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Dental Robotics: State-of-the-Science Dental CAD/CAM

FRANÇOIS DURET

The dental CAD/CAM is a new dental technology, developed through computer science, that is used to produce dental restorations. It is distinguished from other technologies in that it combines a data acquisition (input) system, a data processing unit, and an output system.

In the dental CAD/CAM system, data may be acquired using a camera or any device that digitizes the data gathered from the patient's mouth. The processing of the data allows the clinician to create a model of the future restoration on a computer screen or, as a decision aid, creates a visual image of the proposed treatment. The output system manufactures, or creates a representation of, the data issued from the model.

Although it provides other functions, the dental CAD/CAM is most commonly used to produce a restoration: pictures are taken by the camera, and then the crown is designed on a graphics workstation and manufactured by a numerically controlled milling machine.

This chapter classifies several systems currently on the market or under development.

BACKGROUND

The first prototype of a dental CAD/CAM system[1–3] was introduced in 1983 at the Entretiens de la Garanciere in Paris. Two years later, in November, 1985, the first milled crown directly cemented in the mouth was produced in Paris during the World Congress of the French Dental Association in front of more than 800 dentists.[4]

Since that time, the technology has developed quickly, perhaps too quickly. It seems timely for the author to comment on the current status of this professional concept.

The mechanics of the various CAD/CAM techniques can be presented fairly easily.[5] However, the author is not convinced this is the most effective way to describe a new scientific concept. It has frequently been the case in CAD/CAM studies that researchers have gone no further than a simple presentation of results. Given the profusion of articles on the subject, it is interesting from a scientific point of view to try to incorporate these presentations into a more global analysis of dentistry.

Following is a brief description of the main systems that are currently available on the market as well as the most up-to-date research projects. The author will synthesize the various systems by integrating them into a more general argument relating to the field of dentistry. Throughout the discourse of this study, there is no claim to offer an alterative as the only available one; rather, the goal is to provide the basis for reflecting on where current research is heading. This article continues the ideas proposed in the author's article published in the *Cahiers de Prothèses* in 1985.[6,7]

THE CAD/CAM PROCESS

By definition, dental CAD/CAM is the application of Computer-Assisted Design and Computer-Assisted Manufacturing to the field of dentistry. In addition, a first stage, the input of three-dimensional data or impressions (Fig. 1), has been incorporated.[8–10] Today, it is a complex device that offers three distinct stages of operation: data acquisition, product design, and product manufacture.

During the first stage, the maximum amount of information is collected from the patient's mouth and combined with various clinical data. This guarantees that the software will function smoothly, and that the quality of the restoration's design will be high.

After the dentist finishes preparing the tooth to be treated using conventional methods, he or she proceeds with data acquisition by using either an electro-mechanical sensor,[11] or an optical probe (camera)[9] directly into the mouth or on a model. These devices often rely on the properties of a

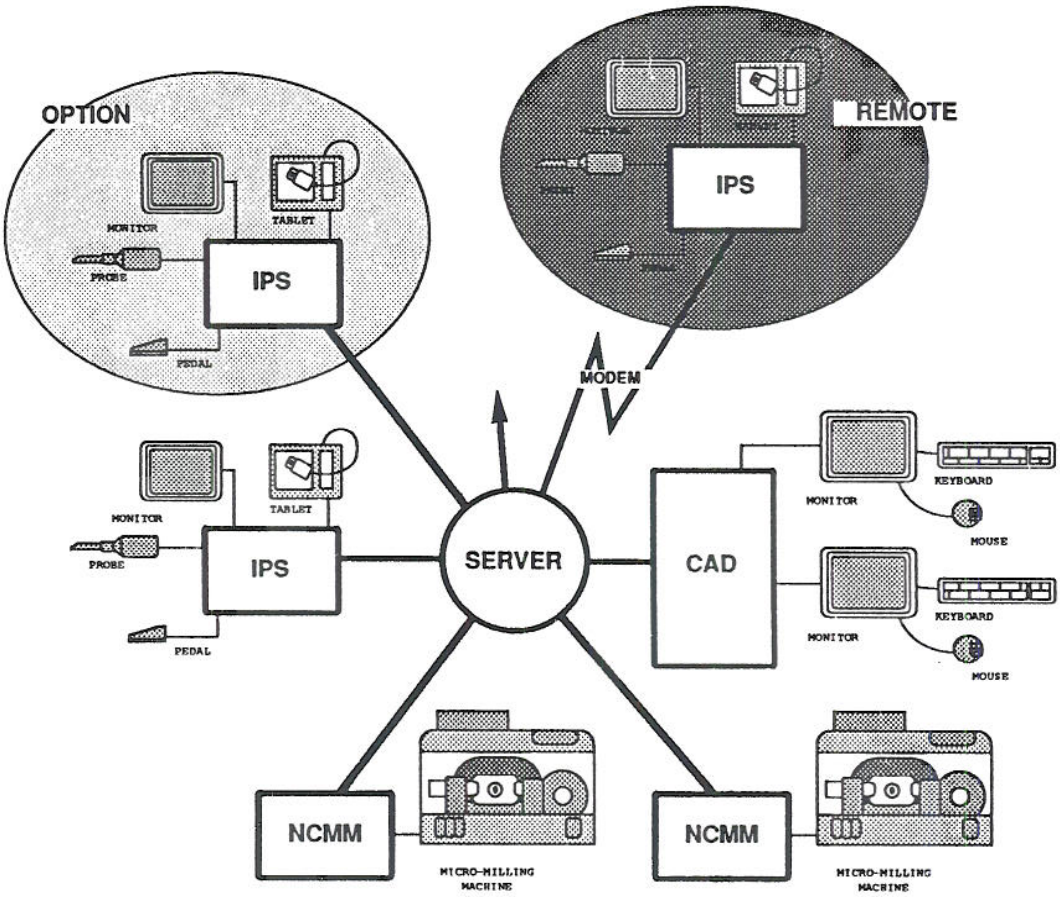

Fig. 1. Dental CAD/CAM system composed of three parts. The IS (impression or data capturing system), the CAD (computer-assisted design), and the NCMT (numerically controlled machine tool or CAM).

laser beam for taking measurements[12] and on a Charged Coupled Device (CCD)[9,13–15] for imaging.

Some systems use a micro-sensor to perform the optical reading and others use a second CCD instead of a laser beam or other three-dimensional recording device. However, the basic concept of these systems remains the same. The author's group generally uses a structured laser beam[16] that may range from the projection of a single fringe or point to the projection of several fringe patterns to obtain a particular physical phenomena such as the Moire.[17] This allows a three-dimensional reproduction of the object.

The second part of this first stage consists of identifying certain points and data on the object appearing on the screen. Identification of these data provides crucial information about certain areas of the restoration (*e.g.*, contacts, marginal limits, occlusal elements). This automatic or interactive operation is generally followed by the calculation of three-dimensional surfaces representing the preparation area.

The second stage generally derives from the industrial CAD system.[18] Specific applications for each branch of dentistry will be developed and used based on general three-dimensional computer programs.

The most important aspect of this stage appears to be the ability to produce a yet unknown object (restoration) by relying solely on oral data, software, and skill in manipulating the objects displayed on the screen. The ability to provide this feature implies the availability of software that is both adaptive in working with all the cases that the user may encounter and reliable to avoid major design errors.

Only the more sophisticated systems offer this type of design capability. Many systems merely reproduce a negative of the cavity shape, which is then adjusted for the cement space.

The third and final stage of this system consists of milling the previously designed object. This is, in general, a conventional milling process based on varying levels of technologic sophistication,[19] from the simple pantographic reproduction device, which duplicates a handcrafted model, to a genuine four-axis milling machine with automatic tool changes and automated controls.

In every case, a restoration produced by dental CAD/CAM is finished by hand before it is fitted in the mouth. The finishing process can range from a few minutes to an hour.

THE SYSTEMS

There are currently several systems available on the market or under development,[20] as evidenced in professional journals. The purpose here is not to select a few but rather to describe the most common systems. Very few actually deserve the name CAD/CAM, as there is only one or two true CAD/CAM systems on the market today. But the author will briefly discuss every system that uses at a minimum a digital system, a manufacturing system, or both together.

The systems will be presented in an increasing order of complexity, although this sequencing does not necessarily correspond to an increasing order of functional capabilities.

THE CELAY SYSTEM

The Celay system (Fig. 2), first presented in Munich in 1989, is the result of the work of Stefan Eidenbenz, an engineer and dentist at the Dental School of Zürich, and the Mikroma Company.[21,22] This is a two-part system: the first part is for data acquisition using a mechanical sensor, whereas the second part is for milling, using a manual milling system with 6 degrees of freedom. The current purpose of this device is to mill ceramic inlays, including the occlusal surface.

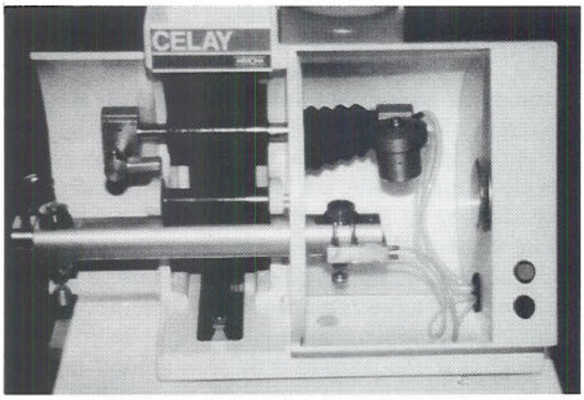

Fig. 2. The Celay system.

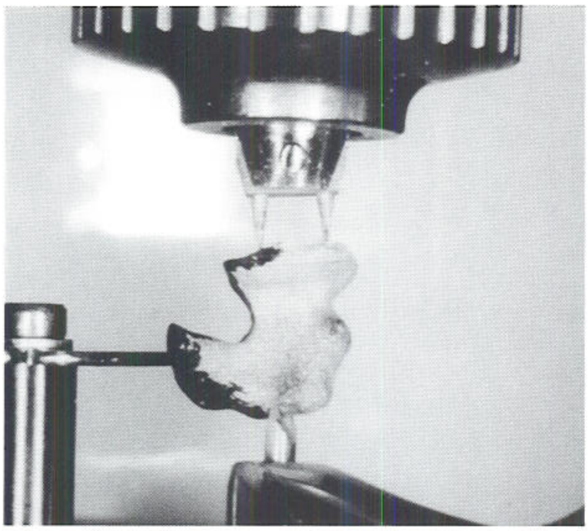

Fig. 3. The data acquisition area of the Celay.

After the clinician prepares the tooth, the inlay is constructed of a resin or wax hard enough to resist the movements of the sensor. The photopolymerisable resin is affixed to the left side of the device (Fig. 3), under the micro-sensor head (reading tool), whereas a piece of ceramic or composite material is affixed under the cutting tool of the micro-milling machine (Fig. 4). The shape of the reading tool is the exact replica of, or is proportionate to, the cutting tool. A pantographic arm links the reading tool to the cutting tool.

The reading tool follows the profile of the resin piece and guides the cutting tool with the pantographic arm, thus reproducing the same shape on the ceramic or composite material (Figs. 5 and 6).

Once the restoration is completed, it is removed, shaded, and glazed according to conventional procedures with conventional ceramics shading kits. Sealing is done with a relatively viscous, auto/photopolymerizable composite (ESPE, Warburg, Germany) and an ultrasonic tool that facilitates insertion of the restoration by its action on the sealant. The Celay system is currently able to make inlays and onlays with their occlusal surfaces for the relatively low price of 35,000 DM (approximately $18,000).

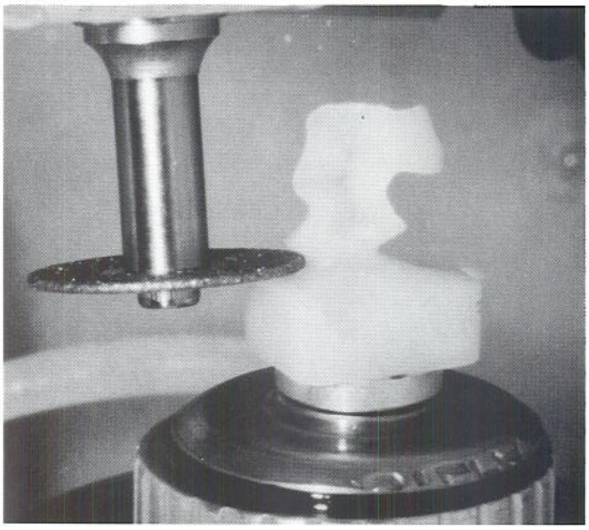

Fig. 4. The micro-milling machine tool (on the right side of the machine).

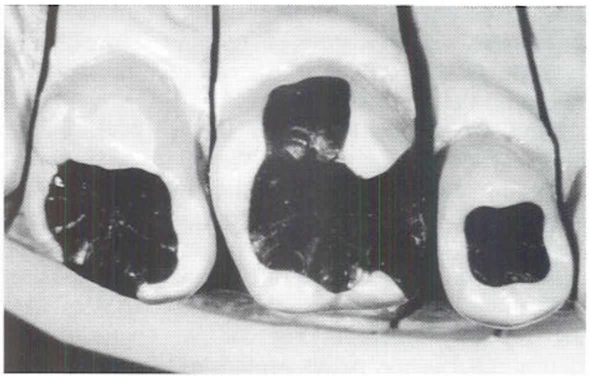

Fig. 5. Inlay wax for the Celay acquisition data.

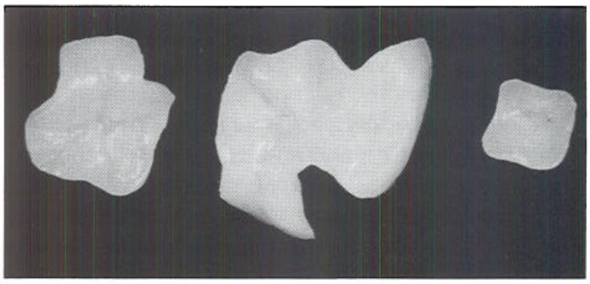

Fig. 6. Inlay result by Celay with the occlusal surface.

Although the accuracy of the system has not been documented, this product is being used with complete satisfaction at the Dental School of Zürich (under the guidance of Dr. Shaerer), and in some dental offices and German laboratories. This system is interesting because it can produce both the internal and occlusal surfaces.

THE PROCERA SYSTEM

The Procera system (Fig. 7) was invented by Dr. Matts Andersson and a team of researchers from Nobel Pharma. Data on this system were first made available in 1987.[23] Concerned with extending the use of titanium in the field of fixed restoration,[24] but aware of the problems associated with casting this material, the Nobel Pharma team, well-known in the field of implants, decided to put Dr. Andersson's ideas into practice. There are several versions of this system, but Andersson himself described the basic principle in 1989.[25]

Several systems are currently being used in Sweden and Germany. A machine is also being tested at the University of Chicago.

The Procera system is a duplicating and milling system that uses a mechanical sensor reading technique with a first milling process, using a pantograph similar to that of the Celay system, and a second milling process by electro-erosion. The purpose of this system is to produce a titanium coping for a conventional porcelain fused-on titanium restoration.

Following is an outline of the various stages of the process:

1. Using a conventional model,[6,7] a die of the preparation is produced that is solid enough to resist the pressure of the pantographic sensor.
2. A resin coping is produced on this die.
3. The die is placed into a reading chamber similar to that of the Celay system. The pantographic arm links the reading head to a milling system (Fig. 8). The die reading makes it possible to mill several carbon graphite dies, which are expanded slightly to provide a space for the cement. The first die must reproduce the preparation, whereas the carbon dies reproduce the inside face of the coping.
4. The same first die is used when milling the external face of the coping. To do this, a blank piece of titanium replaces the carbon piece, and the pantographic arm must be adjusted in such a way that the milling produces a copy taking into account the thickness of the cement and that of the metal.

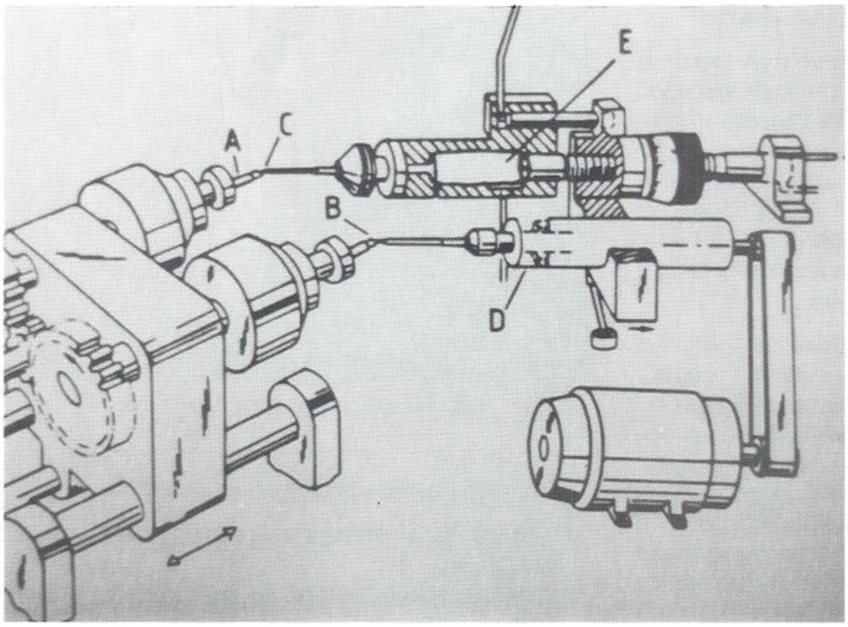

Fig. 7. Concept of the first part (data acquisition) of the Procera system. *A*, die; *B*, carbon die; *C*, pentographic arm; *D*, milling system; *E*, pentographic system (by Andersson).

5. The head of the titanium piece now represents the external portion of the coping. The piece is placed head first in metal melted at high temperature in an oven. It is then removed from the oven and, after cooling, the protruding titanium part is removed.
6. The inside surface of this titanium piece must now be formed. To do so, the previously milled carbon electrodes and the new titanium piece are positioned in the electro-erosion machine. The carbon graphite copy of the internal surface is used as a negative electrode (Fig. 9). The carbon dies serve as the positive electrode. These dies will be pushed little by little into the titanium such that the external surface is shaped by the discharge produced between the metal and the graphite. In general, three electrodes of graphite per element are needed.
7. The technician builds up the ceramic in a conventional manner on the milled external surface.

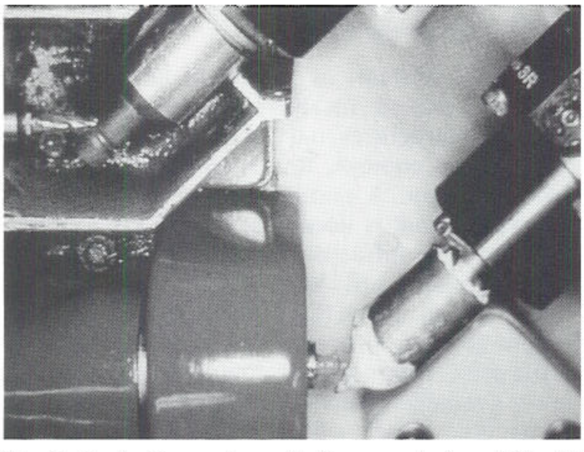

Fig. 8. Duplicating system with the reproduction of the die (top) in carbon graphite (bottom).

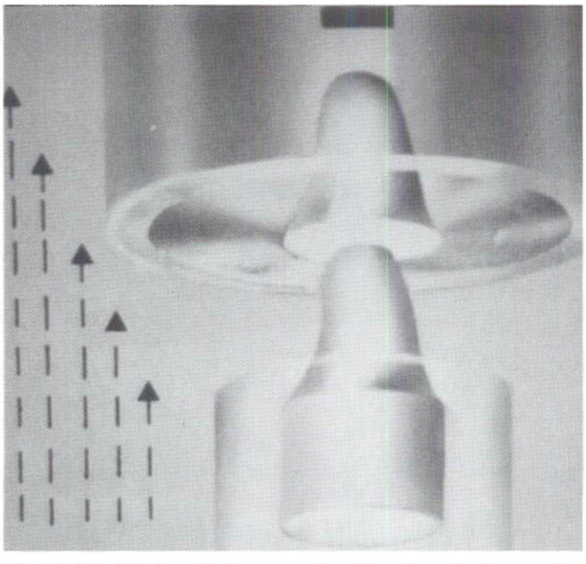

Fig. 9. Sketch by Andersson showing the electro-erosion system.

There are two other versions of this system:

1. The first uses a welding machine that makes it possible to establish a titanium joint between the different copings. It enables Procera to produce bridges as well as single crowns.
2. The second extension, although already presented in Sweden,[26,27] is still under study. It enables telephone transmission of all the data acquired by the imaging system, thereby reducing the high cost of the machine.

Many clinical studies are still needed[26] before a full understanding of all the functions this product can perform is gained. Nobel Pharma is undertaking this research. What is known is that the manipulation, albeit sophisticated, takes a long time. However, it is currently possible to produce a biocompatible titanium coping without having to go through the casting process. Given the medical experience of Nobel Pharma, and in particular its expertise in the field of titanium, future developments are promising.[27]

THE DCS-TITAN SYSTEM

The Titan system (Fig. 10) was designed by Drs. Tavor, Zabordky, and Shafir. It combines a mechanical sensor reading unit, a conventional CAD workstation, and a numerically controlled milling machine.[28,29]

The Titan system which was specifically designed to produce titanium copings, is manufactured by Gim-Alldent (Varel, Germany) and has been on the market since 1991.

Fig. 10. The Dux or DCS Titan system.

Fig. 11. The micro-sensor hand piece.

Following are its principles of operation:

1. The tooth is prepared according to standard practices.
2. A micro-sensor is used to acquire preparation and environment data from an intermediate model. The data are then digitized and transmitted to a computer where a CAD program is in memory (Fig. 11).
3. Although the CAD station is not yet well known, its copings program appears to be similar to that of the Sopha CAD/CAM system. Data transmitted from the previous step are used to create a computer model of the preparation. The model allows modifications of the margin (Fig. 12).
4. The external surface of the coping is designed either from the sensor reading of a resin cap fitted onto the preparation (Procera method) or from a dilation (or expansion) of the preparation model by software.
5. The titanium coping is milled using an industrial-type, numerically controlled machine tool with carbide burs.

This new system, as presented in Cologne in April 1992, extends its application to the milling of bridge infrastructures and also milling of a support arm between copings, thus avoiding the Procera welding station. A parallele piped rather than a cylindrical blank is used (Fig. 13). The CAD station draws the infrastructure, using user-friendly two-dimensional software.

This system offers the same advantages as the Procera system, although it is easier to use and, for the price, offers greater potential for evolution. Newly available clinical data leave room for hope that accuracy levels will range between 100 to 140 μm[29] from the margin. More than 30 German laboratories currently using the system have not re-

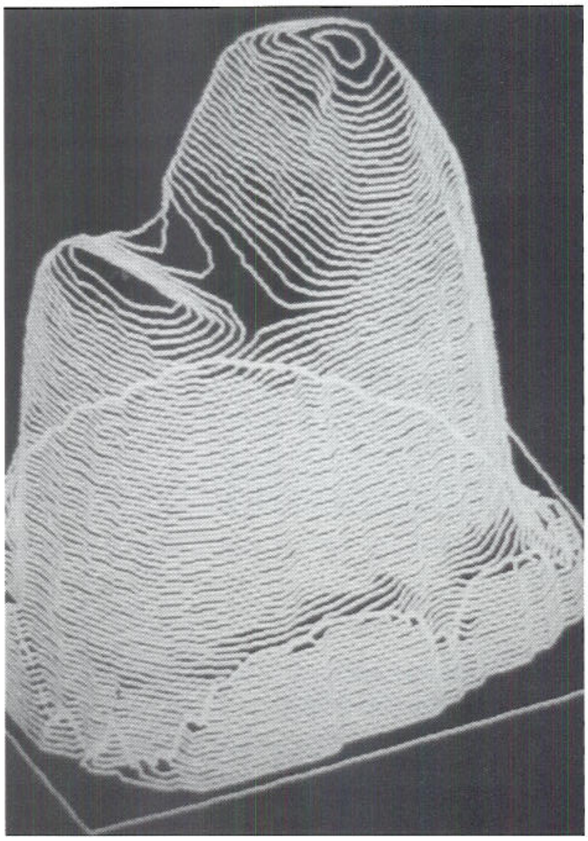

Fig. 12. The design of the preparation on the CAD screen.

futed these results. This system, which has now reached the industrial stage, is estimated to cost about 200,000 DM (approximately $138,000). Although the machine is remarkably good, the price may be too high for the sole production of titanium copings.

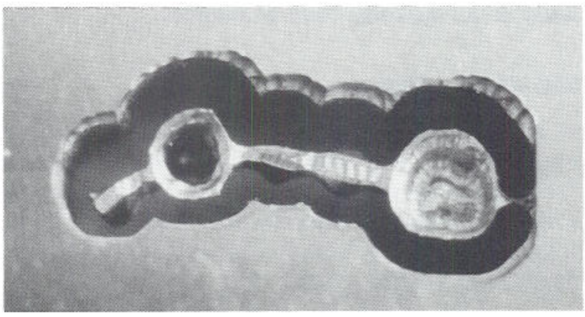

Fig. 13. Blank of material and coping for bridge.

THE CEREC SYSTEM

The Cerec system (Fig. 14) belongs in the domain of optical impressions. This is a device that uses opto-electronic techniques, the only method that makes it possible or will make it possible to forego the conventional impression and stone model.

The Cerec System was invented in December 1980 by Professor Werner Moerman of Zürich and a Swiss engineer, Marco Brandestini. This system is currently manufactured by the dental branch of Siemens,[30] and more than 1,000 systems are used throughout the world today. This system has changed little since it first appeared in 1985.[31] Its purpose is to produce monofaced and multifaced inlays and veneers without having the ability to produce the occlusal surface of the inlays.

The system is compact[32] and made up of a CCD camera (256*256 pixels), an image processing station (currently version 2.0) using a Macintosh-type gray scale monitor, and a 2.5-axis micro-milling machine driven by electrical motors. In the strictest sense, it comes close to being a CAD/CAM system, although it has no CAD surface design capability (in particular, the occlusal surface).

The above is a new version of the system, recently introduced to the market, that substitutes an electric motor for the conventional hydraulic motor. A lubrication fluid is sprayed on the ceramic piece during milling. Under this system, feed movements and circular motions are better coordinated.

Outlined below is the 2.0 version of the process:

1. The inlay cavity is prepared based on prescribed criteria included in the user's manual.
2. The dentist can work with the camera either directly in the mouth or from a stone model.

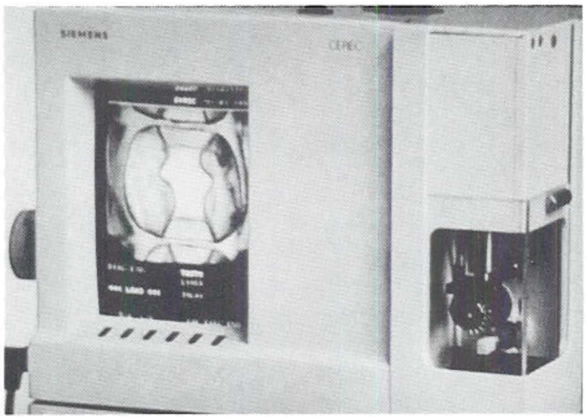

Fig. 14. The Cerec system.

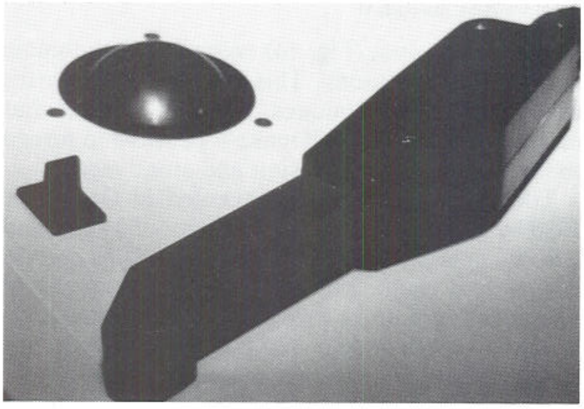

Fig. 15. The probe of the Cerec system used in taking pictures in the mouth of the patient.

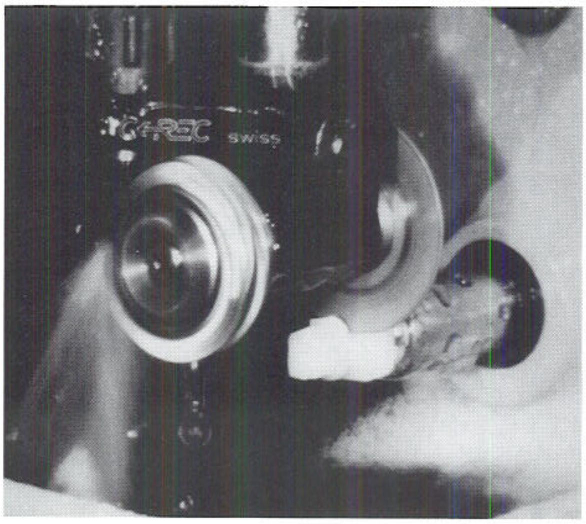

Fig. 17. Milling of the piece of ceramic with the hydraulic motor.

3. A coating (opaque coating giving the tooth surface a regular Lambert reflection) is deposited for good light reflection.
4. A camera (Fig. 15) takes a picture in the axis of the preparation (even distribution of the shaded zones), and the "field depth" is adjusted.
5. The inferior limit of the cavity is traced (Fig. 16) as are the ridge lines on the screen.
6. A ceramic blank (Vita or Dentsply) is installed according to the program instructions and milled with lubrication using a disk approximately 2.5 cm in diameter (Fig. 17).

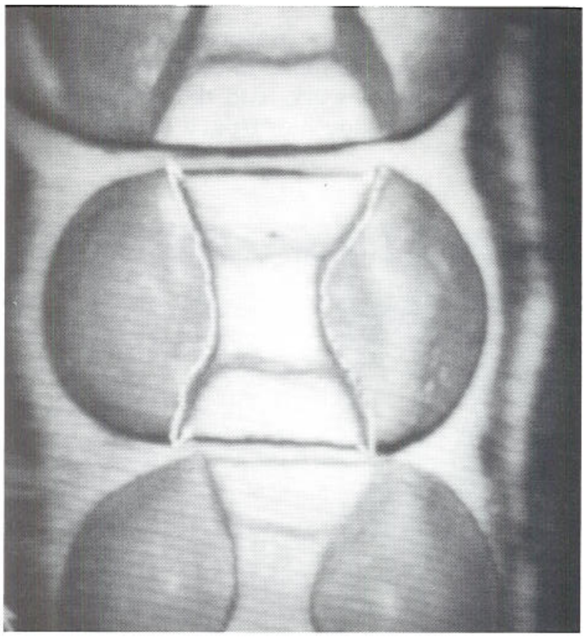

Fig. 16. Adjusting the depth of the preparation.

7. The occlusal surface is shaped manually in the mouth or on the model.

A number of scientific articles, written by various university research groups,[33,34] offer a relatively precise idea of how this system performs.

This system has the primary advantage of 3 or more years of clinical experience.[35] The machine is compact and easy to use, and the new version of the software is practical and executes commands quickly. Milling is quick, and ranges between 4 and 8 minutes.

The major drawback of this system is the need to produce the occlusal surface by hand, which increases the risk that too much of the material will be removed. The user is handicapped, as he must carve in a certain way such as not to lose accuracy. Priced at $55,000, the system is relatively expensive for the features it offers (inlays and veneers), and development potential is probably low. Still, this system is a reasonable tool because it is relatively easy to handle.

THE SOPHA CAD/CAM

In March 1991, the Sopha Development Company acquired the Hennson International Company (Vienne, France); the combined companies are now called Sopha Bioconcept. The previously named Hennson system is now referred to as the Sopha CAD/CAM system (Fig. 18).

The author, Professor François Duret, inventor of the dental CAD/CAM, designed the system that

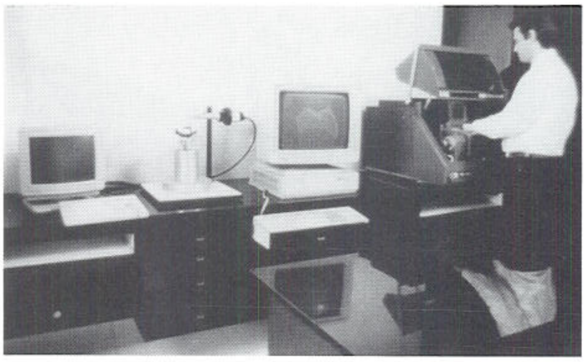

Fig. 18. The Sopha CAD/CAM (we find the three elements of the CAD/CAM: *left*, optical probe; *middle*, CAD station; *right*, CAM machine).

is developed and marketed by the Sopha Bioconcept Company. This system combines the three basic elements of the dental CAD/CAM: data acquisition with analog-digital conversion (using opto-electronics, Fig. 19), a CAD station with wireframe surface representations, and numerically controlled milling (Fig. 20).

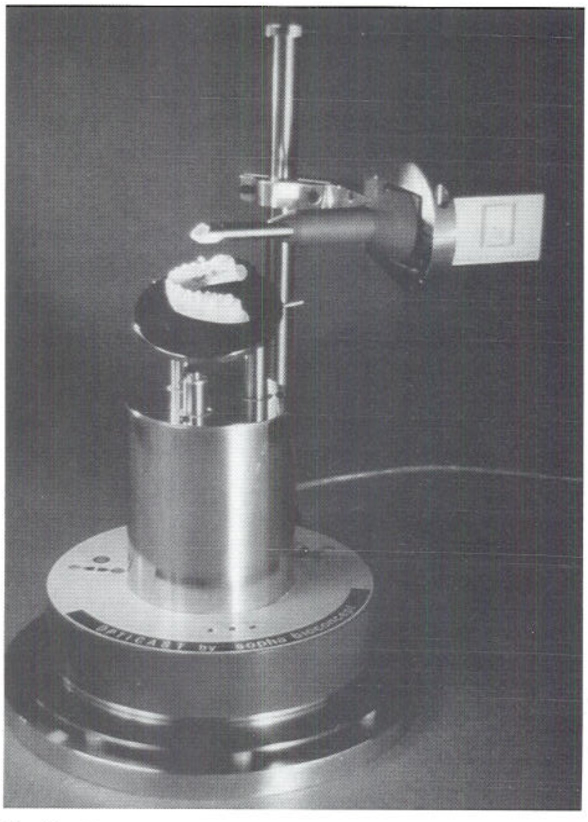

Fig. 19. The opticast with the data computer acquisition (Cubic).

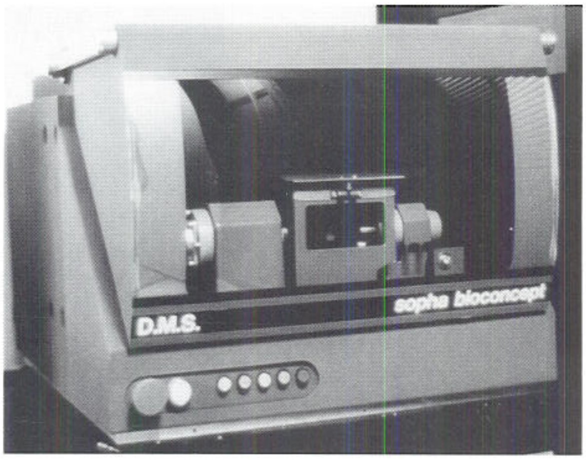

Fig. 20. The DMS: the Sopha micro-milling machine for ceramic.

The Opticast station includes a CCD camera (512*512 pixels) that takes the pictures using an interferometric method derived from electronic Moires.[36] The camera is fixed above a motorized tray supporting the model. The model may thus be positioned at any desired angle and elevation with respect to the camera, making it easier to manipulate and avoid movement of the probe during imaging.

The BioCAD station (Digital Equipment workstation using Euclid CAD/CAM software from Matra Datavision) displays a model of the mouth's environment, the adjacent and antagonist teeth, and the future restoration.

The DMS station (Dental Milling system) is a four-axis micro-milling machine specifically designed for this purpose.

The purpose of this system is to produce posterior and anterior crowns (1987–1990), ceramic copings (1991), and mono- and multi-surface inlays (1992). It is anticipated that future systems will produce bridges (1993) with static (1990) and dynamic (1993) occlusions.

The first step in the process consists of the preparation of the tooth for a crown or inlay, for example. The technician deposits a thin-coating film or uses a model made of adequate light-reflective (Lambertian) properties. Up to 16 views (6–8 is the norm) of the preparation (Fig. 21) and its surrounding area, including opposite teeth, are taken.[37] The image processing system enables the technician to indicate the point and lines needed to produce the restoration (*e.g.*, grooves, contacts, cusps, margin, etc.).

The modelization (Fig. 22) at the BioCAD station uses the model of the preparation (Fig. 23) to

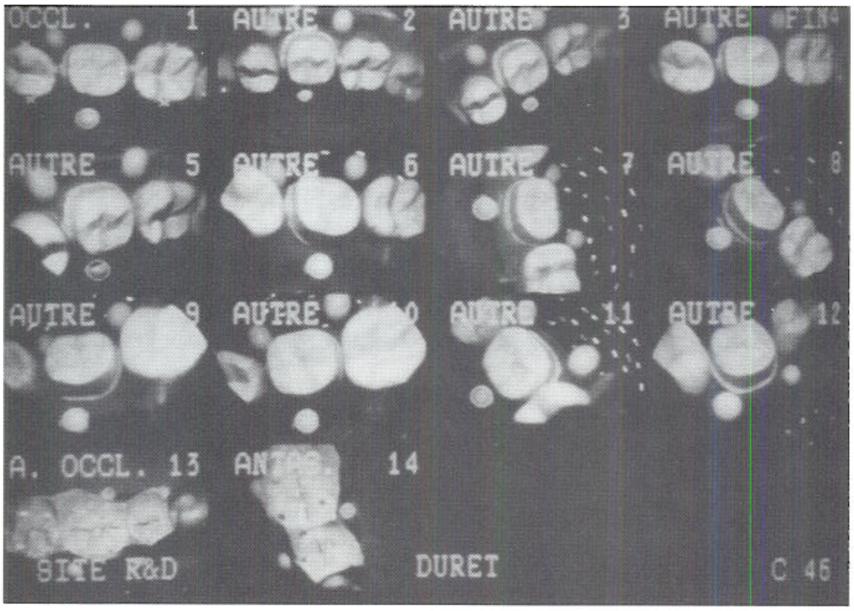

Fig. 21. The general view of the model on screen with the interactive indications.

design the inside, as well as the four external surfaces (Fig. 24) and the occlusal surface (Fig. 25) of the future restoration. A menu automatically controls the design, and any corrections desired by the user may be incorporated at this time. The occlusion menu makes possible a normal, cusp to cusp, inverse, or anterior-posterior occlusion. Another function controls and adjusts the thickness of the material as well as occlusal interferences. The Access articulator (Fig. 26), an electronic articulator currently under development, will provide additional data making it possible to control further the occlusal surface and correct it based on the dynamic mandibular movements.

The DMS will automatically mill a crown-type restoration in 45 to 75 minutes, depending on the

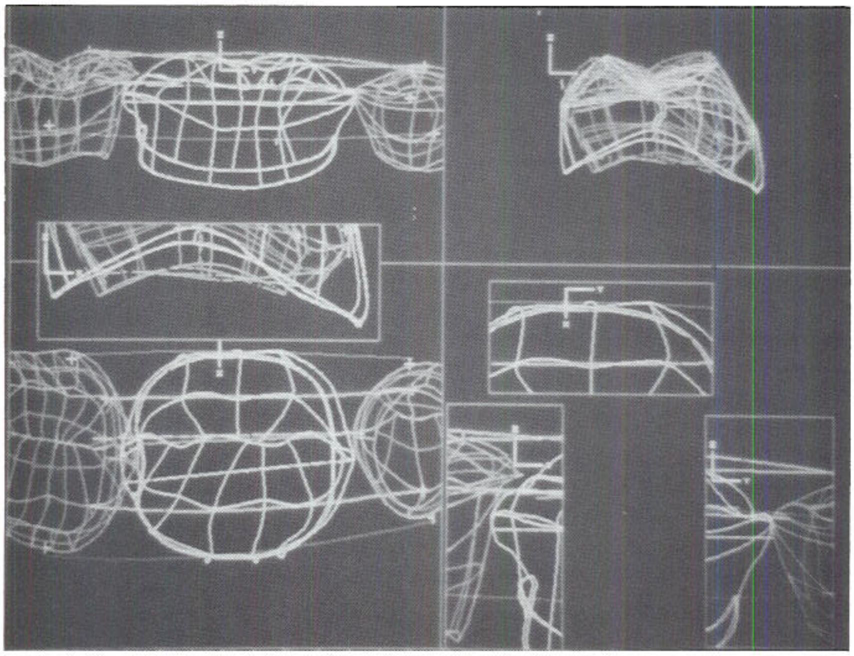

Fig. 22. The design of the outside of the crown (representation with the adjacent teeth).

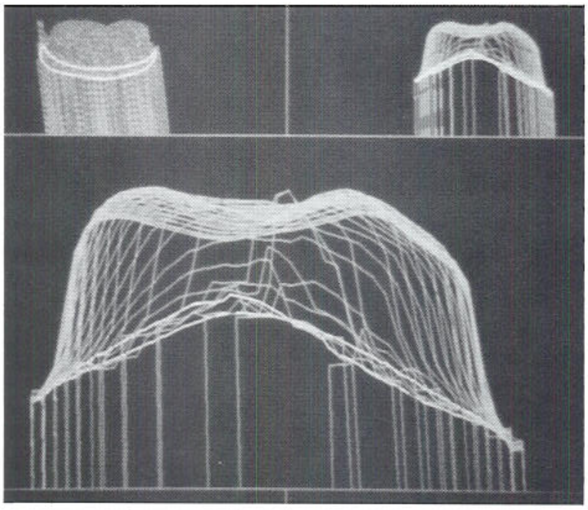

Fig. 23. The preparation of the ceramic reconstruction.

size and complexity of the restoration (Figs. 27–30).

Twenty-seven systems have been installed, and after studying the clinical results of the former Hennson International Company, Sopha Bioconcept has upgraded production to start manufacturing a second-generation machine that allows the manufacture of crowns, inlays, onlays, and copings using such varied materials as resins, composites, ceramics, and metal.

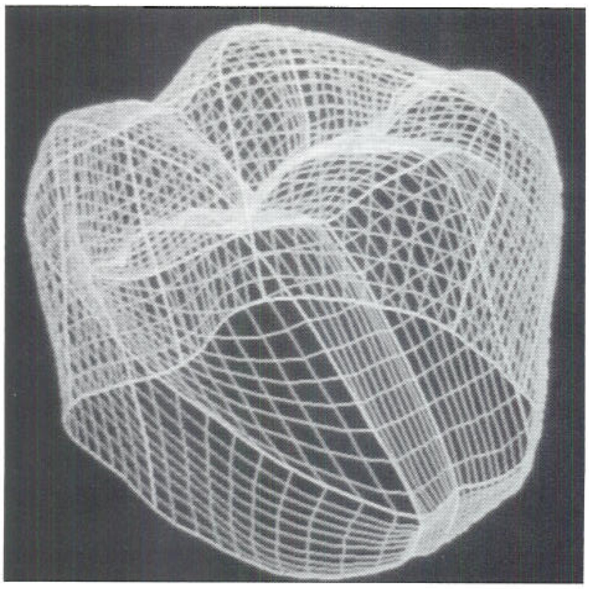

Fig. 24. The theoretic tooth in the CAD memory.

The clinical history of this system shows that (1) procedures for taking impressions in the mouth are in need of, and are, being refined; (2) it can be used by dental laboratories as well as by dentists; and (3) the operator of the system can be a dental technician or other trained dental professional (e.g, dental assistant, hygienist). The initial cost is relatively high ($150,000), but the production costs of restorations are about the same as for the Cerec system. The Sopha CAD/CAM is accurate to between 0 and 50 μm at the margin,[37,38] as shown in research being done at USC dental school and to be reported in the literature in the near future.

The advantages of this system have often been described in the international professional press.[4,20,22,25,28,32] It is the only system available today that can produce a complete restoration, it is simple to use, and a trained user can usually produce a crown in less than 1 hour. The system can be expanded to multiple configurations, and now that ownership has been acquired by a company experienced in medical imaging, the expansion is expected to occur quickly and effectively.

A SPECIAL CAD/CAM SYSTEM

A special CAD/CAM system that uses robotized mechanics and unconventional methods should now be mentioned.

The Krupp system, or dental spark erosion, invented by Dr. Korber of Tubingen, is often overlooked, although it has some interesting features.[39] Not only does it mill crowns and bridges in titanium by means of electro-erosion, but it also mills the same items in nonprecious metals, such as Dentitan and Endocast (Krupp Dental, Essen, Germany). This system has been demonstrated several times at scientific meetings in Europe. It uses the same electro-erosion process described for the Procera s37tem. The principal features of this system are a plaster model, a (special) wax reconstruction that is cast onto two metal and conductive components limited by the line of maximum curvature. As shown in Figures 31 and 32,[40] the operation must be finished manually. This system is being marketed by the Krupp Company. Serious clinical studies have been conducted on this system, which found an accuracy of approximately 40 μm.

SYSTEMS UNDER DEVELOPMENT

Several projects are currently in the development stage, although the results are not yet available for evaluation. It is difficult to determine their true

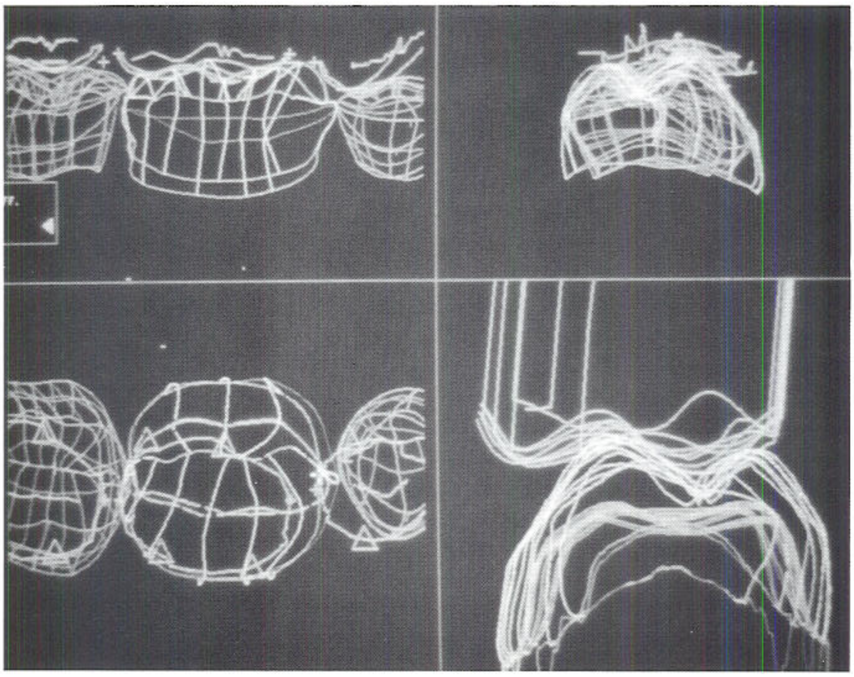

Fig. 25. Adjustment and section at the level of the centric point adaptation.

level of progress, but it seems appropriate to mention them because we can anticipate interesting results given the impressive reputation of the researchers involved.

The first system is being developed in Japan (Fig. 33) under the direction of Professor Sadami Tsutsumi, who is working in collaboration with several universities. For more than 3 years, numerous articles about this system have been published in scientific journals.[41] The system is composed of a dual sensor reading system,[42] which projects a fringe of structured light based on the principles of stereoscopy. The views are automatically correlated, being taken simultaneously on both the buccal and lingual sides of the preparation. The CAD station directly uses the isoplanes

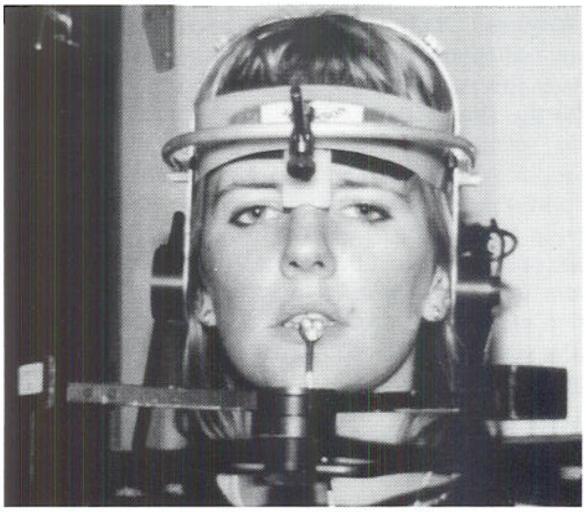

Fig. 26. The optoelectronic recording of mandibular movement with 6 degrees of freedom (the Access Articulator).

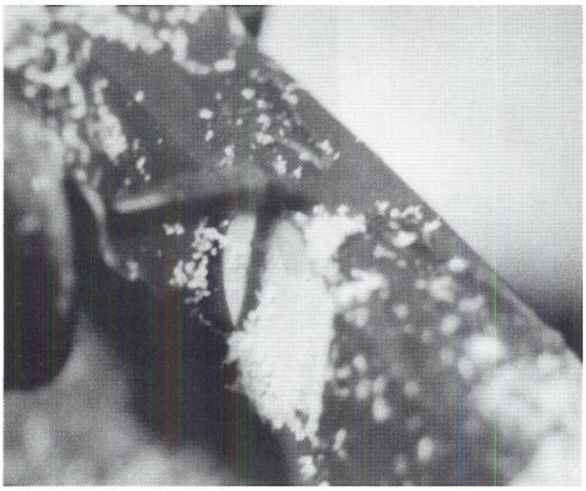

Fig. 27. Beginning of the milling of the crown.

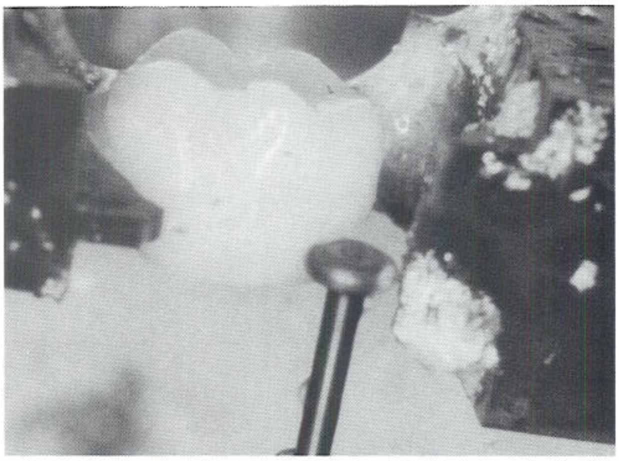

Fig. 28. Inside step of milling.

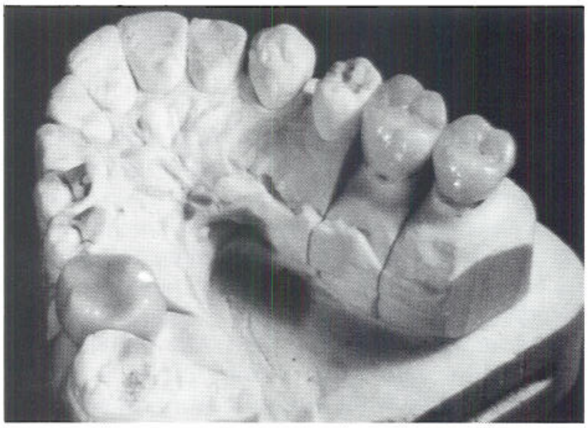

Fig. 29. Finishing of the outside surface by the DMS.

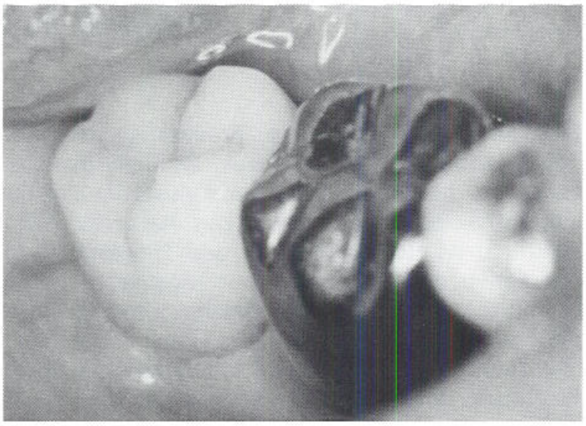

Fig. 30. Sopha CAD/CAM crown in the mouth.

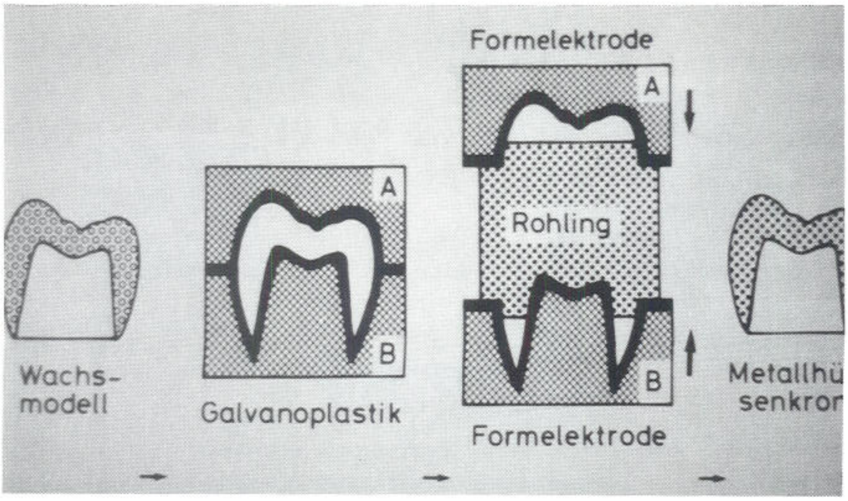

Fig. 31. The Krupp system: wax model, galvanoplasty, spark erosion, and the metal crown (4 steps).

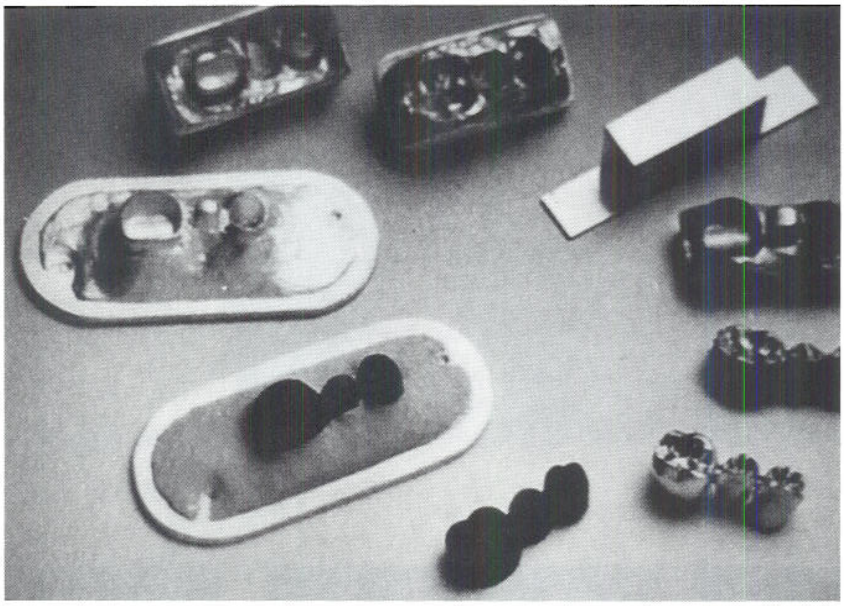

Fig. 32. The different steps of the Krupp system.

from the Tilcompo image processing program (Fig. 34) to model the surfaces. By detecting the margin, a theoretic tooth (Duret process) can be adapted.[43] Some teeth have been mathematically described as Bezier surfaces and B-splines.[44] A complete occlusion menu allows for production of an entire crown. The numerically controlled machine tool is still semiautomatic (Figs. 35 and 36). The quality of the work and the reputation of its developers deserve the profession's attention.

The second system is the Cicero system, which is being developed by Elephant Hoorn in Holland. It has only recently appeared on the research market. This system, invented by Dr. Van der Zel,[45] uses the three conventional CAD/CAM components described for the Sopha CAD/CAM system, that is an optical reader (Fig. 37), a CAD station, and a numerically controlled milling machine (Fig. 38). The optical reader and the milling machine are the same as those used by the Japanese team (sweeping by laser fringe and standard Japanese milling machine). This CAD/CAM system uses Dr. Duret's concepts, which are a theoretic tooth[8,9] adapted to the patient's morphology (e.g., preparation, adjacent teeth, opposite teeth)[9] and dynamic occlusion,[46] among others.

Elephant added the interesting concept of milling the die (as with the Procera system) on the

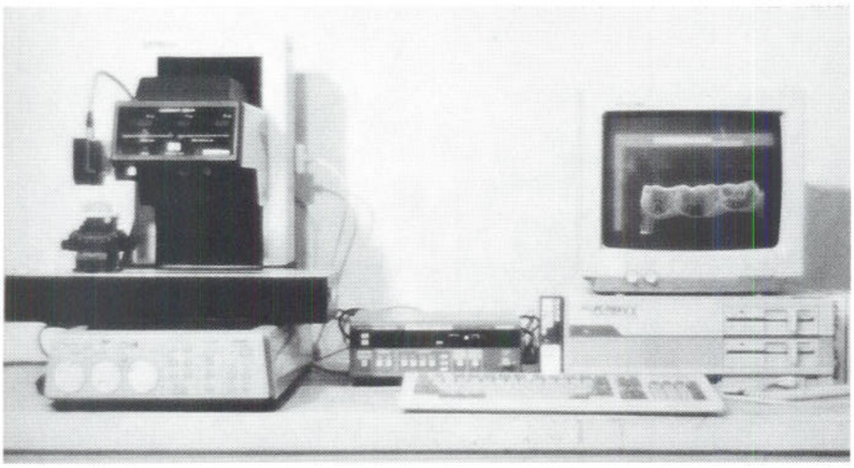

Fig. 33. The Japanese system for casting the model.

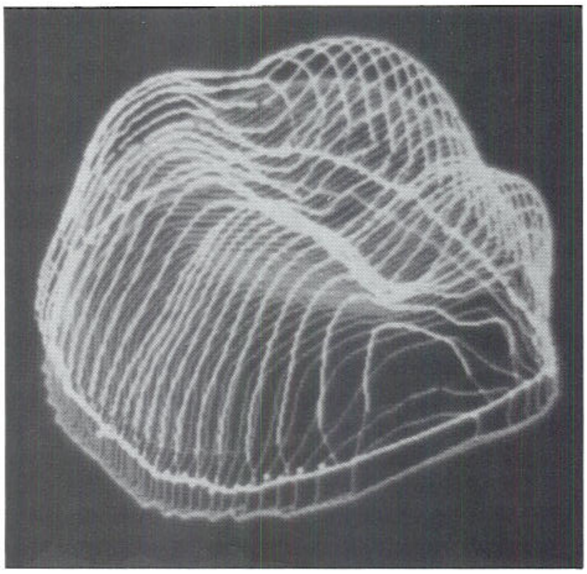

Fig. 34. The design of the crown.

milling machine,[10] based on the reading of the model. A layer of metal is then handpainted with a brush onto the die. A layer of ceramic (Carrara system) is added, depending on the preparation, using the milling machine. No inside surface is produced, but a material is deposited directly by hand onto a tooling die, and then the external surface is milled. As seen in the photos, this system is in its developmental stage.

Fig. 35. The Japanese CAM milling system.

The third system is the Bego DentiCAD system. Since the system was first publicly announced in 1986[47] by its designer, Dr. Diane Rekow, a dentist and engineer, the system has undergone numerous evolutions. The German company, Bego, recently obtained a license for the German market. The system is proposed for laboratories, working on a model.[48]

The system is made up of a Bego electro-mechanical probe (Fig. 39). The CAD system uses a semiautomatic program developed by the Research Consortium Company, as well as an industrial, numerically controlled machine tool manufactured by Servo Products.[49] The system is semiautomatic; the part being milled is turned by air pressure, whereas the tools are changed manually (Fig. 40).

This system has already produced several crowns, although the conditions under which they were made remain unknown. Based on Dr. Rekow's publications, this system may be of interest.[50]

The last system is the Dens Dental system designed by Rohleder and Kammer. This "Berlin system" is the direct result of research conducted by a young research team from Berlin University.[51] Although only in its nascent stage, a prototype was presented in 1992 at the dental show in Cologne. This system includes a fast prototype of optical reader on the model (a matrix projects a special pattern of laser light), a yet to be developed CAD capability, and a numerically controlled milling machine (Fig. 41) with automatic tool changes.

It is impossible to know exactly how much time will be needed before the first prototype of the Dens system can be produced, but give the zeal of the research team involved, it has been estimated that results may be forthcoming within 3–4 years.

THE CAD/CAM CONCEPT

Having completed the description of the various systems currently or soon to be available, this chapter will now provide an initial synthesis of CAD/CAM within the general scope of the dentistry profession. This dental development will first be redefined in terms of the most elementary unit used in imaging technologies: the *point*, the *pixel* or, better, the *voxel* if working in three-dimensional space.

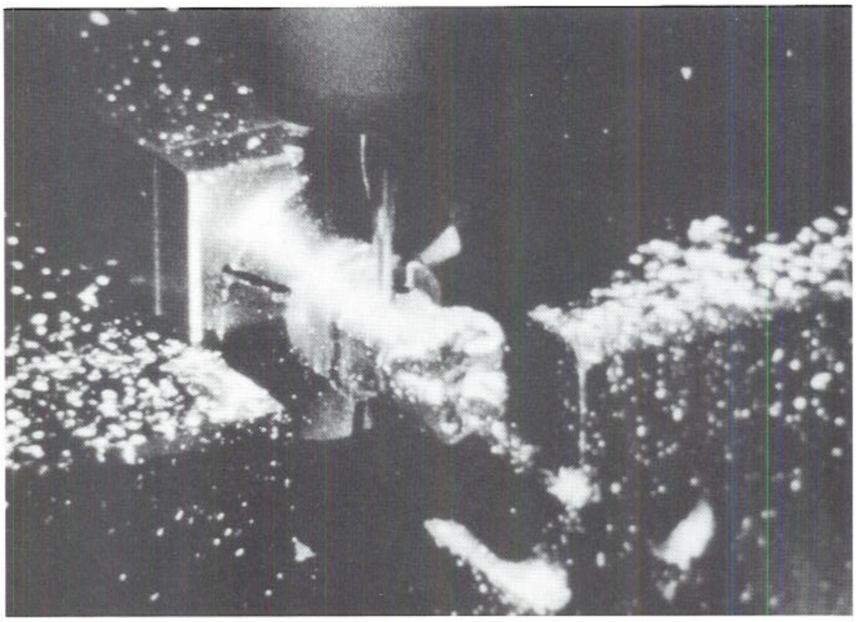

Fig. 36. The result in metal (Japanese system).

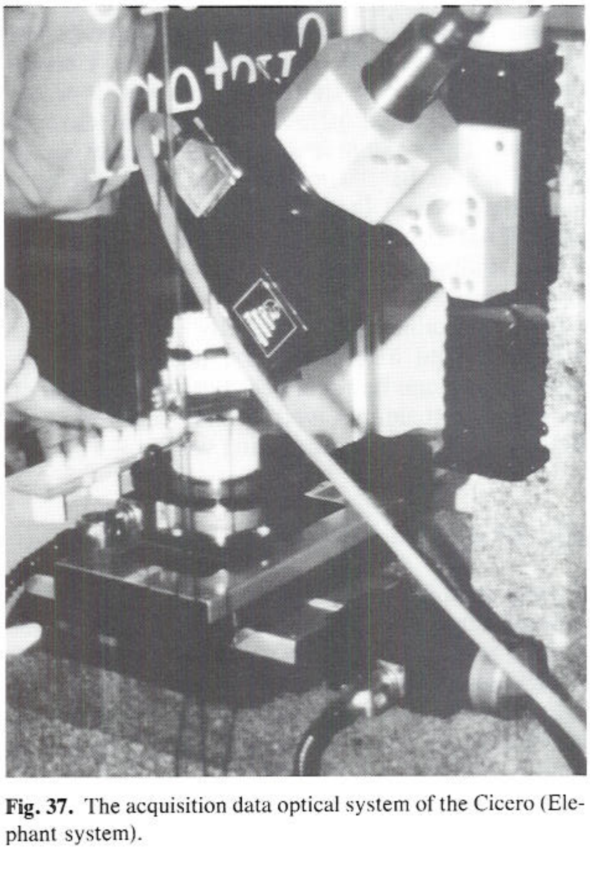

Fig. 37. The acquisition data optical system of the Cicero (Elephant system).

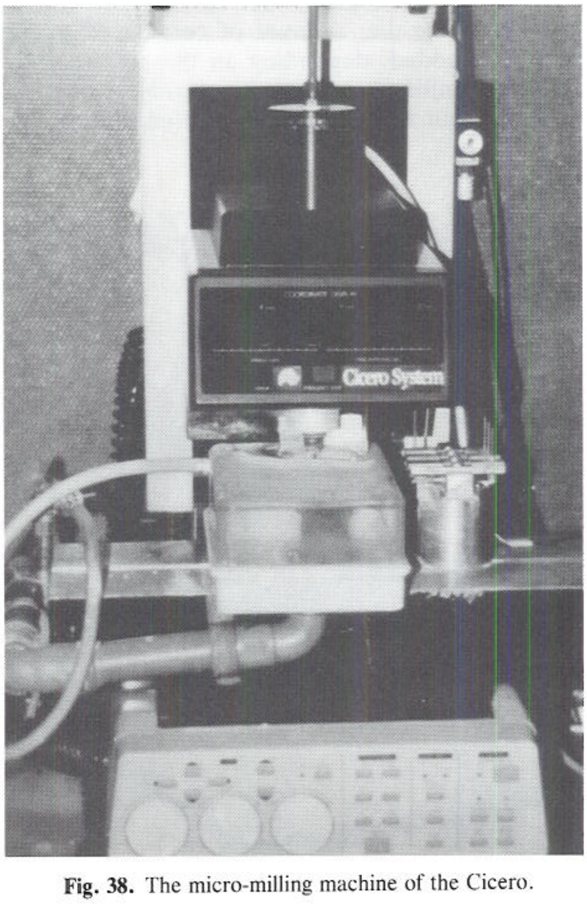

Fig. 38. The micro-milling machine of the Cicero.

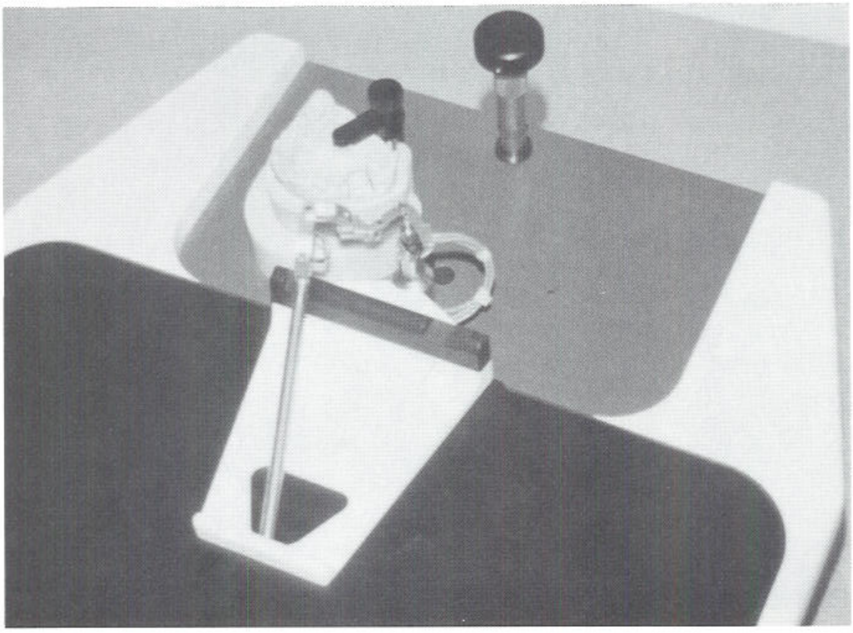

Fig. 39. The micro-sensor system for the Bego DentiCAD system.

After various definitions, professional actions into the variations of these elementary units will be discussed and the prosthetic methods classified based on the elements they use and supply. This explanation of CAD/CAM should not limit the extent of our thinking. It is only an example, which may be extended to other medical fields.

BASIC DEFINITIONS

Any static morphologic study of a part of the universe can be reduced to the analysis of its volumes, whether it is a question of vast spaces or a single part of the human body. Any volume can be defined as a portion of space limited by surfaces,

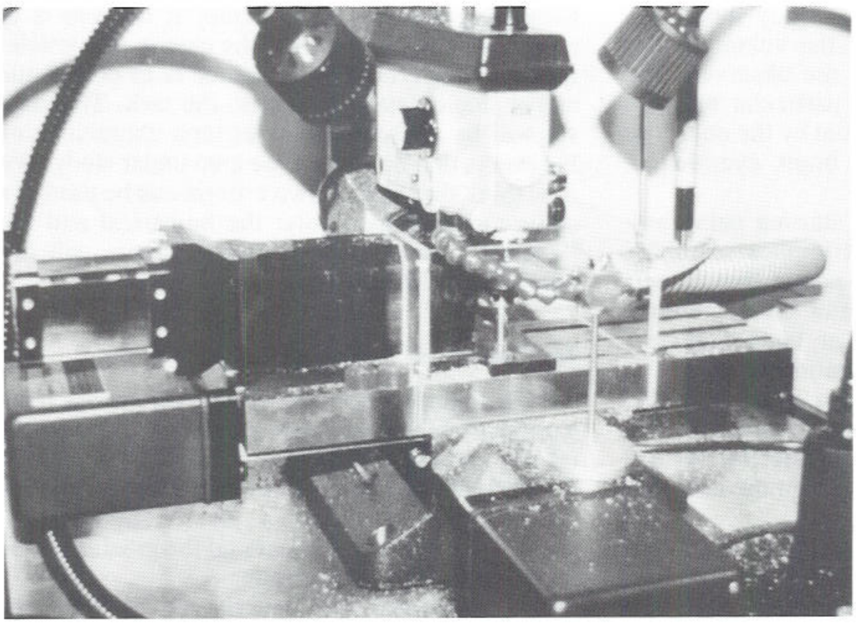

Fig. 40. The mini-milling machine (Servo products).

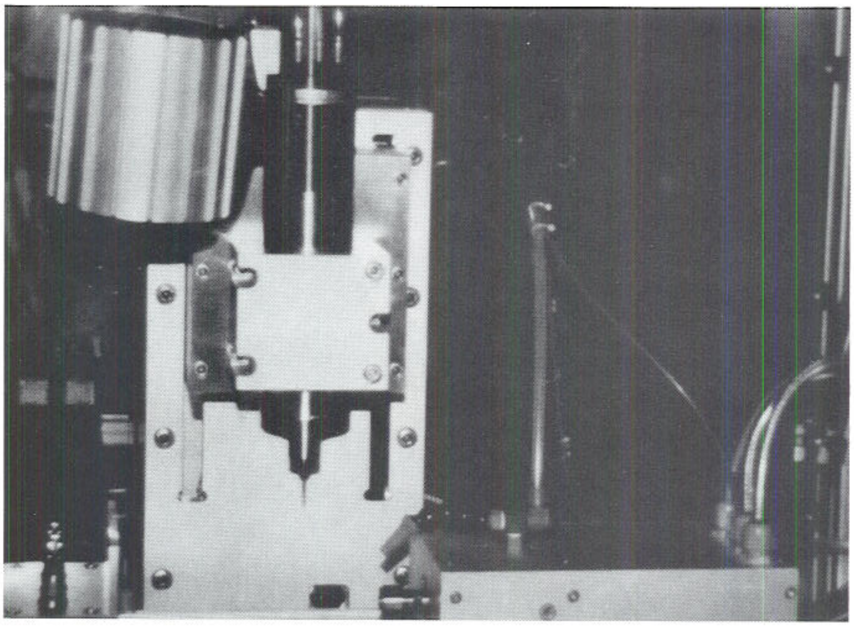

Fig. 41. The milling machine of the Dens prototype system in Berlin.

and control of these surfaces implies knowledge of the points composing them. These points can be classified as primary (or specific) and secondary points. They are identified by the criteria best characterizing them in the chosen space and in accordance with the objective of the study.

Any dynamic morphologic study can be reduced to the analysis of the variation of at least one element in the criteria characterizing the points of the above-mentioned surfaces. To the extent possible, a static or dynamic morphologic study should exclude any interaction between the volume under study and the means used by the observer. The external aesthetic behavior in particular must be considered as a disruption created by the object on the observation medium (e.g., brain, eye, education).

Using these definitions as a starting point, any study of the oral environment implies searching for criteria characterizing the points that constitute these surfaces. This is true of small volumes, such as molecular elements, or large volumes, such as teeth and dental preparations.

When extending this work to a dynamic study, attempts will be made to learn how these criteria vary over time. Regardless of the objective, everything will be reduced to an action on the acquired data.

Claiming to reduce our research to the mere handling of data may seem daring, but it is necessary to understand that our work today does nothing more when it asks the brain to act on discrete (i.e., divided into small units) volumes, namely the pixels of the CCD,[8–10,52] which is a scanner, the photosensitive points of the radiographs, or the cells of the retina.

GENERALIZATION

DATA COLLECTION

Collecting data is the first step. If the aim is to produce a restoration, as is the case in this article, the first concern of the operator is to collect the morphologic data pertinent to the task. This data set will be analyzed using criteria characterizing the points that constitute the area under study. We now think that at least two criteria can be used in a static morphologic study: the numerical and the "energy" values of the points. Others will undoubtedly be discovered.

The Numerical Values of the Impression

Taking an impression is basically the precise measurement of the position of all the points that make up the surface of the restoration's environment. The more precise the knowledge about the points (i.e., their coordinates x, y, and z), the more important will be their number and the greater will be the quality of the impression.

Two numerical data criteria can be used, the coordinates and the number of points. The coordinates determine how precise the impression is, and the number of points define the resolution of the impression.

Dentists routinely use this approach intuitively when describing the "precision" of a given impression material. In this case, the surfaces molded by the impression material are reduced to elementary units representing the smallest precision obtainable. In computer science, this is referred to as "sampling." The variations of the coordinates of some of these small reference surfaces are measured, and the two data ae combined such as to obtain a value of precision. In conventional methods, these numerical data are not known but are contained in the impression paste, which serves as a type of memory. With CAD/CAM, these numerical values are perfectly known.

The Energy Value of the Impression

A more in-depth study shows that all points do not have the same value. We will say that all points do not have the same energy. Some points of particular interest can be distinguished from others, and the degree of interest or energy is often a function of the desired goal. Therefore, a point on the margin is more energetic (more interesting) than the point next to it outside the future crown, and a centric point will not have the same energy, regardless of whether or not opposite teeth exist.

This notion of energy is important because it is quantifiable, that is, it can be classified within a mathematical system. As a concrete example, if an impression of a cube is taken with a desired precision of ± 100 μm and a resolution of 100 μm, and if the variations of the position of the points of its six surfaces never exceed the desired precision, there will be a multitude of points on the low-energy surfaces, others on the medium-energy edges, and eight high-energy (low-entropy) angle points. Indeed, using these eight angle points, the cube can be redefined at any time with the desired numerical characteristics.

Conventionally, our minds have been trained to recognize these eight angle points on a model. We can do the same with the cube displayed on the computer screen. We also know that the computer can be taught to find these eight points by itself. This was made possible by certain techniques using the energy differences of points. It is also the author's opinion that a computer capable of evaluating its own errors would be able to improve its performance by memorizing the corrections made by a dental professional while respecting the individual habits of each clinician.

The purpose of the energy analysis, which is incorporated into, or follows, the numerical analysis of the impression, is to define these high-energy points. On a stone diagnostic cast, this means marking the margin, the line of greatest contour, or the position of the contact areas. It is the same on the screen of CAD/CAM systems (certain points have already been automatically located in the new programs proposed by some manufacturers).

Summary

Data acquisition, or the impression, consists in taking the numerical and energy readings of the elementary points making up the volumes that are under study. The quality of the work will be proportional to the level of knowledge obtained on at least three types of data: the chosen resolution, the precision of the spatial measurements, and the energy of each of these elementary points.

DATA STORAGE

The analyzed surfaces are presented in the form of a large quantity of data, which is generally proportional to the discreteness of the system (*i.e.*, proportional to the number of elements into which the system has been divided). In the conventional method,[6,7] it is the impression material (analog data), whereas in CAD/CAM, it is digital data (a mass of numbers containing the position and energy of each point).

These data are stored in accordance with their form, which may be analog (model) or digital (computer memory). Impressions and disks are two identical storage units in the epistemologic sense of the term. The only difference is the technological system used. The data may also appear in other forms.

Data storage holds no special place in the therapeutic sequence. It is the memory of the state of the "patient" at a time T(0) as well as the memory at each different step of treatment (*e.g.*, T(1), T(2)). The energy selection may precede or follow the storage. The margin is traced on the plaster, whereas the posterior limit of a complete restoration can be drawn on the patient's palate to mark the impression.

MODELING

The quality of this stage depends on how carefully data are input in the data acquisition stage. If the data are faulty, the model will be inaccurate.

During this stage, a computer model of the original actual model is made based on the data input.

This stage may also include diagnostic analysis (RVG, Scanner, or MRI), therapeutic solutions, or the reproduction of any of these analyses using an output device (machine tool, copier, or any other reproduction device).

Modeling leads to the production of a model that can be used with current techniques. In the conventional method and in some CAD/CAM methods, a working plaster is used because the tool remains basically mechanical. In other methods that use the numerical tool, a computer screen reconstruction serves as a working base.

SELECTION

Reasonably priced computers have limited capabilities for handling complex calculations quickly (which is the case with the vast amount of data we must handle). This has forced the designers of dental CAD/CAM programs to make a selection among all the data available at the end of the modeling. The author has thus conceived the notion of energy value. This value makes it possible to recognize the relative importance of each piece of information coming from the data acquisition system.

In my opinion, this data selection is a decisive stage in computerized dentistry, for it requires knowing the necessary and sufficient values of the data received. I have no doubt today that it will become "the" field of research in the years to come, both conceptually and technologically. It also enables us to realize that the real models (as opposed to computer generated "virtual" models), like our castings, are unnecessary forms of energy waste, since only a portion of the information will be used.

Making a selection among the available points is a fundamental step, because it will allow us to know which data is really important to build a dental restoration. It is also a technological step because it will push manufacturers to make this selection increasingly automatic. This computer limitation thus turns out to be of great help to dentistry.

CREATION OF THE THERAPEUTIC ENVELOPE

With all the points furnished by the data acquisition system (*i.e.*, a set of points in space), and the modeling, which organizes them, we have a real copy (the model) or a virtual copy (computer model) of the part of the body being treated.

Relying on past experience, we have learned the rules that make it possible to construct new morphologic contours, such as a crown that corrects the diagnosed anomalies (we reconstruct new volumes and, therefore, new sets of points).

Creating the therapeutic envelope means creating a new therapeutic set of points stemming from the adaptation of general rules to individual cases. This adaptation can be done on real models (working with wax) or on virtual models (working on theoretical teeth).

Working with analog data, such as a stone model, limits our techniques to manual actions that are dependent on the technician's skill. Working with digital data opens important possibilities that are just beginning to be discovered.

This stage is not just a simple restoration of preexisting data, but it is also a true aid to diagnosis and therapy, a convergence point for dental rules, error checks, anatomic corrections, theoretical propositions and expert systems.

Unlike many computerized medical assistance systems, which merely show a picture enhanced with the whole palette of electronic treatments, the dental CAD/CAM proposes a true medical methodology that ends with the actual execution of the therapy.

Various experiments conducted over 3 years at the University of Southern California (USC), in Los Angeles showed that the environment is as much a bearer of information as is the genetic support of the organ itself.

EXECUTION OF THE THERAPY

The execution of the therapy is no more than a "manufacturing" process the value of which depends on the mechanical qualities of the system used and the skill of the operator.

In the case of an analog process, that is the conventional method, the execution is nothing more than a substitution from a moldable substance to another, more resistant substance. In the case of a digital process, a robot executes the orders coming from a computer and manufactures an object conforming to the computer model. These two operations are identical.

In the case of CAD/CAM, we often speak of digital-analog conversion, for we are going from a virtual surface designed on the computer screen to a real crown.

CLASSIFICATION

Review of the author's article, published in the "Cahiers de Prothèse,"[6,7] showed that the three types of data acquisition defined then are now available on the market. They are as follows:

- Chemical-manual acquisition;
- Electro-mechanical acquisition; and
- Opto-electronic acquisition.

Chemical-manual acquisition is the conventional method, for it uses a chemical impression paste that is manually manipulated. Four systems rely on the electro-mechanical acquisition method (the Celay, the Procera, the Krupp, and the Titan), whereas two systems have opted for the opto-electronic method (the Cerec and the Sopha CAD/CAM). In the systems under development, one system relies on the electro-mechanical acquisition method (DentiCAD), and three systems use the opto-electronic method (Japanese, Elephant, and Dens).

As these are all very complex processes, this discussion shall refer to the basic unit, or the point, to derive a general classification of the prosthetic production processes. Because this classification does not yet include the time/deformation ratio, it is based exclusively on static morphologies.

DATA ACQUISITION

The quality of the data acquired is defined by the resolution, precision, and energy of the point. Resolution is nothing more than a rapidly changing technologic expression, especially in the field of electronics. Precision is important. It reflects the stability of the data and is a measurable variable of time. As demonstrated earlier, the difference between the static and dynamic behavior is the variation of at least one characteristic of the elementary points. The criterion of quality here is the speed of acquisition, as the object is subject to movements and deformations. As a result, the acquisition modes are classified according to their speed in integrating data. Energy is currently an added value, which should not be ignored. However, it is not yet a component in the foundation of our argument.

Please note that in the following classifications, the names of the systems under development have been *italicized*.

1. Point-by-point acquisition (micro-sensor reading):
   - Celay
   - Procera
   - Titan
   - *DentiCAD*
2. Linear acquisition (fringe of structured light):
   - *Japanese*
   - *Dens*
   - *Cicero*
3. Surface acquisition (global acquisition in a short time):
   - Krupp
   - Cerec
   - Sopha CAD/CAM
   - Conventional method
4. Multisurface acquisition:
   - Sopha CAD/CAM
   - Conventional method

The further down the scale (from 1–4) one goes, the greater the risk of error between the beginning and end of data acquisition. The multisurface acquisition may be an advantage as it increases the resolution and reduces the acquisition time. It can also be a disadvantage due to potential errors in the correlation of each view.

DATA HANDLING

The numerical and energy values of the data are predominant in data handling. Is it possible to introduce a discretionary data between the different data, and do we know their absolute (digitizing of the data with respect to a theoretic and absolute space reference) or relative positions (incorporated in the object itself within the model)?

1. Analog data (no numerical data defining the acquisition):
   - 1.1. Without energy value given interactively:
     - Celay
     - Procera
     - *Krupp*
   - 1.2. With energy value given interactively:
     - Conventional method
2. Digital data (value expressed in numbers):
   - 2.1. Without energy value given interactively:
     - *Dens* (under production as of this writing)
   - 2.2. With energy value given interactively:
     - Titan
     - Cerec
     - *Elephant*
     - *Japanese*
     - *DentiCAD*
     - Sopha CAD/CAM
   - 2.3. With automatic energy value:
     - None

This classification makes it possible to observe that the durability of the data will be reasonably possible only in categories 2.1, 2.2, and 2.3. Indeed, the digital form may be duplicated; it does not depend on the physical conditions of the environment and is located by a theoretic reference system independent of the object itself.

It should also be noted that the nascent stage of the systems can be seen today by the lack of a product responding to point 2.3, that is, searching automatically for the specific points of an impression (*e.g.*, centric points).

DATA ENHANCEMENT

Data enhancement implies that a new set of points will produce an object other than the object from which data have been acquired. For example, a wax model made from the impression data is a creative act that enhances the data. On the other hand, copying or dilating a copy of the part is not an enhancement action. This stage is important, because it sets simple duplicating systems apart from those that are capable of producing complete restoration.

1. Copy of the part with or without dilation:
   - 1.1. With an intermediary piece:
     - Procera
     - Titan
     - Krupp
   - 1.2. Without intermediary piece:
     - Cerec
2. Copy with creation of a new set of points:
   - 2.1. Provided by the intermediary piece:
     - Conventional method
     - Celay (occlusal surface)
     - Procera
     - Titan
     - *DentiCAD*
     - *Elephant*
   - 2.2. Provided by software:
     - *Japanese*
     - Sopha CAD/CAM

Many systems stop after they have produced a copy of the object and, therefore, do not add anything fundamental to the data. These systems are incorrectly classified as CAD/CAM systems. Only the DentiCad, the Japanese system, and the Sopha CAD/CAM deserve this title. Much work remains to be done with this classification. It is here that a great portion of know-how is stored and processed and it is also here that future generations of clinicians must concentrate their efforts.

PRODUCTION

As previously mentioned, production of the object is only a "passive" step relative to the set of points being worked on. It is the reproduction of an object that has been acquired or created in the previous phases. Each system shall now be classified according to the types of restorations it can produce. Excluded are all systems under development, as their ultimate production capability is impossible to predict.

1. Inlay production:
   - 1.1. Without occlusal surface:
     - Cerec
     - Sopha CAD/CAM
   - 1.2. With occlusal surface:
     - Celay
     - Sopha CAD/CAM
     - Conventional method
2. Veneer production:
   - Cerec
   - Sopha CAD/CAM
   - Conventional method
3. Ceramic coping production:
   - Krupp (using nonprecious metals and titanium)
   - Procera (using titanium)
   - Titan (using titanium)
   - Sopha CAD/CAM (using ceramic and titanium)
   - Conventional method (using precious and nonprecious metals and ceramic)
4. Crown production:
   - Krupp (using nonprecious metals and titanium)
   - Sopha CAD/CAM (using composite, ceramic, and metals)
   - Conventional method
5. Bridges:
   - Conventional method
6. Other (*e.g.*, removable prosthesis):
   - Conventional method

CONCLUSION

"Crown Produced in Less than One Hour" is one newspaper headline that has made dental professionals and researchers grit their own teeth. As Christian Knellesen said, "let us judge in a few years those technologies which survived."[4]

After 7 years of research and development, six systems are currently on the market: Celay, Procera, DCS-Titan, Cerec, Sopha, and Krupp. Four others are under development and may be ready in the next 5 years: Japanese, Cicero, DentiCAD, and Dens. Who can maintain doubts about this technology? Will we still see the dental profession's equivalent of defenders of the horse-drawn carriage block the way when CAD/CAM systems are used in one of 300 dental offices?

It would, of course, be a mistake to think that everything is finished and that dental CAD/CAM has proven itself. It still has a lot to prove, but it has come a long way since it was first demonstrated and the first CAD/CAM crown produced in Paris in 1985.

All those who embrace this concept must be aware that they are entering a marvelous but risky field, and the choice is theirs alone. As did the first test pilots, they will confront risks that no one can predict, and as with those early pioneers, they will experience great joys and disappointments.

For researchers like us, dental CAD/CAM is a difficult field. A new era of dentistry is emerging. Our ideas must be revised, and we must dissect the work of our colleagues to ensure that we have not forgotten anything but have respected our heritage. We must ponder and understand what led a colleague to write or think the way he/she did. Our reflections should be made away from machines, for we know that they are short-lived. At the same time, we cannot leave clinical reality behind. How many hours of hope and disappointment does this work represent? The dentistry that Fauchard, Black, and others originated has made its mark. It provided the basis on which the new dentistry was conceived. (As was the case for the theory of relativity in conventional physics, it will perhaps become a specific case of a general concept in dentistry.)

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