

A Panorama of Dental CAD/CAM Restorative Systems

CE 3

Abstract: *In the last 2 decades, 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. Several highly sophisticated chairside and laboratory CAD/CAM systems have been introduced or are under development. This article provides an overview of the development of various CAD/CAM systems. Operational components, methodologies, and restorative materials used with common CAD/CAM systems are discussed. Research data and clinical studies are presented to substantiate the clinical performance of these systems.*

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Computer-aided design (CAD) and computer-aided manufacturing (CAM) technology systems use computers to collect information, design, and manufacture a wide range of products. These systems have been in general use in industry for many years, but dental CAD/CAM applications were not available until the 1980s. The earliest attempt to apply CAD/CAM technology to dentistry began in the 1970s with Bruce Altschuler, DDS, in the United States, Francois Duret, DDS, MD, in France, and Werner Mormann, BMD, DDS, and Marco Brandestini, PhD, in Switzerland.

Young and Altschuler first introduced the idea of using optical instrumentation to develop an intraoral grid surface mapping system in 1977.¹ In 1984, Duret developed the Duret system, which was later marketed as the Sopha Bioconcept system^a, demonstrating the ability of CAD/CAM to generate single-unit, full-coverage restorations. However, this system was not successful in the dental market because of its complexity and cost. The first commercially available dental CAD/CAM system was CEREC^b, developed by Mormann and Brandestini.

The American Dental Association specifies that a dental restoration must fit its abutment within a 50 μm range.² 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. Another vital factor has been the development of alumina (aluminum oxide) and zirconia (zirconium oxide) ceramic materials, which possess excellent machinability and physical strength.

Integration of these technologies has resulted in the introduction of several highly sophisticated CAD/CAM systems: CEREC 3D^b and inLab^b; DCS

Learning Objectives:

After reading this article, the reader should be able to:

- describe the current status of CAD/CAM systems.
- discuss the advantages of using dental CAD/CAM technology.
- discuss the various materials available for CAD/CAM restorations.
- explain the fundamentals of common CAD/CAM systems.

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Table 1—Common Restorative Materials for Dental CAD/CAM System

Restorative Material	CAD/CAM System	Indications	Adhesive Cementation	Conventional Cementation	Flexural Strength
Dicor MCG (fluor mica)	Cerec	Inlays, onlays, veneers	Yes, dual-cured	No	< 100 MPa
Vita Mark II (feldspathic)	Cerec	Inlays, onlays, veneers, anterior crowns	Yes, dual-cured	No	150 MPa ^a
ProCAD (leucite-reinforced)	Cerec	Inlays, onlays, veneers, anterior crowns	Yes, dual-cured	No	150 MPa ^a
In-Ceram Spinell (magnesium oxide)	Cerec 3D, Cerec inLab	Anterior crowns	Yes, self-cured	Yes	350 MPa ^a
In-Ceram Alumina (aluminum oxide)	Cerec 3D, Cerec inLab, DCS Precident	Crowns and anterior bridges	Yes, self-cured	Yes	500 MPa ^a
Alumina (aluminum oxide)	Procera	Crown and bridge	Yes, self-cured	Yes	600 MPa ^a
In-Ceram Zirconia (zirconium oxide)	Cerec 3D, Cerec inLab, DCS Precident	Crown and bridge	Yes, self-cured	Yes	750 MPa ^a
Partially sintered zirconia (zirconium oxide)	DCS Precident, Lava, Procera, Everest, Cercon	Crown and bridge	Yes, self-cured	Yes	>1,000 MPa ^a
Fully sintered zirconia (zirconium oxide)	DCS Precident, Everest	Crown and bridge	Yes, self-cured	Yes	>1,000 MPa ^a

Precident^c; Procera^d; Lava^e; Cercon Smart Ceramics^f; Everest^g; Denzir^h; DentaCadⁱ; and Evolution D4Dⁱ.

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.

Restorative Materials for CAD/CAM

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 materi-

als used in earlier dental CAD/CAM restorations have been machinable glass ceramics such as Dicor^k or Vita Mark II^l. Although monochromatic, these ceramic materials offer excellent esthetics, biocompatibility, great color stability, low thermal conductivity, and excellent wear resistance (Figure 1).³ They have been successfully used as inlays,^{4,5} onlays,⁵ veneers,⁶ and crowns.⁷ However, Dicor and Vita Mark II are not strong enough to sustain occlusal loading when used for posterior crowns.⁸ 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-Ceram¹, first described by Degrange and Sadoun,⁹ has been shown to have good flexural strength and good clinical performance.^{10,11} However, the manufacture of conventional In-Ceram restoration takes up to 14 hours.¹² 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

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^kDentsply Caulk, Milford, DE 19963; (800) 532-2855

^lVident, Bera, CA 92821; (800) 828-3839



Figure 1—
Ten-year follow-up for a ceramic inlay.

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 Al_2O_3 particles on cementation surfaces removes contamination and promotes retention for pure aluminum oxide ceramic.¹³ 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.^{14,15}

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.¹⁶ Several articles have reported the extension of CAD/CAM technology to the fabrication of maxillofacial prostheses such as the artificial ear.¹⁷⁻²⁰

Review of Common CAD/CAM Systems

CAD/CAM systems may be categorized as either in-office or laboratory systems (Table 2). 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 President, Procera, CEREC inLab, and Lava. Cercon is a laboratory system that possesses only CAM capabilities without the design stage. Several of the more common dental CAD/CAM systems are described below.

CEREC

With CEREC 1 and CEREC 2, an optical scan of the prepared tooth is made with a couple charged device (CCD) camera, and a 3-dimensional digital image is generated on the monitor. The restoration is then designed and milled. With the newer CEREC 3D, the operator records multiple images within seconds, enabling clinicians to prepare multiple teeth in the same quadrant and create a virtual cast for the entire quadrant. The restoration is then designed and transmitted to a remote milling unit for fabrication. While the system is milling the first restoration, the software can virtually seat the restoration back into the virtual cast to provide the adjacent contact while designing the next restoration.

CEREC inLab is a laboratory system in which working dies are laser-scanned and a digital image of the virtual model is displayed on a laptop screen. After designing the coping or framework, the laboratory technician inserts the appropriate VITA In-Ceram block into the CEREC inLab machine for milling. The technician then verifies the fit of the milled coping or

Table 2—Comparison of Common Dental CAD/CAM Systems

System	Market Launch	Process Center	Scanning Mechanism	CAD Program	CAM Process
Cerec 3	2000	Chairside	Optical	Yes, custom design and database	Fully automatic
Cerec inLab	2001	Dental lab	Laser	Yes, custom design and database	Fully automatic
DCS Precident	1989	Dental lab	Optical	Yes, custom design and database	Fully automatic
Procera	1993	New Jersey or Sweden	Manual	Yes, custom design and database	Fully automatic
Lava	2002	Dental lab	Optical	Yes, custom design and database	Fully automatic
Everest	2002	Dental lab	Optical	Yes, custom design and database	Fully automatic
Cercon	2001	Dental lab	Laser	No	Fully automatic

framework. The coping or framework is glass infiltrated and veneering porcelain is added.

One recent in vitro evaluation of CAD/CAM ceramic crowns that compared the marginal adaptation of CEREC 2 with CEREC 3D concluded that crown adaptation for CEREC 3D ($47.5 \pm 19.5 \mu\text{m}$) was significantly better compared with CEREC 2 ($97.0 \pm 33.8 \mu\text{m}$).²¹

DCS Precident

The DCS Precident system is comprised of a Preciscan laser scanner and Precimill CAM multitool milling center. The DCS Dentform software automatically suggests connector sizes and pontic forms for bridges. It can scan 14 dies simultaneously and mill up to 30 framework units in 1 fully automated operation. Materials used with DCS include porcelain, glass ceramic, In-Ceram, dense zirconia, metals, and fiber-reinforced composites. This system is one of the few CAD/CAM systems that can mill titanium and fully dense sintered zirconia.

An in vitro study was conducted evaluating the marginal fit of alumina- and zirconia-based 3-, 4- and 5-unit posterior fixed partial dentures machined by the DCS Precident system. Measuring marginal discrepancies between $60 \mu\text{m}$ and $70 \mu\text{m}$, they concluded that the system easily met the requirement of less discrepancy than $100 \mu\text{m}$.²² Another study evaluated the DCS system for fabricating titanium copings. The mean values of marginal fit for the individual crowns ranged from $21.2 \pm 14.6 \mu\text{m}$ to $81.6 \pm 25.1 \mu\text{m}$. The mean value for all crowns was $47.0 \pm 31.5 \mu\text{m}$.¹⁶

Procera

Procera/AllCeram was introduced in 1994 and according to company data, has produced 3 million units as of May 2004. Procera uses an

innovative concept for generating its alumina and zirconia copings. First, a scanning stylus acquires 3D images of the master dies that are sent to the processing center via modem. The processing center then generates enlarged dies designed to compensate for the shrinkage of the ceramic material. Copings are manufactured by dry pressing high-purity alumina powder (>99.9%) against the enlarged dies. These densely packed copings are then milled to the desired thickness. Subsequent sintering at $2,000^\circ\text{C}$ imparts maximum density and strength to the milled copings. The complete procedure for Procera coping fabrication is very technique-sensitive because the degree of die enlargement must precisely match the shrinkage produced by sintering the alumina or zirconia.

According to recent research data, the average marginal gap for Procera/AllCeram restorations ranges from $54 \mu\text{m}$ to $64 \mu\text{m}$.²³ Literature also confirms that Procera restorations have excellent clinical longevity and strength.²⁴ The flexural strength for Procera alumina is 687 MPa and for zirconia is 1200 MPa. Procera also is capable of generating AllCeram bridge copings. However, the occlusal-cervical height of the abutment should be at least 3 mm and the pontic space should be less than 11 mm. The recommended preparation marginal design for Procera is a deep chamfer finish line with a recommended coping thickness of 0.4 mm to 0.6 mm.

Lava

Introduced in 2002, Lava uses a laser optical system to digitize information from multiple abutment margins and the edentulous ridge. The Lava CAD software automatically finds the margin and suggests a pontic. The framework is designed to be 20% larger to compensate for sintering shrinkage. After the design is complete, a

properly sized semisintered zirconia block is selected for milling. The block is bar coded to register the special design of the block. The computer-controlled precision milling unit can mill out 21 copings or bridge frameworks without supervision or manual intervention. Milled frameworks then undergo sintering to attain their final dimensions, density, and strength. The system also has 8 different shades to color the framework for maximum esthetics.

Hertlein and colleagues tested the marginal adaptation of yttria zirconia bridges processed with the Lava system for 2 milling times (75 minutes vs 56 minutes). They concluded that the milling time does not affect the marginal adaptation ($61 \pm 25 \mu\text{m}$ vs $59 \pm 21 \mu\text{m}$) for 3-unit zirconia bridge frameworks.²⁵

Everest

Marketed in 2002, the Everest system consists of scan, engine, and therm components. In the scanning unit, a reflection-free gypsum cast is fixed to the turntable and scanned by a CCD camera in a 1:1 ratio with an accuracy of measurement of $20 \mu\text{m}$. A digital 3D model is generated by computing 15 point photographs. The restoration is then designed on the virtual 3D model with Windows-based software. Its machining unit has 5-axis movement that is capable of producing detailed morphology and precise margins from a variety of materials including leucite-reinforced glass ceramics, partially and fully sintered zirconia, and titanium. Partially sintered zirconia frameworks require additional heat processing in its furnace.

Cercon

The Cercon System is commonly referred to as a CAM system because it does not have a CAD component. In this system, a wax pattern (coping and pontic) with a minimum thickness of 0.4 mm is made. The system scans the wax pattern and mills a zirconia bridge coping from presintered zirconia blanks. The coping is then sintered in the Cercon heat furnace ($1,350^\circ\text{C}$) for 6 to 8 hours. A low-fusing, leucite-free Cercon Ceram S veneering porcelain is used to provide the esthetic contour. In an in vitro study the marginal adaptation for Cercon all-ceramic crowns and fixed partial dentures was reported as $31.3 \mu\text{m}$ and $29.3 \mu\text{m}$, respectively.²⁶

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 $100 \mu\text{m}$ resulted in extensive loss of the luting agent.²⁷ O'Neal and colleagues reported the possibility of wear resulting from contact of food particles with cement when gap dimension exceeded $100 \mu\text{m}$.²⁸ Essig and colleagues 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.²⁹

McLean and Von Fraunhofer proposed that an acceptable marginal discrepancy for full coverage restorations should be less than $120 \mu\text{m}$.³⁰ Christensen³¹ suggested a clinical goal of $25 \mu\text{m}$ to $40 \mu\text{m}$ for the marginal adaptation of cemented restorations. However, most clinicians agree that the marginal gap should be no greater than $50 \mu\text{m}$ to $100 \mu\text{m}$.³²⁻³⁴ Current research data indicate that most dental CAD/CAM systems are now able to produce restorations with acceptable marginal adaptation of less than $100 \mu\text{m}$.^{21-23,25,26}

Conclusion

CAD/CAM systems have dramatically 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.

Dental CAD/CAM technology is successful today because of the vision of many great pioneers. As Duret concluded in his article in 1991, "The systems will continue to improve in versatility, accuracy, and cost effectiveness, and will be a part of routine dental practice by the beginning of the 21st century."³⁵

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Quiz 3

- The American Dental Association specifies that a dental restoration must fit its abutment within what range?**
 - 25 μm
 - 50 μm
 - 100 μm
 - 150 μm
- The phenomenon called “transformation toughening” actively opposes cracking and gives which material its reputation as the “smart ceramic”?**
 - metal
 - aluminum oxide
 - zirconia
 - leucite-reinforced ceramic
- Conventional conditioning (eg, hydrofluoric acid etch) is required by:**
 - leucite ceramics.
 - aluminum oxide.
 - zirconium oxide.
 - In-Ceram spinell.
- With CEREC 1 and CEREC 2, what type of scan of the prepared tooth is made with a couple charged device (CCD) camera?**
 - contact digitizing
 - optical
 - computed tomography
 - laser digitizing
- With the newer CEREC 3D, the operator records multiple images within seconds, enabling clinicians to:**
 - generate inlay bridges.
 - create immediate temporaries.
 - generate veneer bridges.
 - prepare multiple teeth in the same quadrant.
- Materials used with DCS Precident include:**
 - porcelain.
 - metals.
 - fiber-reinforced composites.
 - all of the above
- For the Procera process, copings are manufactured by:**
 - making a silicone impression for a master cast.
 - computerized subsurface digitization.
 - waxing the prosthesis.
 - dry pressing high purity alumina powder against enlarged dies.
- Procera is capable of generating AllCeram bridge copings, and the pontic space should be less than:**
 - 4 mm.
 - 7 mm.
 - 11 mm.
 - 14 mm.
- In the Everest system, partially sintered zirconia frameworks require:**
 - traditional impressions.
 - additional heat processing.
 - wear of milling unit.
 - added cost.
- The Cercon system is commonly referred to as a:**
 - CAM system.
 - CAD system.
 - CAD/CAM system.
 - sintering system.

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