Biotechnology & Biotechnological Equipment

ISSN: 1310-2818 (Print) 1314-3530 (Online) Journal homepage: https://www.tandfonline.com/loi/tbeq20

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To cite this article: G. Uzun (2008) An Overview of Dental CAD/CAM Systems, Biotechnology & Biotechnological Equipment, 22:1, 530-535, DOI: 10.1080/13102818.2008.10817506

To link to this article: https://doi.org/10.1080/13102818.2008.10817506

AN OVERVIEW OF DENTAL CAD/CAM SYSTEMS

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ABSTRACT

For 20 years, exciting new developments in dental materials and computer technology have led to the success of contemporary dental computer-aided design /computer-aided manufacturing (CAD/CAM) technology.
This article provides an overview of the status of current CAD/CAM systems, describes components of CAD/CAM technologies and suggests future possibilities.

Keywords: CAD/CAM, scanning software, dental materials, future trends

Introduction

Computer-aided design (CAD) and computer-aided manufacturing (CAM) technology systems use computers to collect information, design, and manufacture a wide range of products. With CAD/CAM, parts and components can be designed and machined with precision using a computer with integrated software linked to a milling device. This technology was introduced to dental community in the early 1980s. The earliest attempt to apply CAD/CAM technology to dentistry began in the 1970s with Bruce Altschuler, Francois Duret, Werner Mormann, and Marco Brandestini. Young and Altschuler (51) first introduced the idea of using optical instrumentation to develop an intraoral grid surface mapping system in 1977. The first commercially available dental CAD/CAM system was CEREC, developed by Mormann and Brandestini (25).

A dental restoration must fit its abutment within a 50 µm range (12). This requirement calls for the system to have a very accurate data collection technique, sufficient computing power to process and design complex restorations, and a very precise milling system.

During the last 2 decades, exciting new developments have led to the success of contemporary dental CAD/CAM technology. Several methods have been used to collect 3-dimensional data of the prepared tooth using optical cameras, contact digitization, and laser scanning. Replacement of conventional milling discs with a variety of diamond burs has resulted in major improvements in milling technology.

The hope and expectation was that automation could achieve the following:

- to produce higher- and more uniform-quality material by using commercially formed blocks of material;
- to standardize restoration-shaping processes;
- to reduce production costs.

The use of high-strength structural materials like alumina- and zirconia-based ceramics for restoration cores and frameworks, which can be shaped only by CAD/CAM systems, has both increased the lifetime of restorations and expanded the demand for CAD/CAM-produced restorations (16). As a result, the number of CAD/CAM systems currently available to the dental community has increased substantially within the last few years (14, 39, 49).

All CAD/CAM systems have three functional components: data capture or scanning to capture and record data about the oral environment (tooth preparation, adjacent teeth and occluding tooth geometry); CAD to design the restoration to fit the preparation and to perform according to conventional dental requirements; and CAM to fabricate the restoration.

Data Capture

Data capture differs remarkably between commercially available dental CAD/CAM systems (49). An intraoral digital 3-D scanning device (digitizer) is an integral component of the CEREC system (CEREC 3D, Sirona Dental Systems GmbH, Bensheim, Germany). The Evolution 4D system, currently under development by D4D Technologies (Richardson, Texas), also is expected to have intraoral data capture capabilities. Other commercially available CAD/CAM systems capture data from models, using mechanical or optical digitizers of various types. With few exceptions, these high-precision digitizers use technologies that prevent them from being used intraorally. Mechanical digitizers, for instance, must map the entire surface of a prepared tooth while accurately maintaining the relative position of the device to the tooth. Many optical digitizers are exceptionally sensitive to any motion. Slight movement of a patient during data acquisition with either of these types of scanner would compromise the quality of the data, ultimately leading to a restoration that would not fit. In most cases, the scanner used to capture data is an integral part of the CAD/CAM system and operates only in combination with dedicated CAD software.

Restoration Design

Several CAD software programs are available commercially for designing virtual 3-D dental restorations on a computer screen. Some of these programs can design restorations nearly matching the excellence of restorations produced by master dental technicians. The degree of interaction needed from the CAD/CAM system operator to design a restoration varies, ranging from substantial to no required user operations. Even in the most automated systems, the user generally has the option to modify the automatically designed restoration to fit his or her preferences. Like the data acquisition systems, the software programs usually are proprietary to the CAD/CAM system and can not be interchanged among systems. When the design of the restoration is complete, the CAD software transforms the virtual model into a specific set of commands. These, in turn, drive the CAM unit, which fabricates the designed restoration.

Restoration Fabrication

CAM uses computer-generated paths to shape a part. A diverse set of technologies has been used to create dental restorations. Early systems relied almost exclusively on cutting the restoration from a prefabricated block with the use of burs, diamonds or diamond disks (44). This approach, in which material is removed to create the desired shape, is termed a "subtractive method"; material is subtracted from a block to leave the desired shaped part (the restoration) (13). Subtractive fabrication can create complete shapes effectively, but at the expense of material being wasted. Approximately 90 percent of a prefabricated block is removed to create a typical dental restoration. As an alternative, "additive" CAM approaches like those used in rapid prototyping (also called "solid free-form fabrication") technologies are beginning to be used in dental CAD/CAM systems (26). Selective laser sintering is one of the technologies that can be used to fabricate either ceramic or metal restorations (Medifacturing, Bego Medical AG, Bremen, Germany; Hint ELs, Hint-ELs, Griesheim, Germany). In this method, the computer design of the part (the dental restoration) generates a path much like a cutting tool path in existing CAD/CAM systems. However, instead of cutting, the system sinters material along the path, building a part from a "bath" of ceramic or metal powder and adding material continually until the complex part is complete. No excess material remains. Some commercially available CAD/CAM systems use a combination of additive and subtractive CAM approaches. In one (Procera, Nobel Biocare, Göteburg, Sweden), an enlarged metal die first is milled based on the 3-D data for the prepared tooth with the use of the subtractive approach. (This enlargement takes into account shrinkage associated with sintering the final restoration to achieve its final strength.) Powder is compacted under pressure onto the metal die, creating an oversized block by means of an additive approach; the block then is milled away to create the outer contours of the restoration. The oversized restoration is removed from the die and sintered to make the material as dense as possible and to shrink it to its correct size. Another combined CAM approach (Wol-Ceram, Wol-Dent, Ludwigshafen, Germany) involves the path, building a part from a "bath" of ceramic or metal powder and adding material continually until the complex part is complete. No excess material remains. Another combined CAM approach (Wol-Ceram, Wol-Dent, Ludwigshafen, Germany) involves the application of a slurry of alumina powder directly to a master die using an additive electrophoretic dispersion method, which creates a coping. The operator trims away by hand excess material extending beyond the margin. The outer contour of the restoration is shaped using a subtractive CAM approach. The operator then removes the coping from the die and infiltrates glass. An additive approach also has been used to generate copings and frameworks for bridges from pure alumina oxide and zirconia-based ceramics with superfine nanodispered ceramic particles smaller than 100 nanometers (ce.inovation, Inocermic, Hermsdorf, Germany). This system is housed in a production center, and details of the fabrication have not been disclosed. Brick and colleagues (6) reported that it produces frameworks with high strength. A different additive rapid prototyping technique, 3-D printing, is being used to design and then print a wax pattern of a restoration (WaxPro printer of the Pro 50 system, Cynovad, Saint- Laurent, Quebec, Canada) (45). Operating like an inkjet printer, the machine builds wax patterns of frameworks and full crowns. The wax pattern subsequently is cast or pressed in the same manner as manually waxed restorations would be. An advanced printing unit (Cynovad) prints a resin-type material instead of the wax. This system has an expanded capability beyond that of most CAD/CAM systems for dental restorations; it also can be used to fabricate auricular prostheses (37).

Integration of these technologies has resulted in the introduction of several highly sophisticated CAD/CAM systems: CEREC3 and in lab DCS Precident; Procera; Lava; Cercon Smart C e r a m i c s ; Everest; Denzir; DentaCad; and Evolution D4D. CAD/CAM technology provides several advantages from the dental laboratory perspective. CAD/CAM systems offer automation of fabrication procedures with increased quality in a shorter period of time. Dental CAD/CAM systems have the potential to minimize inaccuracies in technique and reduce hazards of infectious cross-contamination associated with conventional multistage fabrication of indirect restorations. However, capital costs of these CAD/CAM systems are quite high and rapid large-scale production of good quality restorations is necessary to achieve financial viability.

CAD/CAM systems have been created for dental applications other than producing restorations. One system (SL, Perfactory, Envisiontec GmbH, Gladbeck, Germany) uses stereolithography, another additive process to produce 3-D dental components from acrylics (48). Three-dimensional occlusal splints and similar components are created by selectively light-curing sequential layers of acrylic monomer in a liquid. In addition, CAD/CAM systems have been developed to fabricate surgical templates (custom drill guides) to guide dental implant placement (31) (SurgiGuide, Materialise, Leuven, Belgium) and working models, permiting restorations to be inserted immediately after implants have been placed (41) (Nobel Guide software, Nobel Biocare). Both systems use data captured from computerized tomographic scans in conjunction with CAD software to determine the most ideal restoration placement, and CAM Technologies generate the templates and working models.

Restorative Materials for CAD/CAM

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. The combination of materials that can be used and restoration types that can be produced by different systems vary.

CAD/CAM systems based on machining of presintered alumina or zirconia blocks in combination with specially designed veneer ceramics satisfy the demand for all-ceramic posterior crowns and fixed partial dentures. Many ceramic materials are available for use as CAD/CAM restorations (**Table 1**). 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, great color stability, low thermal conductivity, and excellent wear resistance (24). They have been successfully used as inlays (28, 33), onlays (28), veneers (21), and crowns (3). However, Dicor and Vita Mark II are not strong enough to sustain occlusal loading when used for posterior crowns (19). For this reason, alumina and zirconia materials are now being widely used as dental restorative materials. These ceramic agents may not be cost-effective without the aid of CAD/CAM technology. For instance, In-Ceram l, first described by Sadoun and Degrange (30), has been shown to have good flexural strength and good clinical performance (29, 32). However, the manufacture of conventional In-Ceram restoration takes up to 14 hours (15). By milling copings from presintered alumina or zirconia blocks within a 20 minute period and reducing the glass infiltration time from 4 hours to 40 minutes, Cerec inLab decreases fabrication time by 90%. Zirconia is strong and has high biocompatibility. Fully sintered zirconia materials can be difficult to mill, taking 3 hours for a single unit. Compared with fully sintered zirconia, milling restorations from presintered or partially sintered solid blocks is easier and less time-consuming, creates less tool loading and wear, and provides higher precision. After milling, In-Ceram spinell, alumina, and zirconia blocks are glass infiltrated to fill fine porosities. Other machinable presintered ceramic materials are sintered to full density, eliminating the need for extensive use of diamond tools. Under stress the stable tetragonal phase may be transformed to the monoclinic phase with a 3% to 4% volume increase. This dimensional change creates compressive stresses that inhibit crack propagation. This phenomenon, called “transformation toughening”, actively opposes cracking and gives zirconia its reputation as the “smart ceramic.” The quality of transformation toughness and its affect 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. Conventional conditioning required by leucite ceramics (eg, hydrofluoric acid etch) is not needed. Microetching with Al2O3 particles on cementation surfaces removes contamination and promotes retention for pure aluminum oxide ceramic (1). Two *in vitro* studies recommended that a resin composite containing an adhesive phosphate monomer in combination with a silane coupling/bonding agent can achieve superior long-term shear bond strength to the intaglio surface of Procera AllCeram and Procera AllZirkon restorations (4, 5).

TABLE 1

Common Restorative Materials for Dental CAD/CAM Systems

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 Zirconia	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

CAD/CAM systems also can be applied to restorations requiring metal and are used to fabricate implant abutments and implant-retained overdenture bars. The DCS system can fabricate crown copings from titanium alloy with excellent precision (2).

Several articles have reported the extension of CAD/CAM technology to the fabrication of maxillofacial prostheses such as the artificial ear (7, 18, 40, 42).

Review of Common CAD/CAM Systems

CAD/CAM systems may be categorized as either in-office or laboratory systems. Among all dental CAD/CAM systems, Cerec is the only manufacturer that provides both in-office and laboratory modalities. Similar to Cerec is the Evolution D4D. Laboratory CAD/CAM systems have increased significantly during the last 10 years and include DCS Precident, Procera, Cerec inLab, and Lava. Cercon is a laboratory system that possesses only CAM capabilities without the design stage.

Business Models For Producing CAD/CAM Restorations

As might be expected, based on the number of CAD/CAM systems available and the broad range in size and cost, different business models for producing CAD/CAM restorations have emerged. These include in-office systems, dental laboratory systems, dental laboratories working in collaboration with a production center, and a network or open-concept business model.

In-office system model. The first, and so far only, commercially available in-office system is the Cerec system (Sirona). With this system, all three steps involved in the automated production of restorations can be accomplished in a dental office. The dentist can prepare a tooth and, by selecting appropriate materials, can fabricate a restoration and seat it within a single appointment. The supplement to this issue of JADA summarizes the evolution of this system and the performance of restorations produced by it as it reaches its 20th anniversary.

Dental laboratory. The dental laboratory model is similar to that used in producing conventional restorations. The dental office sends an impression or model of the prepared and opposing teeth to the laboratory, and the laboratory fabricates the restoration. The only difference with this CAD/CAM technology is that at least part of the fabrication is automated. Unfortunately, the cost of many of these CAD/CAM systems is high, often precluding all but a few of the largest laboratories from offering this service.

Dental laboratory–production center model. In the dental laboratory–production center model, the dental laboratory has the data acquisition and design software available to it (36). The laboratory technician scans models and designs the restorations, making optimal use of his or her skills. The laboratory sends the finished design to a production center, where it is converted into appropriate commands to drive the CAM component of a CAD/CAM system. This model minimizes the cost to the laboratory and has the potential to improve fabrication efficiencies.

Network or open-concept model. The network or open-concept model is similar to the dental laboratory–production center model, but in this model multiple commercial laboratories and/or production centers collaborate. The dental laboratories have data acquisition and design capabilities and the production center and/or other dental laboratories have the CAM capabilities. In general, only limited types of materials can be fabricated with any one CAM system. With this network model, greater flexibility with regard to material choices is possible; the same restoration design can be produced from a broader array of materials. In the most open concept, a standard file format (similar to that used in solid free-form fabrication) facilitates transfer of design data to any number of different CAM systems, permitting interesting and more flexible material choices and pricing strategies. Only a few manufacturers of digitizers and software programs offer networking or openconcept possibilities. Most dental CAD/CAM systems operate as closed-data systems. That is, all components are linked by a unique data format, precluding data from one system from being used to shape a restoration with a different system (46, 47). The notable exceptions are the ZENO Tec (Wieland Dental+Technik GmbH, Pforzheim, Germany) and Hint ELs (Hint-ELs) systems.

CAD/CAM Systems of the Future

No automated system currently offers the flexibility with regard to restoration types and material choices that is possible with traditional fabrication methods. However, new and emerging technologies will continue to push the boundaries we face today. An emphasis on intraoral data acquisition scanners and digitizers is likely. This could lead ultimately to the elimination of impressions and stone models. It is likely that future digitizers or scanners will be more robust, facilitating accurate data capture despite the differences in foundation restorations within teeth, as well as differences in saliva and soft tissue. This means that data pertaining to the prepared, adjacent and opposing teeth could be sent directly to a CAD/CAM system without being interpreted by a technician or clinician. CAD software is relatively mature and probably will not change dramatically. However, likely enhancements may include a simpler user interface and integration of virtual articulators, which would facilitate automatic design of the occlusal surface.

The CAM component of dental CAD/CAM systems likely will undergo the most remarkable changes. A major challenge that has not been addressed completely in existing systems is the completely automated, economical, high-precision production of restorations. Highspeed machining is being adapted, permitting faster removal of material. This reduces machining time and could reduce production costs. Femtosecond lasers have been introduced for cutting dental materials, including zirconiabased ceramics (43). Direct shell production uses a rapid prototyping process similar to selective laser sintering to create ceramic investments in the shape needed, without a wax pattern (50).

Other systems may shape parts using additive techniques such as selective laser sintering, stereolithography and 3-D printing, as described above. Another rapid prototyping approach that has shown much promise is direct-write assembly (34). With this system, the material from which the part is made is incorporated into special inks. The ink is delivered through specialized nozzles along the "tool path," defining the designed restoration to create the complex 3-D part. As the ink leaves the nozzle, it freezes instantaneously into the desired shape; however, for high-strength parts such as ceramic dental restorations, the materials need to be made more dense. This technology could expand the breadth of material choices, eliminate damage induced during subtractive shaping operations and minimize the amount of material needed to produce a restoration.

One limitation of current CAD/CAM systems is their inability to incorporate esthetic veneers with strong (but relatively unesthetic) cores and frameworks. Lasers have been shown to sinter translucent veneering silicate ceramics after they have been applied to a core using a plotter system and direct shell production casting (50). Other approaches such as direct-write assembly also may be able to improve esthetics by applying an esthetic outer layer onto a strong core layer within a single additive CAM process. Many new technologies are being applied in industrial fields, resulting in the creation of complex 3-D parts from an array of materials. In the future, practical application of these technologies to dentistry may provide unexpected paradigm shifts in fabrication approaches and materials options.

As more scanning and fabrication technologies are introduced to fabricate restorations, it is likely that more cooperative networks and open systems will be used (47). People with special expertise may be required to select and combine the components of open CAD/CAM systems. Informed decisions will be needed to optimize the choice of materials, hardware for shaping the materials and specific dental indications.

Marginal Integrity of CAD/CAM Restorations

One of the most important criteria in evaluating fixed restorations is marginal integrity. Evaluating inlay restorations, Leinfelder and colleagues reported that marginal discrepancies larger than 100 µm resulted in extensive loss of the luting agent (20). O'Neal and colleagues (27) reported the possibility of wear resulting from contact of food particles with cement when gap dimension exceeded 100 µm. Essig and colleagues (11) conducted a 5-year evaluation of gap wear and reported that vertical wear is half of the horizontal gap. The wear of the gap increased dramatically in the first year, becoming stable after the second year. McLean and Von Fraunhofer (23) proposed that an acceptable marginal discrepancy for full coverage restorations should be less than 120 µm. Christensen (9) suggested a clinical goal of 25 µm to 40 µm for the marginal adaptation of cemented restorations. However, most clinicians agree that the marginal gap should be no greater than 50 µm to 100 µm (8, 17, 35). Current research data indicate that most dental CAD/CAM systems are now able to produce restorations with acceptable marginal adaptation of less than 100 µm (10, 22, 38).

Conclusions

CAD/CAM systems have enhanced dentistry by providing high-quality restorations. The evolution of current systems and the introduction of new systems demonstrate increasing user friendliness, expanded capabilities, and improved quality, and range in complexity and application. New materials also are more esthetic, wear more nearly like enamel, and are strong enough for full crowns and bridges. Existing CAD/CAM systems vary dramatically in their capabilities, each bringing distinct advantages, as well as limitations. None can yet acquire data directly in the mouth and produce the full spectrum of restoration types (with the breadth of material choices) that can be created with traditional techniques. Emerging technologies may expand the capabilities of future systems, but they also may require a different type of training to use them to their full capacity.

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