An Overview of Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) in Restorative Dentistry

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Abstract

Objective: To review the current knowledge of CAD/CAM in dentistry and its development in the mentioned field. **Sources:** An electronic search was conducted across Ovid Medline, complemented by manual search across individual databases, such as Cochrane, Medline and ISI Web of Science databases and Google Scholar for literature analysis on the mentioned topic. The studies were reviewed thoroughly. This paper summarizes the current scientific and clinical opinions through a brief overview regarding the preferred way of utilizing CAD/CAM in dentistry. **Conclusions:** The importance of CAD/CAM systems has seen a dramatic development in the number of products and procedures over last decades, with a concomitant rise in publications on the topic. Literature suggests that using this technology permits carrying out dental treatments feasibly particularly for fixed dental appliances. Based on the previous findings, it is concluded that in office CAD/CAM technique appears to be the most common technique currently available, which is rapid, easy and keeps time. CAD/CAM systems are variable; therefore, using the right system with a logical approach for treating patients are quite mandatory.

Keywords: CAD/CAM, CEREC system, Digital dentistry, Restorative materials, Marginal adaptation.

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Introduction

During the last quarter of the 20th century, there was a breakthrough in dentistry regarding introducing a new technology, i.e. the Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) system (1-4). A new age started with the appearance of this technology (5). The notion of using this recent technology in dentistry, particularly restorative dentistry, commenced with diverse research approaches. For instance, in the 1970s Francois Duret in France introduced the Duret system (3, 6-12); which was named after him and supported by “Hennson International”(13). Using this system, Duret pioneered optical impression from which design and milling of an abutment tooth were possible (1). However, due to the complexity, large size, inadequate digitizing and high cost, this system did not take off in dental markets (7). Later another system launched into the market named “Sopha System”, which was supported by “Sopha Bioconcept” (1, 3, 6, 7). Then, in the 1977 Young and Atlschuler (6, 7, 13-15) suggested an optical impression method, which depended on laser holography.

Subsequently, in the 1980s at the University of Zurich in Switzerland, Dr. Werner Mormann and Marco Brandestini introduced the first commercial CAD/CAM system to a dental clinic (8, 10, 16). This technology made major changes in dental practice by permitting dentists to finish multiple works for ceramic restorations such as full crowns, inlays, onlays and veneers in a clinic or laboratory (16, 17).

The first chair-side ceramic inlay with the CEREC1 CAD/CAM system (Sirona “Siemens old name of Sirona” Dental System, Charlotte, NC.) was fabricated and used in 1985 (14, 16, 18-20). However, a study by Culp and Touchstone showed that this system was introduced earlier in 1982 (21). In addition, Freedman in a literature review argued that this system was introduced into the market in the 1987 (22).

Following this period, Dr. Anderson attempted to introduce the Procera System (1, 3). This system enables the machining of titanium copings by spark erosion. Using this system, Anderson tried to carry out a process of composite veneered restoration (1). Eventually, it becomes a popular system in the worldwide to fabricate all-ceramic frameworks through a centralized network process with satellite digitizers (1).

Apart from these systems, several other groups have tried to introduce others from 1985 to 1990s such as the Aoki group in Japan, Diane Rekow's in Minnesota and Reggie's at Alabama University (6). The most developed amongst the various systems was that of Diane Rekow, which was supported by the Bego company under a particular name, the so-called the DentiCAD or Minnesota system (6). This system provided 3D measurement on the teeth surface via stereophotogrammetry. However, it was complicated to operate. Therefore, it did not remain in use for long, only until 1994 (6). Then, the technological revolution in dentistry further developed. Hence, there were certain changes, and various other systems were developed. For instance, the DCP analogue system, the Celay system, the DFE (Krrup) system and the Erosonic system (ESPE) (13). Since then, several varieties of commercial CAD/CAM systems were developed.

In the past, the CAD/CAM system was used either at the laboratory side or in-office "chair-side" (23). However, recently it has become feasible to merge the concepts. Hence, both dental professionals and experienced technicians have benefited (23). Therefore, CAD/CAM systems have branched into other dental fields such as oral surgery, periodontology, orthodontic treatment, implantology and maxillofacial surgery; it is no longer found only in the restorative field. These are signs for a significant role and ongoing evolution of this technology, from simple fabricated machine to recently developed one (24). This paper aims to show a short glance relating to CAD/CAM system and focusing on certain other aspects.

CAD/CAM Components

CAD/CAM systems are composed of three major parts: First, a data acquisition unit, which collects the data from the area of the preparation, adjacent and opposing structures. Then converts them to virtual impressions (25) through intraoral scanners (in-office CAD/CAM or in-office CAD or image acquisition systems) or indirectly using a stone model generated through making a conventional impression. Second, the software used for designing virtual restorations on a virtual working cast and then computing the milling parameters. Third, a computerized milling device used for manufacturing the restoration from a solid block of restorative material or additive manufacturing.

General classification of CAD/CAM systems

The CAD/CAM systems are classified into laboratory systems and chairside systems. The laboratory system is further classified into laboratory CAD/CAM, in which the company has its own scanner and milling units such as (Amann Girbach, 3M ESPE, Sirona Dental Systems, Zirkon Zahn, vhf camfacture AG, Weiland Dental, Pou-Yuen and U-Best Dental, Planmeca, KaVo Dental, Dentsply Prosthetics). The CAD unit in which the company has only the scanner (e.g. D2000, 3 Shape; Dental Wings 7 series, Dental Wings; IScan D104, Imetric 3D SA; Ceramill Map, Amann Girrbach; Activity 850 3D, Smart Optics). The CAM unit in which the company retains the milling machine unit such as (DWX-50, Roland DGA Corporation; inLab MC X5, Sirona; M5, Zirkonzahn; Tizian Cut 5 Smart, Schütz Dental; S2 Model, vhf camfacture AG; Ceramill Motion 2, Amann Girrbach).

The chairside CAD/CAM system is further classified into: first, chairside CAD/CAM system in which the company has its own scanner and milling units (Sirona and Planmeca). Second, image acquisition system in which the company has only a scanner without designing capabilities (e.g. True Definition Scanner, 3M ESPE; iTero, Align Technology, Inc; Trios, 3Shape; Apollo DI, Sirona; CS 3500, Carestream Dental LLC). These, in turn, must be connected to an open laboratory scanner for designing of the restoration.

CAD/CAM can be further classified into open and closed systems (26) according to data sharing. Closed systems offer all CAD/CAM procedures, including data acquisition, virtual design, and restoration manufacturing by the same company. Further, all the steps are integrated into one system, and there is no interchangeability between different systems from other companies. Open systems allow the adoption of the original digital data by CAD software and CAM devices from various companies (26).

The laboratory CAD systems must always be an open system because after acquiring the data and designing the restoration, the data has to be stored in an STL file "Stereolithography or Standard Tessellation Language. However, many manufacturers use their own specific data formats, with the result that data for the construction programs will not be compatible with each other" (27), and then sent to an open laboratory CAM system, which accepts that type of STL file from that laboratory CAD system where the restoration will be fabricated. Additionally, the image acquisition unit is always an open system, and the STL file of a certain restoration can be accepted by an open laboratory CAD system for the restoration to be designed and then sent to an open CAM system for the restoration or model to be fabricated.

When complex restorations are intended to be fabricated such as an implant bar or attachments, the model can be scanned through open laboratory CAD/CAM or laboratory CAD systems and the STL file sent to an outsource production center such as (InfiniDent, Sirona; Procera, Nobel Biocare; Lava, 3M ESPE; TurboDent, Pou-Yuen and U-Best Dental; Ceram M-center, Amann Girrbich; PlanEasyMillTM, Planmeca) for restoration designing and fabrication. In addition, when a digital model is intended to be fabricated through scanning of the teeth intraorally, the STL file of the image acquisition unit or open chairside CAD/ CAM system can be sent to an outsource production center for the digital model to be fabricated through milling or additive technology. General classification of CAD/CAM system is summerized in Table 1 (5, 22).

Table 1. General classification of CAD/CAM system (5, 22)

Types	Descriptions
1- Chairside production	It saves time and offers the patient indirectly fabricated restoration at one appointment. In general CEREC system (Sirona) gives this opportunity. This system was the 1st CAD/CAM sytem and currently the 4th recent generation available in markets. The benefit is the ability to use software (3D) program and obtaining precise reconstruction of the occlusal surface.
2- Labrotary production	It is similar to traditional working sequence between dentist and technician. 3D data are produced depending on master die. Takes longer time than 1st type. Permit technician to work more carefully for final design fabrication.
3- Centralized production	Satellite scanners are connected with a production center through the Internet. This is an open system, compared to other systems, which are closed type.

Development of CEREC systems and comparison to former generations

CEREC; is the abbreviation of "Chairside Economic Reconstruction of Esthetic Ceramic" (1); however, in certain literature, this acronym is just explained by the terms "Ceramic Reconstruction" (19, 28). This system is more applicable than other available systems (29). The 1st version was launched onto the market in 1985 (16, 30), whereas Akbar et al. argued that that CEREC 1 was introduced in 1984 (29). Then, after technical improvements, the next generation of CEREC 2 was fabricated and introduced to dental clinics in 1996 (1).

Recently, Akbar et al have examined CEREC 3 (29) in a similar way and found that this system was identical to the second system. However, other studies showed that CEREC 3 is better than CEREC 2 regarding marginal integrity (1,7). Previous literatures have established that CEREC 2 can be utilized to fabricate partial crowns, inlays, onlays and overlays (31). However, CEREC 3 can be used for three-unit bridge, veneers, onlays, inlays, full and/or partial crowns and copings (31). For specific crown designs such as veneers, inlays, onlays and temporary bridges CEREC 4 and 4.5 are the most appropriate systems.

Different restorative materials can be used with the CEREC system including; VITA Blocs Spinell, Zirconia, Alumina, Zirconia Mark II, YZ (VITA Zahnfabric, Bad Säckingen, Germany). Lucite reinforced ProCad (Ivoclar vivadent, Schann Liechtenstein) (31, 32).

Compare CEREC system properties to earlier versions systems

There are certain properties presented with the previous systems; the infra-red intraoral camera, and an optical image can be obtained with CEREC 2, CEREC 3, and CEREC 4. However, the two last versions improved in such a way that blue ray enhanced better properties in comparison to previous generations. In addition, the design of models can be fabricated (Extrapolation, Function and Correlation).

The CEREC 3 and later versions have the ability to complete all the work in one appointment without the need for a second visit. In addition, it does not require to take of impressions or making a temporary restoration, i.e. preparation, designing and milling process can be completed in one visit (8, 28).

Due to significant progress in both hard and software computer programs, varieties of laboratory CAD/CAM systems have been launched into the market. In 2002, CEREC inLab was launched into the market. With the CEREC InLab, a die can be either scanned with a laser scanner automatically or separately through inEos system.

Then, a 3D image has been achieved by computer program the restoration is designed (28, 33). The subtracting process through milling chamber can be carried out automatically (7).

Recently, both the InEos and CEREC inLab system can be used as a combined unit that can conduct each scanning and milling independently. The former system was previously used only for milling or scanning purpose. However, both processes can be carried out together in combination.

With CEREC, two types of laser mode scanning are present. The overview can be used for multiple works such as crowns, inlays, onlays and bridges. It has the ability to scan upper and lower arches for occlusal restoration. The rotational scanning mode can be also used for taking eight scanning pictures, as indicated for a single die or unit (28)

The modern versions of the CEREC software 4 and 4.5 (Bensheim, Germany) were also released in last few years into the market by Sirona. Major steps in CEREC system development are shown in Table 2 (19).

Table 2. Major steps in the development of CEREC CAD/CAM system (19)

Year	Hardware	Software capability	Restoration Type	Developer
1980	Basic concept	2D	Inlays	Mormann and Brandestini (University of Zurich)
1985	CEREC1	2D	First chairside inlay	Mormann and Brandestini (Brains, Zurich)
1988	CEREC1	2D	Inlays, onlays and veneers	Mormann and Brandestini
1994	CEREC2	2D	Copings, Partial and full crowns	Siemens (Munich,Germany)
2000	CEREC3 and InLab	2D	3 and 4 unit bridge frames	Sirona (Bensheim, Germany)
2003	CEREC3 and InLab	3D	3 and 4 unit bridges	Sirona (Bensheim, Germany)
2005	CEREC3 and InLab	3D	Automatic virtual occlusal adjustment	Sirona (Bensheim, Germany)
2011-2015	CEREC 4 and CEREC 4.5	3D	Automatic virtual occlusal adjustment, full arch recording	Sirona (Bensheim, Germany)

Strengths and weaknesses of CEREC CAD/CAM systems

The system lies on the triangulation technique which requires a uniform reflective surface since different materials such as dentin, amalgam, resin, gum reflect light differently. Therefore, it is necessary to coat the teeth with reflective powders before the scanning to provide uniformity in the reflectivity of the surfaces to be scanned precisely. Earlier versions of CEREC® employed an acquisition camera with an infrared laser light source. The Bluecam version employs blue light-emitting diodes (LEDs); the intense blue light with a shorter wavelength projected by the blue LEDs allows for greater precision of the produced virtual model (34). Even at the periphery, the images are free from distortion, so multiple images such as a complete quadrant can be stitched together with high accuracy (34).

The CEREC® AC Bluecam offers image stabilization systems. This means that the practitioner does not have to rest the camera wand on a tooth to get a steady focus. The camera automatically captures an image when the wand is motionless, avoiding the need for a foot pedal as the previous model required. Recently, with further development of CEREC software, it is possible to scan full arches. Earlier versions of the device made a single image from one perspective. At the end of the scanning stage, the preparation is shown on the monitor and can be viewed from every angle to focus or magnify areas of the preparation (35).

Restorative materials for CAD/CAM system

With using CAD/CAM systems, operators can fabricate restorations from an array of materials. These include ceramics, metal alloys and various composites. The ceramics currently being used for restorations are predominantly alumina including those subsequently infiltrated with glass, zirconia and porcelain based ceramics (36).

CAD/CAM systems based on machining of pre-sintered alumina or zirconia blocks in combination with specially designed veneer ceramics satisfy the demand for all-ceramic posterior crowns and fixed partial dentures. Many restorative materials are available for use as CAD/CAM restorations as shown in Table 3 (37). Common ceramic materials used in earlier dental.

CAD/ CAM restorations have been machinable glass ceramics such as Dicor (Dentsply Caulk, Milford, DE 19963) or Vita Mark II (Vident, Bera, CA 92821). Although monochromatic, these ceramic materials offer excellent esthetics, biocompatibility, excellent color stability, low thermal conductivity, and excellent wear resistance (38). They have been successfully used as inlays, onlays (39), veneers and crowns (40). However, Dicor and Vita Mark II are not strong enough to sustain occlusal loading when used for posterior crowns (41). Therefore, alumina and zirconia materials are now being widely accepted as dental restorative materials. These ceramic agents may not be cost-effective without the aid of CAD/CAM technology (42). For instance, In-Ceram l, first was described by Sadoun and Degrange, has been shown to have the acceptable flexural strength and clinical performance (43). However, the manufacture of conventional In-Ceram restoration takes up to 14 hours. A milling copings from presintered alumina or zirconia blocks within a 20 minutes period and reducing the glass infiltration time from 4 hours to 40 minutes, CEREC inLab decreases fabrication time by 90% (44).

Zirconia is strong enough and has high biocompatibility (45). Fully sintered zirconia materials can be difficult to mill, taking 3 hours for a single unit. Compared with fully sintered zirconia, milling restorations from pre-sintered or partially sintered solid blocks is easier and less time consuming, creates less tool loading and wear, and provides higher precision (46).

The dimensional change of zirconia material creates compressive stresses that reduce crack propagation. This phenomenon, called “transformation toughening”, actively opposes cracking and gives zirconia its reputation as the “smart ceramic”(47). The quality of transformation toughness and its effect on other properties is unknown. Zirconia copings are laminated with low fusing porcelain to provide esthetics and to reduce wear of the opposing dentition. If the abutment lacks adequate reduction, the restoration may look opaque. Because they normally are not etchable or bondable, abutments require good retention and resistance form. Alumina and zirconia restorations may be cemented with either conventional methods or adhesive bonding techniques (48). Conventional conditioning needed by leucite ceramics, such as hydrofluoric acid-etch, is not required. Microetching with Al_2O_3 particles on cementation surfaces removes contamination and promotes retention of pure aluminium oxide ceramics (49).

Table 3. Common Restorative Materials for Dental CAD/CAM Systems (37)

Restorative material	CAD/CAM system	Indications	Cementation
Dicor MCG	Cerec	Inlay, onlay veneer	Adhesive(dual-cured)
Vita Mark II	Cerec	Inlay,onlay veneer,anterior crown	Adhesive(dual-cured)
Pro CAD	Cerec	Inlay,onlay veneer,anterior crown	Adhesive(dual-cured)
In-Ceram Spinell	Cerec 3D, Cerec inLab	Anterior crown	Adhesive(self-cured),conventional
In-Ceram Alumina	Cerec 3D, Cerec inLab, DCS Precident	Crown and anterior bridge	Adhesive(self-cured),conventional
In-Ceram Zirconia	Cerec 3D Cerec inLab, DCS Precident	Crown and bridge	Adhesive(self-cured),conventional
Alumina	Procera	Crown and bridge	Adhesive(self-cured),conventional
Partially sintered Zir-conia	DCS Precident, Lava, Procera,Everest, Cercon	Crown and bridge	Adhesive(self-cured),conventional
Fully sintered Zirconia	DCS Precident, Everest	Crown and bridge	Adhesive(self-cured),conventional

Marginal integrity of CAD/CAM system

A principle concern surrounding CAD/CAM technology is the accuracy of fit of the ceramic crowns fabricated using CEREC system (50). A wide range of variables can affect the marginal accuracy of CAD/CAM restorations such as the scanning process, software design, milling and shrinkage following the final firing of the restoration (51).

Holmes et al. introduced classifications for the marginal gap (52). They measured “misfit” as internal gap, marginal gap, vertical marginal discrepancy, horizontal marginal discrepancy, overextended margin, underextended margin, absolute marginal discrepancy and seating discrepancy (52). According to their classification “the perpendicular measurement from the internal surface of the casting to the axial wall of the preparation is called the “internal gap”, and the same measurement at the margin is called the “marginal gap”. “Absolute marginal discrepancy “was defined as the angular combination of horizontal and vertical discrepancies and represents the total misfit of the restoration (52).

One of the most important criteria in evaluating fixed restorations is marginal integrity. There are controversies about the acceptable marginal integrity, certain studies have evaluated that a marginal fit ≤100 microns is more acceptable (53), others consider a fit ≤75 microns clinically acceptable (54). Another study has been reported that the marginal discrepancies larger than 100µm resulted in extensive loss of the luting agent (55).

A study reported that the marginal fit of CEREC 3 CAD/CAM all-ceramic crowns changed when the setting of cement space was altered from 10 µm to 30-50 µm. The marginal fit of the crowns with the cement space setting of 30-50 µm created a marginal gap range of 53-67 µm. When a cement space setting of 10 µm was used marginal gap range of 95-108 µm was observed (56).

In addition, a study reported the possibility of wear that is resulting from contact of food particles with cement when gap dimension exceeded 100µm (57). McLean and Von Fraunhofer (58) proposed that an acceptable marginal discrepancy for full coverage restorations should be less than 120µm. A study suggested a clinical goal of 25-40µm for the marginal adaptation of cemented restorations (59). However, most clinicians agree that the marginal gap should be no greater than 50-100µm (60, 61).

In general, research has shown that CAD/CAM crowns fabricated via the CEREC 3 and later sophisticated systems demonstrated better marginal fit compared to CEREC 1 and CEREC 2 CAD/CAM generations (62, 63).

Advantages and disadvantages of CAD/CAM technology

The use of CAD/CAM technology for dental restorations has numerous advantages over traditional techniques. These advantages include speed, ease of use, and quality. Digital scans have the potential to be faster and easier than conventional impressions because casts, wax-ups, investing, casting, and firing are eliminated (64).

Having a milling machine on site means that patients can receive their permanent restoration on the same day they come in, without making a second appointment. Patients no longer need to have provisional restorations, which take time to fabricate and fit. If anesthetics are needed, they only need to be administered once (64). The quality of CAD/CAM restorations is extremely high because measurements and fabrication are extremely precise (65). Perhaps this difference in the finished product should not be surprising, given the wide variation in quality of traditional impressions. Traditional impressions suffer from problems, such as bubbles and tears in the impression material, cords or other debris embedded in the impression material, and missing teeth (66).

CAD/CAM restorations have a natural appearance because the ceramic blocks have a translucent quality that emulates enamel, and they are available in a wide range of shades (64). Ceramic wears well in the mouth, even when used for posterior teeth; because it is no more abrasive than conventional and hybrid posterior composite resins, it causes minimal wear to the opposing teeth (64).

The quality is consistent due to the prefabricated ceramic blocks which are free from internal defects, and the computer program is designed to produce shapes that will stand up to wear (67).

Savings in time and labor have the potential to reduce costs, and the promise of faster, high-quality restorations should appeal to patients (67). Patients are satisfied with digital technology as they are far from gag-inducing impressions. Another benefit is that all the scans can be stored on the computer whereas standard stone models take up space and can chip or break if stored improperly (68).

The digital systems are not free from drawbacks. The initial cost of the equipment and software is high, and the practitioner needs to spend time and money on training (64). Dentists without a large enough volume of restorations will have a difficult time making their investment pay off.

Just as with conventional impressions, in taking an optical scan, the dentist requires to achieve an accurate recording of the tooth to obtain a precise restoration (67). The scan needs to emphasize the finish line and duplicate the surrounding and occlusive teeth. Digital scanning requires the similar type of soft-tissue management, retraction, moisture control, and hemostasis that is extremely important for conventional impressions (67).

Digital impression systems may not save time as they are currently used because of the need for multiple steps. For example, dentists who use certain scanners must first send the images for a cleanup process, which is followed by setting of the margins by a dental technician. The images then sent to the clinician's dental laboratory for checking. Then a completed models and dies are then sent to the clinician's dental laboratory for fabrication process (69).

The absence of glass-ceramics in a disc form is a deficiency. Once it becomes available in disc form, the pressing technique will most likely vanish. In addition, additive technology is limited to polymeric and metallic materials and thus far does not include ceramics in dentistry. One more limitation is the limited full arch accuracy of digital impressions as compared with conventional impressions (70).

It has been noted that zirconia frameworks on teeth requiring longer curved frameworks are subjected to a greater sintering distortion than the shorter straight frameworks, which may potentially affect fit and adaptation. The zirconia frameworks exhibit accurate fit for partial arch prosthesis only (71).

Future implications of CAD/CAM technology

In the future, ultrasound impressions will be implemented using ultrasonic waves, which have the capability to penetrate the gingiva non-invasively without retraction cords and not be affected by saliva, sulcular fluid, and blood. This will lead to decisive advancements, as detailed cleaning and drying of the oral cavity and associated tooth structure will become unnecessary, as well as reducing treatment time and increasing patient comfort compared with optical impressions (72).

Conclusion

There are no doubts that treatment technologies and materials in dentistry have progressively advanced over the past 50 years, especially in the field of restorative dentistry and prosthodontics. CAD/CAM systems have progressed very rapidly in the past 25 years, where a variety of systems has been launched into the market. It can be used for multiple purposes in dentistry. It is predicted that CAD/CAM will undergo further development in the near future decades.

The evolution of developed versions will bring better quality, excellent ability and increase work procedure friendliness. Materials will be available with high mechanical and physical properties such as better esthetic, marginal integrity, wear resistance, and high strength which permit remaining for a long period in the oral environment. Additionally, dental CAD/CAM may also be available in educational settings and as training tools for daily dental practice, with explanatory materials for patients, diagnostic materials, and for simulations of surgical procedures.

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