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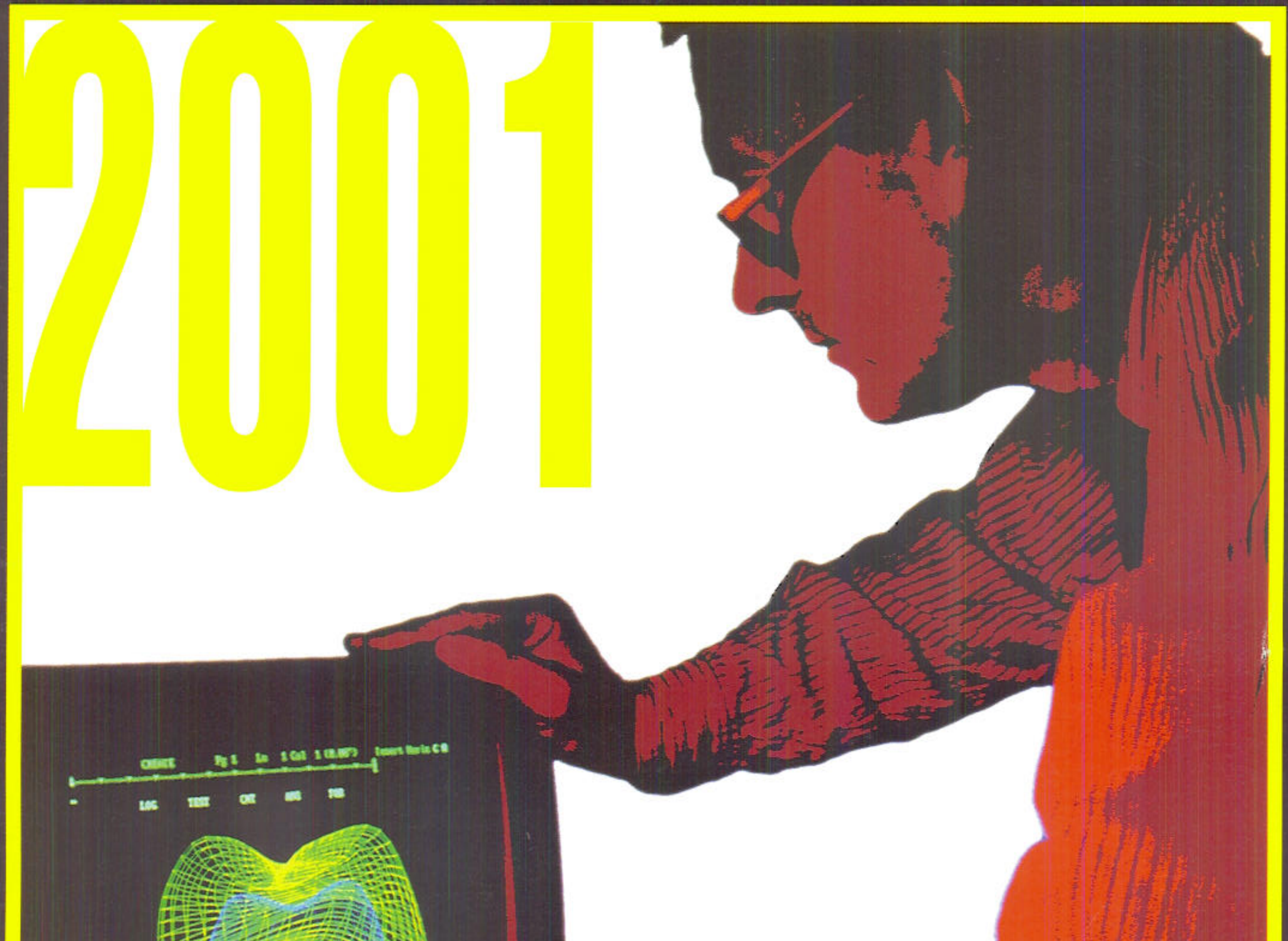

Technology for the New Millennium

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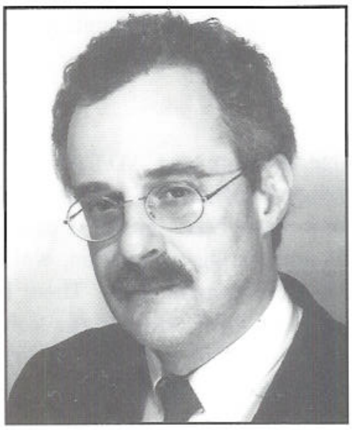
CAD/CAM in Dentistry



Jack D. Preston, DDS
François Duret, DDS, PhD

Dr. Preston received his Dental Degree in 1957 from the University of Southern California. A Diplomate of the American Board of Prosthodontics, Dr. Preston is currently The Don and Sybil Harrington Foundation Professor of Esthetic Dentistry, and Chairman, Department of Oral Maxillofacial Imaging at the University of Southern California. He has lectured throughout the world, as well as organized and directed several international conferences.

Dr. Preston has published many papers, has been both a contributing and primary author on several textbooks, and has worked on films and videotapes on clinical laboratory procedures in fixed prosthodontics. His primary interests in dentistry are in conducting prosthodontics education and research, and using imaging and computer applications, fixed and implant prosthodontics, ceramics and dental materials.

Dr. Duret holds a Doctor of Dental Surgery (1974), a PhD in Biochemistry (1980), and a PhD in human biology (1981), having concurrently undertaken courses in three disciplines. He is currently a research professor in the Department of Oral and Maxillofacial Imaging at the University of Southern California where he chairs the Section of Restorative Imaging. Dr. Duret has received numerous awards for his research and was made Office of the National Order of Merit by the French government in 1988. He has published numerous articles in scientific books and journals and has lectured internationally. He continues his research in CAD/CAM and other electronic applications in dentistry.

Dr. Duret lives with his wife Elizabeth, also a dentist, and their family in Fleury d'Aude France and commutes to Los Angeles for professional duties.

The most sophisticated application of computers in dentistry is the use of Computer Assisted Design-Computer Assisted Manufacturing (CAD/CAM) for fabricating dental restorations. The promise of one-visit quality restorations, eliminating the need for provisional units, no impressions or laboratory requirements, and the use of a machine that does not take days off, leave town in the middle of summer, raise its fees, or vary its quality certainly is alluring. Are such promises realistic? Like so many other simple questions, the answer is a complex *yes* and *no*. Whereas the technology certainly makes all these promises feasible, there are many other factors such as cost/benefit ratio, accuracy, esthetic acceptability, and availability of suitable materials that complicate the answer. CAD/CAM has become a commonplace essential in industry where it is used to design and fabricate virtually every product marketed. In such applications, however, many units are produced from each design whereas in dentistry, every restoration is unique, and only one unit is made, placing rather severe restrictions on dental CAD/CAM.

Although there are very few commercial CAD/CAM systems currently available, there is a substantial amount of research and development being conducted throughout the world. This paper will review some of those developments and present the current status of CAD/CAM in dentistry.

How Are CAD/CAM Restorations Different?

Dental CAD/CAM substitutes electronically assisted procedures for conventional methods. There are various CAD/CAM systems that can produce inlays, onlays, crowns, copings, veneers, and even the frameworks for short-span fixed partial dentures. Not all systems are capable of fabricating all restorations, and most are designed for specific purposes and have limited application.

There are a number of ways that CAD/CAM systems might be classified. One of the simplest is based on the method by which the needed information is obtained. CAD/CAM systems may acquire data about the prepared tooth either directly in the mouth or from a cast of the preparation and surrounding teeth. Some systems use a special camera to obtain the image(s) while others trace the entire surface of the preparation, either manually or automatically, with a stylus. The tip of the stylus is oriented in space and precisely located by the computer. Such "contact digitizing" is currently done from a die, but is theoretically possible directly in the mouth. However, the complexity of intraoral contact digitizing has precluded any such system from being offered commercially. Intraoral digitizing using an optical system is routine with one commercially available system and possible with another. Certainly, the intraoral acquisition of data is preferred by both patients and dentists, as it obviates the need for impressions. Eliminating impressions and casts also removes the errors that accompany these procedures.

In many ways, CAD/CAM dentistry does not differ greatly from the conventional process of making a restoration, it just uses different instruments and different technology. Generally speaking, the tooth preparations do not differ from traditional designs, although some systems require the rounding of line angles, elimination of bevels, or similar modifications. With traditional procedures, once the impression is obtained, a cast is poured, and a die of the prepared tooth is made. The CAD/CAM process uses a "virtual die," a three-dimensional replica that contains all the needed spatial information. Unlike the traditional cast, this model resides in the computer, not on the laboratory bench. Although it is necessarily viewed on the monitor in two dimensions, all the data are correlated in three dimensions, just as a solid die would be. With the more complex systems, that die is precisely related in space to the adjacent and opposing teeth, just as the stone die is in the mounted cast.

Conventionally, a wax pattern is made on the stone die or porcelain is layered to form the restoration using numerous intermediate procedures. Such a pattern requires some skill and artistry to accurately fabricate, and the quality of the completed restoration varies greatly. With CAD/CAM the "virtual pattern" is designed on the screen, using specialized software. The pattern may still be "carved" and formed to the operator's liking or it may be automatically developed by the computer with little external operator intervention.

CAD/CAM Materials

Whereas traditionally, the wax pattern must be invested and cast, or the ceramic material fired, added to, and fired again, with CAD/CAM the final restoration is machined from a block of the restorative material—ceramic, resin composite, or metal. The waxing and casting procedure involves a series of numerous variables and is subject to substantial quality differences. All the steps of the traditional laboratory methods are devised to compensate the variables that occur in the changes of state of the materials involved: making impressions, pouring casts, heating and cooling wax, melting and cooling alloy, sintering ceramic, etc. CAD/CAM offers more consistent results. The material block is prefabricated and the desired physical properties are not altered by casting or sintering. The ability to prestructure a material and machine the restoration offers many opportunities for improved physical properties since the material can be factory processed under conditions, such as increased heat, pressure, and controlled atmosphere, not possible in a dental laboratory. However, having to machine the restoration from a block of material imposes some rigorous limitations on esthetics and necessitates that the material be machinable without chipping, crazing, or otherwise damaging the completed restoration.

Data necessary to fabricate a restoration must include not only the prepared tooth itself, but its relationship with the adjacent and opposing teeth. Ideally, one should have information about excursive mandibular movements, as well as static intercuspal relationships. Currently, all CAD/CAM systems use only static data although prototypes for dynamic recordings have been reported.[1,2]

CAD/CAM Systems

To the authors' knowledge, there are ten CAD/CAM systems that have been developed sufficiently to either be commercially available or to have been shown at dental expositions. Other systems are nearing completion, while still others are in the early development stage. There is obvious international interest in CAD/CAM and the technology promises to become a routine part of dentistry. Table 1 lists the essential information about the known systems.

The CEREC System

CEREC, an acronym for *ce*ramic *rec*onstruction, is the first commercially viable, widely available system for producing inlays, onlays, and veneers. It is produced by Siemens (Siemens GmbH, Bensheim, Germany) and is currently available in two designs, CEREC 1 and CEREC 2. Both are self-contained, single-unit systems and both use a camera to obtain a single image of the prepared tooth directly in the mouth or on a cast.[3-5]

The first model of CEREC 1 consists of a 3-cm diamond disk driven by a hydroturbine. The second model incorporated an electric motor. Using a disk as the sole cutting tool limits the ability of the unit to make certain restorations or to complete certain functions, such as carving occlusal anatomy but it decreases the time needed to machine the

Table 1: Dental CAD/CAM Systems

System	*Manufacturer*	*Data Acquisition*	*Restorations*	*Materials*	*Commercially Available?*
Contact Digitizing:					
Ceramatic	Ceramatic Inst.	Automatic digitizing	Inlay, onlay, coping	Ceramic	Yes
PRO-CAM	Intra-Tech Inc.	Automatic digitizing	Coping	Ceramic	Yes
Procera 1 & 2	Nobelpharma	Automatic digitizing	Coping	Titanium (1)	Yes
				Ceramic (2)	No
DCS Titan	Gim-Alldent	Manual digitizing	Coping, FPD* framework, (Titanium)	Titanium, ceramic	Yes
Optical Digitizing:					
Nissan	Nissan	Optical point	Inlay and crown	Titanium, ceramic	No
CAP	Nikon	Optical point	Inlay and crown	Titanium, ceramic	No
Cicero	Elephant	Optical line	Crown	Ceramic	No
CEREC 1&2	Siemens	CCD camera, 1 image	Inlay, onlay, veneer	Ceramic	Yes
DENStech	Microdenta	CCD camera	Crown, inlay, onlay	Ceramic, titanium	No
Duret	NIMC	CCD camera, multiple images	Crown, coping, FDP*	Titanium, ceramic	No

*FPD = fixed partial denture.

restoration. The unit uses a 256 × 256 CCD (charge coupled device) camera and has a 50-micrometer pixel display. A single intraoral image is made of the prepared tooth and the complete preparation must be captured in that image. This system is being phased out in favor of the CEREC 2.

CEREC 2 (Fig. 1) is pending FDA approval and is not commercially available in the United States at the time of this writing, except for testing purposes, but is being used in Europe. It has expanded electronics, an improved 512 × 512 CCD camera, a 25-micrometer pixel resolution, and adds a second cutting tool, a 2-mm diamond instrument. The unit is capable of more spatial operations, such as establishing the height of a cusp or cutting a groove and is electronically more complex. Both the disk and the diamond tool operate simultaneously, reducing the time needed for producing an inlay or onlay. No image of the opposing teeth is made and the occlusal surface is only oriented to the cusp height or fossa depth of the remaining tooth structure or adjacent teeth. However, an image of the occlusal surface before preparation, or of a wax pattern can be superimposed on the preparation to provide a design matrix. The CEREC 2 unit offers an optional camera for intraoral imaging. Software for crown fabrication is being tested.

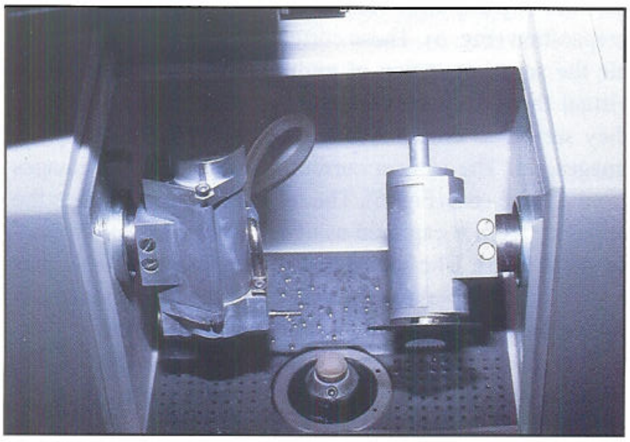


Figure 1: The CEREC II system incorporates a diamond point that functions concurrently with the diamond disk.

The CEREC system is ergonomically well designed and each model has had increasing sophistication. There has been progressive automation of the functions, reducing operator time. Reports of accuracy vary,[6,7] and a recent study[8] validated longer term efficacy of the procedure.

PRO-CAM

Currently the only CAD/CAM unit produced in the United States is the PRO-CAM system (IntraTech, Dallas, Texas), a recently released unit designed to produce ceramic copings. It consists of two stations, one for control and design and the second a combination contact digitizing/CAM station (Fig. 2). The system works from a single die trimmed to clearly define the margin. A laser beam analyzing unit is used to survey the die and establish the long axis

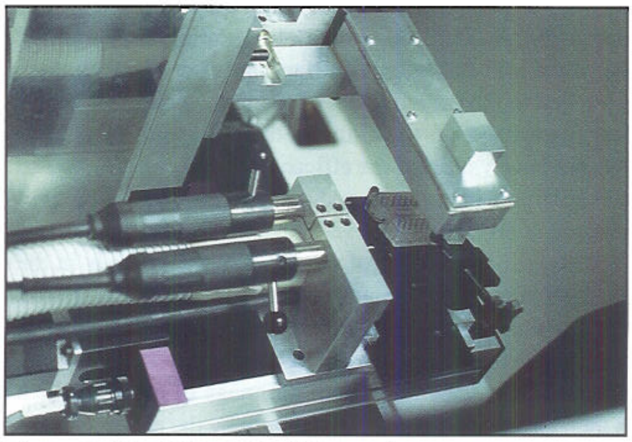


Figure 2: The PRO-CAM CAM station.

for positioning prior to contact digitizing. The die is placed in the digitizing unit and a contact probe automatically traces the die surface (Fig. 3). The image is displayed on the control monitor and the coping is designed by the operator.

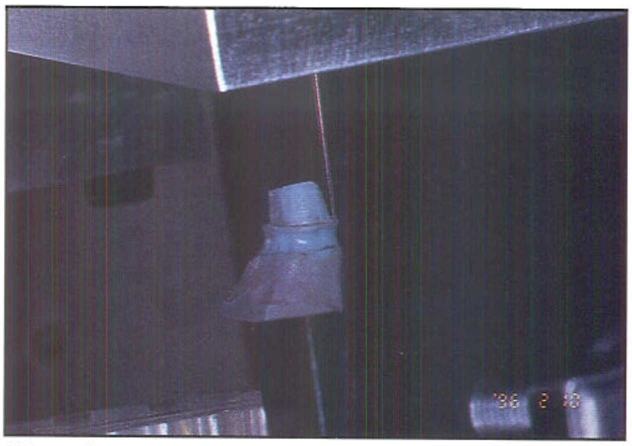


Figure 3: The PRO-CAM contact probe.

The CAM unit uses two cutting engines each with a single tool to produce the ceramic coping. A ceramic block is oriented in the machine and the program initiated. All the machining is accomplished automatically, without operator intervention. The finished coping requires some manual refinement prior to veneering. No studies are yet available concerning marginal integrity or internal adaptation.

Procera

The Procera (Nobelpharma, Gothenburg, Sweden) is an unusual system that uses CAD/CAM in a rather unconventional fashion. Two different applications are available. The first uses a copy milling approach to replicate the die. The die is automatically traced with a probe, contact digitized, and 1-3 carbon electrodes are copy milled, reproducing the tooth form. The external surface of the coping is designed on a simplified CAD system, and the coping surface is machined from this pattern. The titanium block is then reoriented to allow for the electro-milling (spark gap erosion) of the internal surface using the machined carbon electrodes. An intricate system of mounting and orienting keeps the oral and internal surfaces related. The technique is limited to the development of titanium copings and is no longer available in the United States. Reports of clinical success have validated the efficacy of the technique.[9-11] The unit is large and complex and no reports of cost effectiveness are available.

A second application of the Procera technique is in the production of a high-strength ceramic coping.[12] The special Al_2O_3 material used is highly sintered, extremely strong, and would be difficult to machine because of tool wear. CAD/CAM is used to produce an image of the die, which is then expanded three-dimensionally by the computer program. The die expansion of 18-22 percent exactly equals the sintering shrinkage of the porcelain, compensating the dimensional change. The coping is designed on the CAD unit and the porcelain restoration is isostatically pressed (heat and pressure) on this oversized die. The resulting coping is extremely strong (508 -780 MPa) and accurately fits the master die (Fig. 4). Again, this process is not available in the United States at the time of this writing, but its availability is anticipated in mid-1997.

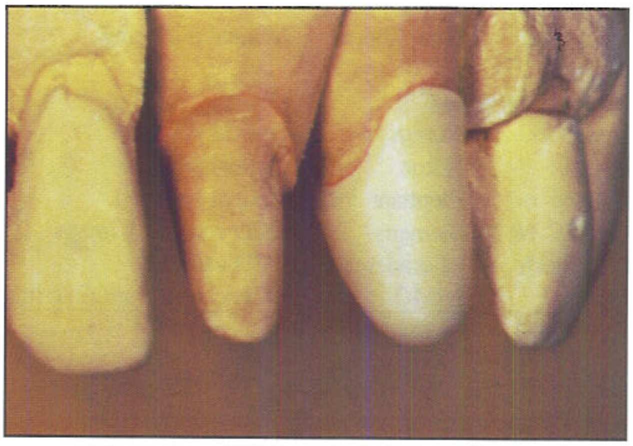


Figure 4: A Procera ceramic coping.

The Duret System

Dr. François Duret[13,14] has been involved in CAD/CAM design and development for over three decades and he should be acknowledged as the "father of dental CAD/CAM." His work was first embodied in a system produced by Hennson (Hennson Intl., Vienne, France) which was later acquired by another company (Sopha Biomedical, Vienne, France). The system is no longer commercially produced, but development has continued (Noble International Medical Systems, Paris, France).

The Duret system is probably the most sophisticated of the dental CAD/CAM systems. A laser imaging camera with complex optics is used for image acquisition. This camera was initially intended to be used intraorally; however, this proved to be difficult with patient movement and the need to place three correlation spheres in the area of the preparation (Fig. 5). These correlation spheres made possible the superimposition of multiple images to construct a virtual three-dimensional image of the area, inasmuch as they served as constant reference points in the computer images set. The system currently makes multiple images from a stone cast (Fig. 6). The relationship of the die to the opposing teeth is captured using an interarch record reseated on the cast. The imprint of the opposing teeth is thus related to the correlation spheres, and therefore, automatically related to the preparation and adjacent teeth.

The CAD system is a unique development of Dr. Duret,[15,16] as it incorporates a "library" of 96 teeth—32 teeth each in Class I, Class II, and Class III occlusion. Once multiple images are acquired and correlated and literally assembled into a single three-dimensional virtual die, the

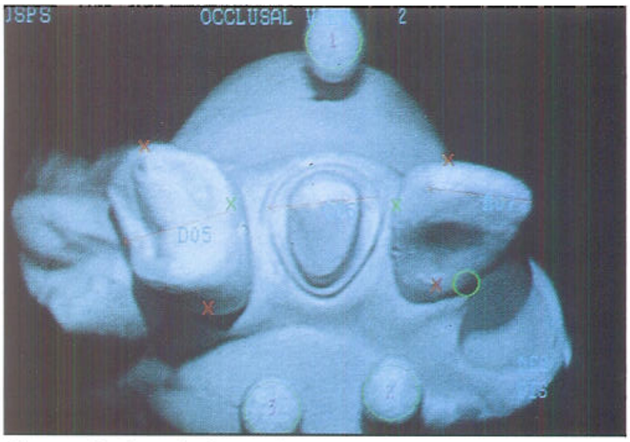


Figure 5: Correlation spheres placed in the area of the preparation.

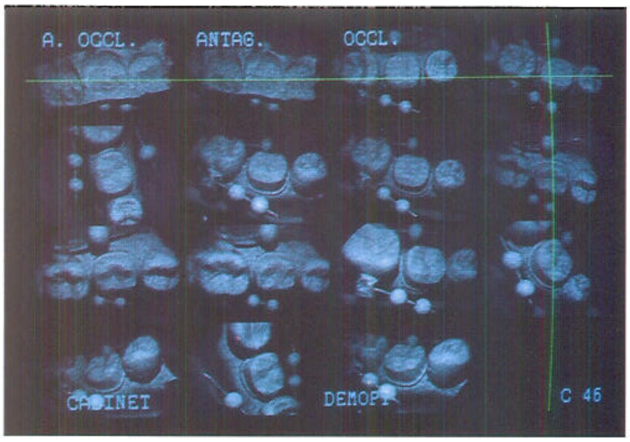


Figure 6: Multiple images have been recorded and are ready for correlating.

operator defines some landmarks such as the height of contour and grooves and cusps of adjacent teeth, and the margin. The computer assimilates this information and builds a representation of the preparation and its environment. It then extracts a crown form from the library and places it over the preparation, automatically fitting it to the margin, adjacent, and opposing teeth. The operator then has the opportunity to make any corrections or design such elements as the amount of cement space, the type of occlusion, and any contours that may need changing. Once the restoration is designed, the information is sent to the CAM station, where the restoration is automatically milled. A special composite material was used for many restorations,[17] but this has been replaced with a ceramic block. Complete ceramic anterior or posterior crown restorations have been the focus of the Duret system, but it is also possible to machine titanium crowns or copings.

In a study at the University of Southern California School of Dentistry, a series of 50 crowns were machined, luted on their respective dies, and sectioned faciolingually and mesiodistally. The mean gap at the gingival margin was 35 micrometers, well within clinical tolerance.[18,19]

DCS Titan

The DCS system (Fig. 7) is a complete system that includes a manual contact digitizing station, a CAD station, and a CAM system that is capable of machining titanium and ceramic materials.[20] The operator works on the die without any special preparation. The system was originally developed in Israel (Tavor and Co.) and is presently manufactured in Germany (Gim-Alldent, Varel, Germany). Manipulation is slow (for example, digitizing a cast requires 20 minutes) and the accuracy is said to be approximately 100 micrometers. What makes the unit more interesting is its capability to produce not only copings, but also to machine the substructure for a fixed partial denture from a titanium block. The production of the unit is quite confidential, but it is said that approximately 30 units have been sold in Germany and two have been tested in the U.S.A.

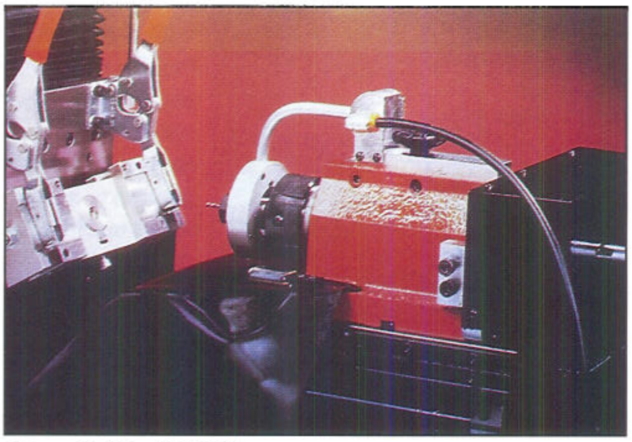


Figure 7: The DCS Titan system.

CAP System

The Japanese have been very involved in the development of dental CAD/CAM and the first visible fruit of these labors was exhibited in March of 1996 at an exhibition in Yokohama (Figs. 8a, 8b).[21,22] The prototype system was developed by Nikon and uses an automated laser imaging system to read the die and cast and produce the three-dimensional virtual model. It is done very rapidly and the process is repeated to ensure accuracy. The design station allows development of the crown and much of the procedure is automated. Although the prototype unit is large, it will undoubtedly be streamlined before it is released for public use. There are no data concerning accuracy available.

Copy Milling

The CELAY system (Mikrona AG, Spreitenbach, Switzerland) is not a CAD/CAM system, but rather a copy milling device that allows the replication of a resin inlay, onlay, or coping pattern in porcelain.[23,24] It operates much like a key duplicating machine, using a pantographic machining process. The resin pattern is mounted on the left

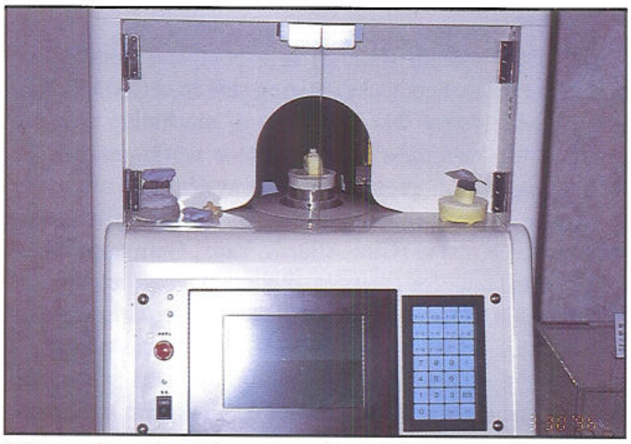


Figure 8a: The Computer Assisted Prosthesis system imaging station.

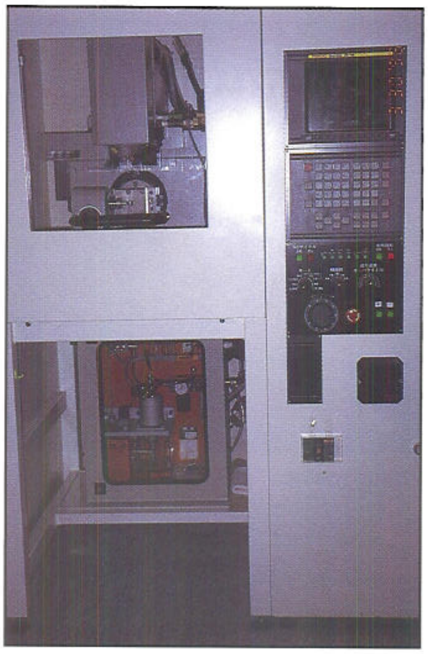


Figure 8b: The CAPS machining station.

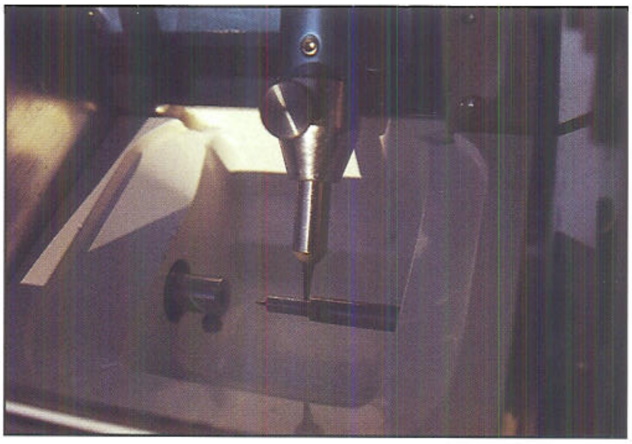


Figure 9a: The tracing side of the Ceramatic system.

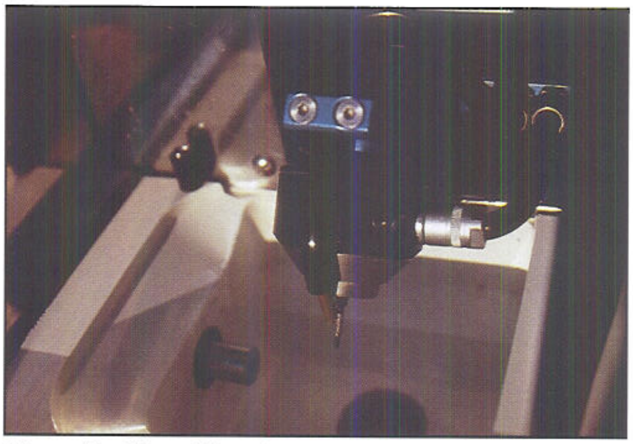


Figure 9b: The milling side of the Ceramatic system.

side and sprayed with a powder to facilitate tracking the tracing stylus. A cutting tool having the same geometry as the stylus machines a duplicate of the pattern from a ceramic block. Although the CELAY system is *not* a CAD/CAM system, another device, the Ceramatic, (Ceramatic Inst., Askim, Sweden) automates the tracing procedure, much like the contact digitizing procedure of some CAD/CAD systems. The data are used to electronically control the milling system. The Ceramatic (Fig. 9a, 9b) is included on the CAD/CAM table, although it is a hybrid machine that lacks a design station (CAD).

The Future of Dental CAD/CAM

The broad interest in dental CAD/CAM indicates that there will be progressive development and eventually CAD/CAM will be used routinely. All dental applications of computers follow the general commercial computer development and are largely dependent upon the rate at which progress is made. In 1965 Gordon Moore stated that the number of components on a computer chip will double every year.[25] "Moore's law," as it is now called, still holds today, and indicates the exponential course of computer development. This gives the personal computer power that previously existed only in much larger and more expensive computers. Dental CAD/CAM benefits greatly from this development, making routine use faster, more accurate, and more cost effective. Thus, it is probable that dental CAD/CAM will become a routine application and, as such, has the potential to greatly alter the manner in which restorative dentistry is practiced. It also can make excellent technology available to third world countries where the basic technical skills may be lacking and where development and training impede progress of routine dentistry.

CAD/CAM units will not only become more common in the dental operatory, they will find increasing use in dental laboratories as well. Does this mean that the position of the dental laboratory technician is in jeopardy? Not at all. CAD/CAM will not remove the need for laboratory technicians, but it will change the nature of their tasks.

There are many other potential applications of computer science to CAD/CAM. The problem of having to work with a monochromatic block of material may be solved by incorporating colorants that are sensitive to specific wavelengths of laser light into the ceramic block. The colorants may then be activated by photostimulation, potentially reproducing the desired color in the proper area of the restoration.

Eventually it will be possible to design a preparation with knowledge of the internal and external tooth morphology and robotically prepare the natural tooth in the mouth. Inasmuch as the preparation is designed in advance, the restoration can also be created before the patient arrives. Ridiculous? No—such a scenario admittedly strains the imagination, but it is only our imagination that limits the extent of our progress. Technical capabilities are far ahead of our ability to use them.

In short, the future of dental CAD/CAM is probably not known by anyone, but may surpass our most imaginative concepts. The fact is that most dentists do not realize that dental CAD/CAM is real *today*. The future will only make it more pragmatic, more efficient, more cost effective, and bring greater benefits to the patient and the dentist.

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