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Digital Data Management for CAD/CAM Technology. An Update of Current Systems.

M. Andreiotelli*, P. Kamposiora† and G. Papavasiliou†

Abstract - *Computer-aided design/computer-aided manufacturing (CAD/CAM) technology continues to rapidly evolve in the dental community. This review article provides an overview of the operational components and methodologies used with some of the CAD/CAM systems. Future trends are also discussed. While these systems show great promise, the quality of performance varies among systems. No single system currently acquires data directly in the oral cavity and produces restorations using all materials available. Further refinements of these CAD/CAM technologies may increase their capabilities, but further special training will be required for effective use.*

KEY WORDS: CAD/CAM, scanning software, hardware, digitizing, dental materials.

INTRODUCTION

Nowadays, in the search for the ultimate aesthetic restorative material, there has been increasing emphasis on the use of metal-free prosthetic restorations. New high-strength ceramic materials have been at the forefront of indirect restorations [1-3]. These materials cannot be managed with conventional dental processing methods and new sophisticated fabrication technologies have been developed [4].

Computer-aided design/computer-aided manufacturing (CAD/CAM) was introduced to dentistry in the early 1970s and commercialized by 1990. Several research teams have worked to automate manual processes in dental technology in order to obtain higher material quality and accelerate fabrication. The first key steps were done by shifting to commercially formed blocks of material, standardizing the manufacturing process and minimizing technician intervention. This has also reduced production costs [5].

The earliest proposal to apply CAD/CAM technology to dentistry occurred in the 1970s with Bruce Altschuler in the United States. Similar efforts were occurring in Europe with Francois Duret, in France, and Werner Mörmann and Marco Brandestini, in Switzerland. Young and Altschuler introduced the idea in 1977 of optical techniques to capture three-dimensional information (3D) by using an intraoral grid projected on surfaces to map dental structures [6]. In 1984, Duret introduced a complete CAD/CAM to dentistry (the Duret system) [7]. His idea assumed that established technologies in other industries could be easily transferred to dentistry. The Duret system was not successful in the dental market, due to its complexity and high costs. Furthermore, in dental medicine the restorations are designed as one-of-a-kind because of the uniqueness of the individual patient [4]. In contrast, commercial operations involve mass production and shapes are represented using functional equations. For each unique dental situation, the numerical representation of the shape of a crown or FPD is complex.

The first commercially available dental CAD/CAM system, CEREC, was developed by Mörmann and Brandestini [8]. It was challenged by the requirements for expensive computer support. The evolution of high-power personal computers in the mid-1990s permitted rapid development of 3-D scanning and CAD technology in dentistry. CAD/CAM systems have continued to increase with each new system adopting the latest higher speed technologies. There are always others in the pilot stage [9]. The acronym CAD/CAM came from machine-tool technology. CAD (computer assisted design) designated the three-dimensional planning of a work piece on the screen of a computer. CAM (computer assisted manufacture) was the subsequent automated production by a computer controlled machine tools [4]. All CAD/CAM systems consist of three functional components: (1) mechanical or optical data capture or scanning; (2) CAD to design the restoration; and (3) CAM to fabricate the restoration [5]. Manufacturing only systems are simply designated as CAM systems [10].

The extent to which materials were available for fabrication by CAD/CAM techniques influenced which systems could be used. The purpose of this review is to provide an overview of all current commercial CAD/CAM systems and focus on the way data is scanned and transformed into a virtual 3-D object. Several popular 3D dental digital scanning systems are presented as examples and reviewed in further detail.

An overview of dental CAD/CAM

A great variety of CAD/CAM systems have been employed for fabricating restorations such as inlays, onlays, veneers, crowns and bridges (Fig. 1). They also have been involved in fabricating restorations requiring metal substructures, implant abutments, and implant-retained over-denture bars[11]. Finally, they have been used to fabricate surgical templates to guide dental implant placement and working

* DDS, Dr Med Dent
† DDS, MSc, PhD

Table 1. *Comparison of common CAD/CAM systems (Ve: veneers, In/On.: Inlays/Onlays, Cr.: single crowns, Br.: bridges, other ceram.: other ceramics, compos.: composites, *: information not available)*

CAD/CAM System (manufacturer, website)	*Digitizing method*	*Process center*	*Restoration type*				*Material*				
			Ve.	*In./On.*	*Cr.*	*Br.*	*Al_2O_3*	*ZrO_2*	*Other ceram*	*Metal alloys/Ti*	*Compos/ Acrylic/ Others*
CadentiTero® (Cadent, NJ-Carlstadt) www.cadent.biz	Laser	Chairside/ Dental lab	x	x	x	x	-	*	*	*	*
CEREC AC®/inLab® (Sirona, D-Bensheim) www.sirona.de	CCD/ laser	Chairside/ Dental lab	x	x	x	x	x	x	x	-	x
Cercon® (Degudent, D- Frankfurt) www.degudent.de	CCD/ laser	Dental lab	-	-	x	x	-	x	-	-	-
Decim® (Cad. esthetics AB, SE-Skellefteá) www.esthetics.com	Optical	Dental lab	-	x	x	x	-	x	-	-	-
Evolution 4D™ (D4D Technologies, TX-Richard-son) www.d4dtech.com	Laser	Chairside/ Dental lab	x	x	x	-			x		
Etkon® (etkon AG, D- Gräfelfingen) www.etkon.de	PSD/laser	Dental lab	-	-	x	x	x	x	-	x	x
Everest® (Kavo, D- Leutkirch) www.kavo-everest.com	CCD/ White light	Dental lab	x	x	x	x	x	x	x	x	x
GN-1 (GC Internatio-nal, JP-Tokyo) www.gcdental.co.jp	PSD/laser	Dental lab	-	-	x	x	x	x	x	x	x
Hint ELs DentaCAD system® (Hint-ELs, D-Griesheim) www.hintel.de	CCD/ White light	Chairside/ Dental lab	-	-	x	x	x	x	-	x	x
KATANA System® (Noritake dental supply co., LTD, Japan) www.noritake-dental.com.jp	CCD/ laser	Dental lab	-	-	x	x	-	x	-	-	-
Lava® (3M ESPE, D-Seefeld) www.3mespe.de	CCD/ White light	Chairside/ Dental lab	-	-	x	x	-	x	-	-	-
Medifacturing® (BEGO Medical AG, D-Bremen) www.bego-medical.de	Laser	Dental lab	-	-	x	x	-	x	-	x	-
Precident DCS® (DCS AG, SE-Allschwil) www.dcs-dental.com	PSD/laser	Dental lab	-	-	x	x	x	x	x	x	x
Procera® (Nobel Biocare, SE-Göteburg) www.nobelbiocare.com	Touch probe	New Jersey or Sweden	x	-	x	x	x	x	-	x	-
Pro 50, Wax Pro® (Cynovad, Qc-Sain-Laurent) www.cynovad.com	CCD/ Color light	Dental lab	x	x	x	x	x	x	x	x	x
Wol-Ceram® (Wol-Dent, D-Ludwigshafen) www.wolzdental.com	Laser	Dental lab	-	-	x	x	x	-	-	-	-
Zeno® Tec System (Wieland Dental+Technik GmbH, D-Pforzheim) www.wieland-dental.de	CCD/ laser	Dental lab	-	-	x	x	-	x	-	x	x

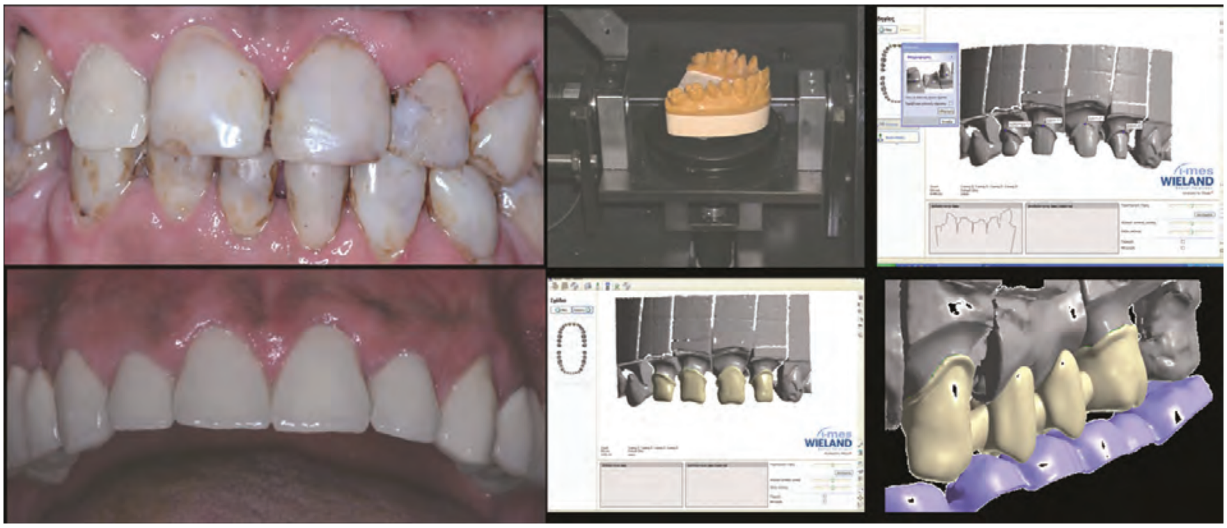

Figure 1. *A CAD/CAM-produced zirconia based restoration (Zeno® Tec system, Wieland Dental+Technik GmbH, D-Pforzheim) (photographs reproduced with the permission of Dr. G. Papavasiliou).*

models, permitting restorations to be inserted immediately after implant placement [12].

Today, materials available for use with the current CAD/CAM systems include silicate ceramics, glass-infiltrated aluminium oxide ceramics, densely sintered aluminium oxide ceramics, densely sintered zirconium dioxide ceramics, titanium; precious and non-precious metal alloys, acrylics, and wax. Material options and restoration types vary for different systems. An overview of the current dental CAD/CAM systems and applications is presented in Table 1.

CAD/CAM systems are mainly categorized as either in-office or laboratory ones[13]. For in-office systems, all three key steps involved for automated production of restorations are accomplished in a dental office (i.e. Cerec®, E4D system®). For laboratory based systems, a process similar to that used for conventional restorations is followed. An impression of the prepared and opposing teeth is sent to the laboratory and master models are poured. Most of the systems use stone models. Some systems scan stereolithographic models (Lava C.O.S® and Cerec Connect®) or polyurethane models (Cadent iTero®). The models are digitally scanned to create copies onto which the restorations are made. In such cases only part of the fabrication is automated via CAD/CAM technology (i.e. DCS President, Cerec inLab, Everest, Lava). There are also laboratory systems that work in concert with a production center (Bego Medical; Decim; etkon; Nobel Biocare; infiniDent Cynovad; Inocermic). Finally there are systems that work within a network or an open-concept business model. The technician sends via e-mail the design of the restoration to a production center, where a CAM component of a CAD/CAM system is situated (Bego Medical; Cad.esthetics; etkon; ZFN-CAM, Workstation (Medical Solutions, Essen, Germany)). This model minimizes the cost to the laboratory and has the potential to improve fabrication quality [5]. It should be recognized that some manual finishing is still required for all materials and systems used.

Among all dental CAD/CAM systems, CEREC (Sirona Dental Systems GmbH, Bensheim, Germany) provides options for either in-office and laboratory modalities (Fig. 2a,b, 3) [8, 14]. Similar to CEREC is the Evolution D4D system (D4D Technologies, Richardson, Texas), the 3M ESPE Lava Chairside Oral Scanner C.O.S. (3M Espe, Seefeld, Germany) and the Cadent iTero (Cadent, Carlstadt, New Jersey).

Most CAD/CAM systems operate as proprietary systems in which all components (such as the scanner, the CAD and the CAM units) are linked by the specific data format of the manufacturer. Only certain materials can be used for producing the restorations

Few CAD/CAM systems operate with an open format that allows 3-D volume information for the design to be transferred from CAD to CAM in a neutral format. An open format (such as stereo lithography) permits choice then among final production centers and CAM systems [10]. Examples include the ZENO Tec (Wieland Dental+Technik GmbH, Pforzheim, Germany) and the Hint ELs (Hint-Els) systems.

Data capture / Data digitizing

The quality of the 3-D image of the prepared tooth, accuracy of the design sequence, and the milling sequence all significantly influence the internal and marginal accuracy of the final machined restoration. It is possible to obtain precise results with a CAD/CAM system if all three dimensions (x,y,z) of the image matrix are of uniform quality[10].

Most commercially available CAD/CAM systems for fabricating crowns and FPDs use a stone model as their starting point. Different tools can be used to obtain the digital image that represents the morphology of the target tooth. These are called digitizers and scanners [15]. The most common approach involve a contact probe [16], a laser displacement gauge, or a line laser beam with a CCD (charge coupled device) camera. Their operational characteristics preclude using them intraorally. Digital 3-D scanning devices fall into three groups:

Mechanical scanners. These systems detect the surface of the prepared tooth on the die, using a sphere (Procera), needle, or pin (Precident DCS) [17] (Fig. 4). The latter will not capture undercuts of the surface. The process is time-consuming and results in an irregular data distribution of the image matrix.

Optical scanners. Optical reading of a die surface is possible using a white or colored light laser-beam.[18] (i.e. Cercon®, Everest®, Lava®) To access the whole surface of the object with its undercuts, the mounted die must be tilted and rotated. Different measurements are overlapped and superimposed to stitch them together into a final image matrix.

Figure 2. *The Cerec® AC imaging unit.* **(2a)** *BlueCam camera (which uses a shorter wavelength blue light source via active triangulation sampling) and separate milling unit MC XL.* **(2b)** *Image of the prepared tooth captured using the Cerec AC BlueCam camera (figures retrieved from promotional site on Internet).*

Intraoral scanner. Single optical scans of the prepared tooth and the anatomic structures of adjacent teeth can be captured, provide a digital image (i.e. Cerec 3D, Vincron, Evolution 4D). In the improved version of Cerec 3 several images of the prepared tooth can be captured, overlapped, and stitched together into one digital image of the surface [19]. (Fig. 2b, 5, 6b)

For occlusal reference most systems digitize a check bite registration. For FPD frameworks data from the neighbouring teeth and antagonists, as well as from the special relation of the prepared teeth to one another, are scanned as well for a path of insertion to be produced. In some systems, the occlusion is modeled (designed) freely on the screen by choosing the anatomic form from a library and stretching it onto the virtual die [10].

The quality of the digitizers of the Procera, DigiDent and Cerec systems has been examined in several studies [16-18]. Systems differ in their scanning requirements, the time needed for a measurement, the detection of the preparation line, and the indications for different restorations to be fabricated. According to Witkowski [10] the main performance criteria of a scanner are summarized in Table 2.

Advantages vs. disadvantages of intraoral scanners

In-office digital impression devices are becoming more widespread and popular in the dental market with new ones in the near future. These include Cadent iTero (Carlstadt, N.J.), Hint-ELs directScan system (Hint-Els GmbH, Griesheim, Germany) and the 3M ESPE Lava Chairside Oral Scanner C.O.S. (St. Paul, Minn.). Manufacturers of computer-directed in-office milling systems CEREC (Sirona Dental Systems, Charlotte, N.C.) and the new E4D system (D4D Technologies, Richardson, Texas) are already working on the field of digital impressions [20].

The CEREC system has enjoyed success for more than three decades and has been continually improved in terms of both apparatus and software. Extensive studies have been published on this system and include satisfactory long-term results [21-23]. The most recent iteration of the system

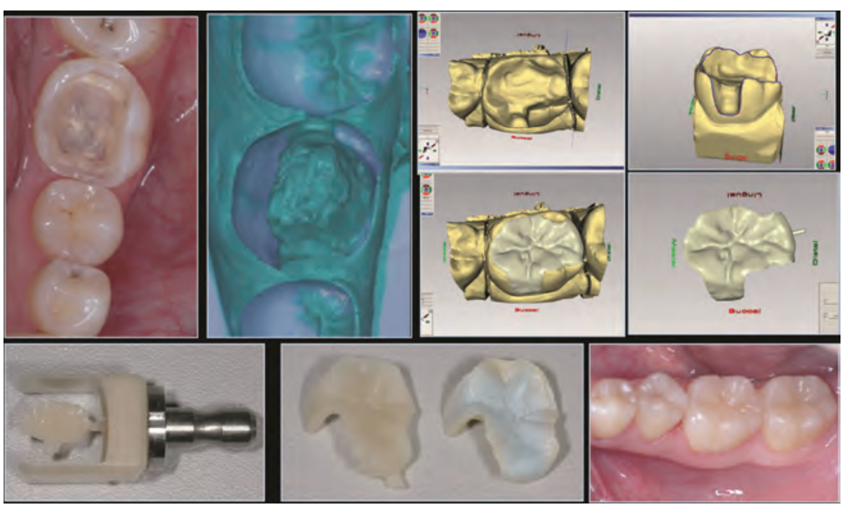

Figure 3. *Case presentation of an onlay ceramic restoration designed and manufactured with CEREC inLab® CAD/CAM system. The whole procedure is demonstrated step-to-step (tooth preparation, elastomeric impression, screen shot of the onlay preparation, design and milling of the onlay, final cementation) (photographs reproduced with the permission of Dr. G. Papavasiliou).*

Figure 4. *Currently available digitizing method using a contact probe (figure retrieved from promotional site on Internet).*

Figure 6. *Lava Chairside Oral Scanner (C.O.S).* **(6a)** *Note the absence of a keyboard. Data entry is done via touch-screen.* **(6b).** *The Lava C.O.S camera employs the smallest wand among currently available chair side CAD/CAM systems (figures retrieved from promotional site on Internet).*

Figure 5. *E4D imaging unit and IntraOral digitizer (not requiring a reflective powder in most cases) (figure retrieved from promotional site on Internet.)*

Table 2. *Main performance criteria of a scanner, according to Witkowski (10)*

Main performance criteria of a scanner
Indication
Perception of the preparation line
Perception of undercuts
Time needed for scanning a die and a full arch
Precision of measurements
Mounting system for die and model
Number of axes
Resolution of the charge-coupled device (CCD) camera
Format of the outgoing data

allows fabrication not only of inlays and onlays, but also of crowns and the frameworks of FPDs in both clinical and laboratory settings. Earlier versions of CEREC® employed an acquisition camera based on an infrared laser light source that was projected onto surfaces coated with a thin film of contrast agent. New advancements in the performance of blue light-emitting diodes (LEDs) for 3D acquisition cameras have now surpassed the earlier quality of the longer-wavelength infrared light source. The new camera projects a changing pattern of blue light onto the object and then reads the image at a an offset angle permitting "active triangulation". Its telecentric beam permits the capture of essential information from all of the prepared tooth's surfaces in a single view and allows greater precision of the resultant optical image (Fig. 2a,b) [24]. E4D is a chair-side digital image capture system for use with preparations for inlays, onlays, full crowns, and veneers (Fig. 5). It uses high-speed laser technology to capture hard and soft tissue data intraorally, from impressions or from models without the need for a contrast agent. E4D's laser acquires data points from multiple views to produce an accurate image. Rapid Scan™ allows automatic capture of digital images at the operator's preferred speed [25]. The iTero system (Cadent, Carlstadt, New Jersey) has been available since 2007. It uses parallel confocal imaging (laser and optical scanning) to digitally capture the surface and contours of hard and soft tissues. Surface contrast powders that coat the teeth are not needed. However, it requires inclusion of a colour wheel into the acquisition unit itself, resulting in a camera with a larger scanner head than the other systems.

The Lava™ Chairside Oral Scanner (C.O.S) was created at Brontes Technologies in Lexington, Massachusettes, and acquired by 3M ESPE (St. Paul, Minn.) in October 2006. The product was officially launched in February 2008. The system consists of a mobile cart containing a central processing unit (CPU), a touch screen display, and a scanning wand (Fig. 6a, b). It used an entirely new approach for capturing 3D data. This 3D-in-Motion technology collects 3D data in a video sequence and models the data in real time. The Lava C.O.S. can capture approximately 20 3D data sets per second to allow an accurate and high speed scan. The Lava C.O.S. requires almost no contrast powdering for the scanner to locate reference points (powderless technique). Unlike video imaging, "point and click" uses individual "snapshots" to assemble a model. After scanning the tooth preparation, the dentist is able to rotate and magnify the view on the screen, and can also switch from the 3D image to a 2D view of the exact images captured. A further option allows the dentist to view these images while wearing 3D glasses. Once all necessary scans are captured, the patient is instructed to close into the maximum intercuspal position, and a scan of the occluding teeth is captured. The maxillary and mandibular scans are then digitally articulated on the screen. Unlike other systems the Lava C.O.S. simultaneously displays the images that are being captured in the mouth onto the touch screen monitor. With this real-time visibility, a dentist can assess whether enough information has been captured for a completed digital impression [26].

DISCUSSION

A wide range of advantages exist for employing digital image capture and CAD/CAM fabrication techniques for production of restorations. One of the key advantages is that ceramic materials can be more easily processed for use and new high-strength materials can be employed. The total production time is reduced and there is a better quality control of the restoration [20]. Time-consuming steps in the dental clinic including tray selection, dispensing and setting of materials, disinfection, and shipment of the impressions to the laboratory, can be eliminated.

Dental laboratories save time by not having to pour base and pin models, cut and trim dies, or articulate casts. Production costs are reduced. Processed data can be stored and used for subsequent follow up during the functional period of the device, something that has not been available with conventional production systems [9].

Digital impressions address many issues associated with conventional impression materials including problems of the properties of impression materials, inappropriate soft-tissue management, improper impression tray selection, and potential distortion of the impression before pouring [20].

Each scanning method confers certain advantages but also has some limitations. When a probe is used, even if it's a very precise one, it takes time to scan the entire model surface. A laser gauge is relatively inexpensive and measurement takes less time, but. because the reflected light of the projected laser beam is recognized by a PSD (position sensing detector) sensor, the precision decreases with the effect of diffusion (spread of the laser beam). Corner precision is particularly difficult to obtain [27]. That affects accuracy on both internal and external finish lines as well as preparation line angles. To resolve such problems a thicker "cement space" is designed on the model leading to a less precise fit of the final restoration. When a line laser is used, the scanning time may be reduced, but the resolution of the CCD camera affects the precision of the measurements. Therefore multi-axial control of the carrier of the stone model and the projection beam is required [15].

Further refinement of intraoral data acquisition scanners and digitizers is needed. Future digitizers should be even more versatile and allow complete replacement of all conventional impressioning techniques. New systems should ideally improve accurate data capture despite the differences of the structure between teeth, saliva and soft tissue [5]. This process would offer more patient comfort, shorter treatment times, early functional recovery for the sake of convenience, and options for aesthetic tooth-coloured restorations in one appointment and at very reasonable cost [28]. In-office fabrication systems currently still have limitations.

The milling precision for the inside contours of the restorations are limited by the smallest usable tool suitable for each material. Tools are still too large for many dental applications and fragile parts cannot yet be manufactured. However, there are reasonable expectations that those challenges will be managed at some point in the future.

Although, special training is required for clinicians and technicians to be able to use these novel technologies to their full capacity, the daily practice shows that the technician's learning curve is less steep than that for handmade traditional production steps. As more and more laboratory procedures are replaced by digitally supported manufacturing processes, savings in time and enhancement in quality will increase the productivity of the laboratories.

Encouraging global standardization of dental CAD/CAM systems and data management may eventually increase the popularity of these approaches but to date this does not seem to be the case. Standards will also provide a reference system for comparing initial outcomes for different equipment in creating restorations as well as establishing target values for success for the controlled clinical trials which are now ongoing.

CONCLUSIONS

CAD/CAM technology can be used to provide high quality, indirect restorations.

ADDRESS FOR CORRESPONDENCE

Marina Andreiotelli, 74 Sapfous Str., 15126, Athens, Greece.
E-mail: marina.andriotelli@gmail.com

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