D digital images, and can include a mock-up model if desired.

***Cerec SW (Dentsply Sirona, USA):*** Converts a full-face 2D image into a 3D image by identifying key points. It supports three-dimensional smile design and can be used with CAD/CAM systems to create both temporary and final restorations that replicate the designed smile.

***Coachman App (Digital Smile Design, Spain):*** Requires dental photos from three angles (Maximum Smile, Rest, and Occlusal) along with side profiles and videos. The app facilitates faster and more objective smile design compared to manual methods.

***Romexis Smile Design (Planmeca Oy, Finland):*** Operates on both Windows and MacOS without additional software. It generates images of the teeth from full-face frontal photos, determines aspect ratios, and uses a library of tooth colors to identify existing shades.

***Smilecloud (SM Biometrics, USA):*** A cloud-based platform for storing patient data, photos, videos, and scans. It aligns teeth automatically and allows design adjustments, with outputs compatible with CAD/CAM and 3D printers.

***Smile Creator (Exocad GmbH, Germany):*** Integrated into the Chairside CAD platform, this tool converts patient photos or webcam images into 3D objects and synchronizes them with 3D scans of the teeth.

## VIRTUAL ARTICULATORS

Virtual articulators have transformed dental practice by simulating jaw movements and dynamic occlusal contacts using digital 3D data and patient-specific movement data. They reduce the limitations of conventional articulators by providing more accurate, measurable, and repeatable results. Virtual articulators are categorized into (79,80):

***Mathematically Simulated Virtual Articulators:*** Use average values and simulate mechanical movements, but lack individualized movement paths.

***Fully Adjustable Virtual Articulators:*** Record individual mandibular movements to achieve personalized occlusion for precise restorations.

***Semi-Conventional Virtual Articulators:*** These combine digital and conventional methods by scanning plaster models or using extraoral scanners to digitize models and integrate them into a virtual environment.

***Fully Digital Virtual Articulators:*** These connect intraoral scanner data directly to a virtual articulator, enabling the simulation of all mandibular movements and improving treatment planning accuracy. The integration of virtual facial arch systems enhances precision and meets both aesthetic and functional patient expectations.

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