USE OF CAD/CAM IN DENTISTRY

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I. INTRODCUTION

A series of closely linked steps are required to make a fixed dental prosthesis. After any preparation, dentist must take an impression of prepared tooth, together with adjacent d opposing teeth, using elastic impression material. This impression is used obtain a hard stone model, and a wax pattern of the crown or inlay is carved. The actual cast restoration is obtained using the "lost wax method.1

Regardless of the advanced state of this 300-year-old technique, information must still be transferred by hand from the impression to the finished crown, via a series of materials, each of which may induce error in the final castings. This system of casting does not allow us to take advantage of tremendous advances in computers and robotics. For these reasons, we introduced CAD-CAM technologies to the dental profession in 1971. 1

The advent of interactive computer graphics, computer-aided design and computer-aided manufacturing laid the groundwork for a revolution in engineering-and dentistry. CAD-CAM provides tools to automate design and production, improving productivity and quality.2

Dental CAD-CAM systems are being developed to bring this automation to produce dental restorations. Restoration design, whether with the lost wax casting technique or a CAD-CAM system, has three functional components:

- data acquisition;
- restoration design;
- restoration fabrication. 2

With the CAD-CAM systems, data acquisition (all the steps currently involved in taking an impression and with some systems, creating models and dies) can be automated. Design, currently the waxing process, is replaced with computer commands supplied either interactively by the user or by special programs called an expert system. 2

Investing and casting techniques can be replaced by faster fabrication techniques used in modern manufacturing. Varied technologies can accomplish the automation in the dental CAD-CAM systems. 2

It is now possible to design and fabricate ceramic restorations at a single appointment, as opposed to the traditional method of making impressions, fabricating a provisional prosthesis, and using a laboratory for development of the restoration. Eliminated are certain errors and inaccuracies that are inherent to the indirect method. Additionally, CAD-CAM-generated restorations save the dentist and patient time, provide an esthetic restoration, and have the potential for extended wear resistance.3

II. HISTORY

Early studies have been more experimental and theoretical than clinical. Although these outstanding works have been consulted, we have stressed the clinical aspects of application rather than the fundamental. 1

Optical scanning and computer generation of restorations were attempted as early as 1971 (Altschuler, 1971/1973). In 1979, Heitlinger and Rodder, followed by Moermann and Brandestini in 1980, began to share this approach. The former researchers milled the equivalent of the stone model used by a dental technician to make the crown, inlay, or Pontic, while the latter team took single picture and milled only the internal surfaces of the inlay. During the next 5 years, little was heard. The first dental CAD-CAM prototype was presented at the Garanciere conference (France) in 1983, and the first crown was publicly milled and installed in a mouth without any laboratory involvement in 1985. Though 1985 was a decisive year for computer-aided dentistry, there was still a long way to go. Several engineers took 2 hours to operate the first usable system in a dental office. Nevertheless, this demonstration at the French Congress vindicated principles established 14 years earlier. 1

Two new names appeared at this time, the Aoki team in Japan and Diane Rekow at the University of Minnesota. Dr. Rekow chose a photogrammetric method to acquire the third dimension and used the principle of the theoretical tooth. It should also be mentioned that Reggie Caudill, at the University of Alabama, started a project aimed in the same direction. 1
With the continued improvement in the technology, a number of systems are currently being investigated at this time (Duret et al, 1988; Williams, 1987; Rekow, 1987; Brandestini et al, 1985; Duret and Preston, 1991). Additionally, other computer systems for creating dental prostheses are being developed (e.g., The Celay System, The Procera System, The Titan System, and several projects from Japan). It appears that the teams most actively pursuing this technology of CAD/CAM in dentistry are the French group, headed by Dr Francois Duret, the Duret system, the DentiCAD unit at the University of Maryland, led by Dr Dianne Rekow; and the Brandestini/Mormann unit working on the Cerec system3

III. THE DURET SYSTEM

1. **Equipment needed in dental office:** Instead of using a physical model (die) to acquire and transmit information, the CAD-CAM system uses a three dimensional probe system, surface modeling, and screen display, and an automatic milling machine. Exchanges and transformations of information from one material to another during which precision may be lost, are thus limited. 1

   An electro-optical method is used to obtain the "impression" (that is, the necessary three-dimensional information). This method combines holography19 and Moire2°: the light carries volumetric information, which is digitized by camera and fed into the computer. The resulting data are stored by the computer. Because all of the variables contained in a single impression (more than I million values for three teeth) cannot be measured, dentists had to use visualization. They understood quickly that measuring and reproducing with a model are identical functions. The only difference between an optical and a traditional impression is that the former uses numerical values in place of a physical model. The stone model or die is thus analogous to a memory system in which information is stored, as on a computer disk.

   The CAD system (hardware and software) uses encoded information to allow the operator to visualize an impression on a graphic screen, and to design a prosthesis. This step is equivalent to the creation of the wax pattern on the stone model. Modifying the surface of a crown or inlay as displayed on the screen is equivalent to adding or removing wax material to or from the die.

   In the last step of the process, the lost wax technique is replaced by the milling of a preformed cubical block of material. Although traditional materials may be used, this new technology encourages the development of new dental materials. 1

The CAD-CAM system includes three parts, which correspond to the three basic steps of the process:

- First, a device is used to input the existing dental shapes into the system. This device includes a laser source (diode) which, through the first endoscope, projects light on the desired picture area. A second endoscope, adjacent to the first, allows a camera to take pictures in the mouth. This camera is connected to a system that digitizes the information and correlates the different views
- Next, the CAD system, including all necessary hardware and software, allows the operator to create an electronic model of the impression, display it on the screen, and use it to design the prosthesis. The CAD system is linked to a proprietary articulator, called the Access Articulator, which provides the data relating to the dynamic movements of the jaw. 1
- Third is the CAM system, which includes a numerically controlled machine tool with four-axis capability. This machine will automatically mill the prosthesis from conventional or special materials. 1

These three parts can be linked in several different ways. Three possible configurations are presented:

- A complete system may be used in a dental office with a single operating room. The optical probe system should be located near the dental chair; the CADCAM parts should be placed in another room. This configuration allows for immediate milling of the prosthesis while the patient is still under local anesthesia. It is possible to reduce costs if several practitioners share the system which could be installed in a specific area. 1
- A dental office with several operating rooms may have one CAD-CAM System installed in a separate room, while each chair would have its own Optical probe system. Although somewhat expensive, this configuration eliminates the necessity of moving the patient to the equipment or of waiting to use system. It is also possible to connect a second machine tool to the system thereby greatly increasing the number of prostheses that can be done in a single day. 1

  A dentist who is equipped with an optical probe in a remote location cc have access to the CAD-CAM sys either through the phone line (with modem) or by sending a picture containing floppy disk to the home base of the computer and the micro-milling machine, whether a dental office or dental laboratory. 1

2. **Clinical production of crown:** The production of a fixed prosthesis with a CAD-CAM system, regardless of its configurations, includes a series of simple and precise steps that are the same for crowns, inlays, or bridges. The process may be divided into seven step -- some clinical, others theoretical. 1

3. **Preparation of the tooth:** The preparation of the tooth for a CAD-CAM crown does not require methods and rules that are different from those used today. The traditional rules of sparing dental tissue, retention, and Stability of the future crown to maximize the life span of the prosthesis are still followed. It is wise to avoid proximal surfaces that are too vertical when the space between teeth is small, and occlusal planes containing deep grooves that will cause projected shadows on the video screen. For a clear continual view of the finish line of the crown preparation on the video screen, some operators prefer to use a chamfer with or without a shoulder. 1

4. **Preparation of the impression area:** For optimum visibility of the sulcus, the impression area must be cleaned of of debris, water, blood, or saliva, as required for a conventional impression, even if a light source is developed that is capable of penetrating the buccal fluids and selectively reflecting on the tooth surface. Moreover, drying and gingival retraction with conventional methods are desirable. Retraction must be routinely used if the crown finish line is more than I mm below the free margin of the gingiva. Retraction will allow a proper view of the sulcus during the impression; an adequate angle of incidence is necessary between the plane of the tooth and the axis of projection of light from the probe, to obtain three dimensional acquisition. 1

   The tooth must be dry before any impression is taken with the probe, so that a thin coating of white, nontoxic material can be sprayed on the tooth to enhance the quality of the picture. Light that strikes the uncoated tooth is reflected in part, while the remainder penetrates the structure, thus considerably reducing the quality of the three dimensional acquisition. It is advantageous to have a regular (lambertian) reflection on the tooth, as the natural tooth reflection would blind the camera. Special clamps, which include certain references that are recognizable in each view, have been designed to help achieve a good correlation between views. These clamps are placed around the preparation, much like rubber dam clamps, after the tooth has been dried and coated. 1

5. **The impression:** The dentist or an assistant starts the laser and the camera controls. The operator holds the probe like a handpiece, and places it in the patient's mouth to take the pictures. Some operators use a suspension arm for more comfort. Several views are taken of the preparation, including one buccal view, one lingual view, two proximal views, and one view of the occlusal surfaces of the opposite teeth.

   To take these pictures, the dentist moves the probe around the preparation, controls the positioning of the probe on a TV monitor facing him, and activates a foot switch to record the picture. 1

   A final, important view must be taken with the teeth in occlusion. The patient's masticatory apparatus is placed in an occlusal position of reference, according to the dentist's preference. It could be, for example, either the centric relation or the maximal intercuspal position. Considering that the preceding views have led, like the models of the maxilla and the mandible, to the creation of two objects, the view in centric occlusion will enable the practitioner to determine the relative position of these two objects with a minimum risk of error. It is possible to make this correlation process entirely automatic without taking the view in centric occlusion. But today, it is faster and less costly to keep the process interactive by requiring input from the operator. It must be noted that this last view is also a starting reference point for the analysis of the dynamics of the occlusion. 1

   This third step takes 2 to 3 minutes, depending on the case. After recording each view, the camera is immediately available to take a new view, which ensures the comfort of the dentist and the patient. (The storage of views in the computer's memory is rapid.) After all views have been taken, the probe must be sterilized1

6. **Work on the video model:** All views taken are stored in the memory of the computer, as a stone model would be stored in a tagged laboratory pan. Before figuring the computations needed to develop the three-dimensional shape of each view and to correlate the views to obtain two objects in a correct relative position, additional information must be given to the computer. 1

   The complete set of pictures is first displayed on a high-resolution video screen, and each is recalled one by one from the memory so that characteristic zones, such as the contact areas, certain cusps, and the alignment of grooves and cusps of the upper and lower arch, can be identified. Identification takes place on the video screen with the help of a mouse and a tablet-input devices that are user-friendly. 1

   One of the more interesting operations is the tracing of the margin. Using a view of the preparation on the screen, the dentist defines a series of points along the desired position of the margin, thereby tracing the line as would be drawn with a fine pencil on the stone die. 1

After completion of this step, the computer automatically calculates the three dimensional shapes of the impressions and transfers them to the CAD system to design and build the computer model (also called the "virtual model") of the crown. 1

7. **Design of the crown:** In dental CAD-CAM, there is a big difference between the initial object (the preparation) and the final object (the prosthesis). It is possible to go beyond the stage of a mere reproduction because prosthetic rules can be integrated in the software. Therefore, a form of creativity called artificial intelligence exists in the dental application as defined in the early 1970s. 1

   The design of the crown includes four stages: design of the interior of the crown; design of the buccal, lingual, and proximal surfaces of the crown; buildup of the occlusal surface; and modification of the shape of the crown. 1

- **Design of the interior of the crown:** The optical impression is defined by a large number of small picture elements (called "pixels"), as would be seen in a highly magnified photograph. Together, these elements form a mosaic like representation of the surface. Although only certain elements are useful in designing the crown, it is desirable to show the operator a complete model on the screen, including the preparation and the margin. 1

  A computer (virtual) model may be viewed from different angles, just as a physical model. Buccal, lingual, or perspective views may be displayed instantly on the screen. Among the latter, the axonometric view will be widely used, as it is the easiest to understand. 1

  The operator can recall to the screen, at any time, the views of the adjacent and opposite teeth, although there is no need to do so at this stage of the procedure. The system displays a menu of actions that may be executed. The menu is executed from top to bottom in a simple, strict order; it is impossible to skip over an operation. Although a short procedure exists to design a crown without any intervention, it is more interesting to describe the interactive method, because it is more precise and provides better control over the successive operations. 1

  The operator checks the impression and the margin, which may be modified if an error or imperfection is detected. The display of one of four points is sufficient. As the hidden lines and surfaces have been automatically removed by the system, it is possible to work as with a stone model.

  When the display is deemed correct, a value is entered for the desired cement space, and the interior of the crown be automatically generated, starting with the margin line. No cement space enlargement is applied to the margin. 1

- Design of the buccal, lingual, and proximal surfaces of crown. The crown to be designed is first retrieved from the memory bank of theoretical teeth store in the computer. A special program built with a set of contours that will allow esthetic modification of the shape of the theoretical tooth (Figs 8, 9). The program first modifies the' retical shape to fit the existing morphlogy while respecting the buccal lingual curvatures, the alignments and the grooves and cusps, and the contact' areas of the arch. The operator may make additional modifications for example change the shape of the lingual or buccal surfaces, or create a diastema between adjacent teeth. Any contour line may be moved to achieve the desired result. Use of a theoretical library of teeth allows the anatomy recognized by anatomists to be respected. With the interactive editing capabilities, the practitioner can personalize anatomy as desired. The deformation of the tooth, taken from memory in the environment of the patient, results in a custom crown. This operation may be compared with the development of a wax pattern in which the technician uses the shape of the tooth that he has, from experience and memory, to sculpt it on the physical model (die). 1

Build-up of the occlusal surface. The term "build-up" is used to emphasize that the CAD design is much like the "wax-up" technique used in the laboratory. The occlusal surface is, roughly aligned according to the opposite grooves and cusps, after the wax-up technique of Lundeen or according to the adjacent teeth. The choice is defined by the operator. To have a correct "buildup" of the centric points of the crown on the opposite centric points, their positions are first proposed to the operator on the basis of a theoretical, arch corresponding to the opposite arch. These points can be freely moved to; obtain a cusp-to-fossa or cusp-to marginal ridge occlusion. In addition, the choice between functional and gnathologic options allows the morphology of the contact (centric freedom or tripodic blockage) to be defined. The CAD system does not Impose a concept but leaves choices open to the practitioner. 1

When these elements have been defined, a program projects the cusps and the grooves of the crown onto the opposite teeth, according to Lundeen's technique. Functional occlusion is achieved with the use of a specially designed articulator.

- Modification of the shape of the crown. If the shape is not satisfactory, the practitioner may modify the shape by moving point or retracing a contour. It is also possible to raise a cusp (although care should be taken with the resulting occlusion) or to create a diastema. 1

  In all cases, it is sufficient to indicate which point must be moved and to show the new position. The software reshapes the tooth while respecting the rules of esthetic dentistry. The result compares to the work on the wax pattern of the physical model. Adjacent and opposite teeth may be displayed at the same time, and their presence on the screen is often helpful. 1

8. **Milling the prosthesis:** The milling of the prosthesis is performed on a robot. This robot is a micro-milling machine (28 x 20 x 20 in) with four axis machining, coolant, and automatic tool change capabilities. All fixed prosthesis can be milled with eight tools placed on a rotating disk near the spindle. The machine retrieves them automatically according to the machining program. Before starting a cycle, the condition of the tool is checked automatically. 1

To start the milling process, the block of material must be installed in the machine and the start button must be pushed. The process is automatic and delivers a crown that is ready to be polished and colored, with an accuracy of fit that meets accepted dental standards in the United States. The operation includes two phases: computation of tool paths and execution of milling. 1

- **Computation of the tool paths:** Each tool is basically a cylinder or a sphere, removing material progressively to shape the exterior and interior of the crown. The software computes the path that must be followed by each tool, the feed and spindle speed, and the machining sequence, to permit a smooth, efficient operation. 1

  The software controls not only the tool movements but also technological factors such as coolant, tool changes, or checks for wear. Instructions are read sequentially and translated into electrical impulses that drive the moving parts of the machine tool. 1

- **Execution of the milling:** This second phase automatically follows the preceding one. After a surfacing operation is completed to take into account manufacturing tolerances of the preformed block of material, the material is rough-cut in the form of a prism corresponding to the line of greatest circumference of the crown. Several tools are used successively to obtain a precise occlusal surface, which is completed by the fine milling of the secondary grooves. A realistic occlusal morphology results. All tool paths are calculated in three-dimensional space. 1

- After the occlusal surface is completed, the material is automatically rotated for the milling of the interior and base of the crown. The interior is milled first to keep a maximum amount of material at the level of the margin. The portion of the exterior buccal, lingual, and proximal surfaces below the margin is milled last. 1

  A precise tool is used to finish the margin because it is obviously the area of the crown that requires the most precision. When this step is completed, the machine removes all waste material, except for two attachment pieces (that may be compared with a sprue) located below or above the proximal contact areas. The operator then removes the crown from the machine. 1

9. **Coloration:** The last step in the production of a CADCAM crown is a quick polishing, followed by coloration of the inside and surface of the crown. 1

   Coloration principles defined 20 years ago and recently reintroduced by Dentsply for their Dicor crowns are followed. Although CAD-CAM can mill all traditional dental materials, appealing alternatives exist with Dicor (Dentsply), and Aristee (Spad)-a new ceramic composite with an oriented fiber structure specially designed for CAD-CAM. 1A preformed cube of Dicor is placed in the milling machine. After it is milled, coloration is applied. 1

   With Aristee, cement provides the basic color (type A, B, C, or D), whereas surface coloration accounts for local effects. Blue colors, for example, increase translucency at the incisal edge; yellows increase color density of the cervix. More intense colorants have been added to these base colors to simulate grooves or imperfections in the enamel. To maintain this added color for wear resistance, the crown, bridge, or inlay must be fired at 200 C. To facilitate the coloration process and better control the results, a proprietary spectrocolorimeter (Bertin) can be integrated into the CAD-CAM system. 1All that remains is to cement the crown, following standard practice. 1

10. **Draw backs associated with CAD/CAM:** Great progress in dentistry appears possible with CAD-CAM technology, which uses the most advanced scientific concepts. It is nevertheless necessary to answer practical questions concerning, for example, the accuracy of userfriendliness of the system. 1

In systems that use CAD-CAM technology, the number of points defining views varies between 50,000 (Moermann) and 16.000,000 (Rekow). 1

Clinical experience has shown, contrary to intuitive beliefs, that a high number of points is no guarantee of accuracy. On the other hand, it is possible to compensate for the limitation because of the number of points by increasing the number of views (provided the correlation is correct). By working with these two factors, better accuracy can be obtained than is normally achieved in most dental offices and laboratories (the prepared tooth is defined by 200,000 to 400,000 points). The quality' of the restoration does not require accuracy greater than 40μm. In addition, it must be noted that during the CAD and CAM stages, precision cannot be guaranteed beyond 5 μm because of the smoothing of curves and the positioning of tools in the milling process. It is therefore necessary to be cautious in terms of precision (not to be confused with resolution) and to realize that to reach a level of precision equivalent to 10μm, although technically feasible, an uneconomical investment of human, material, and financial resources would be required.

The interaction between the operator and the system has been simplified as much as possible, to a level comparable to the user-friendly aspect of a Macintosh computer, which allows for complete training of the user in less than a week. 1

IV. THE DENTICAD SYSTEM

1. **Denticad System Description:** The underlying principle in developing the DentiCAD system was to create a system that enhances what practitioners do. No changes in preparation design are required. No changes in material selection are needed, although the clinician may want to use new materials that are more easily fabricated with CAD/ CAM than with castings. The marginal fit must be at least as good as with good castings and it should free the clinician for production, not tie him to a new technology.4

The DentiCAD system is capable of producing an array of restorations from alloys, composites, and ceramics. Like other CAD/CAM systems, it has three functional components: data acquisition, design, and fabrication. DentiCAD uses a miniature mechanical linkage, designed by Foster Miller Inc (Waltham, MA) that can be used intraorally for data acquisition without impressions or the required data can be acquired from casts and dies. Restoration design is accomplished using a customized expert CAD package running on a personal computer. The CAD software designs the restoration and automatically generates the machine tool paths. Fabrication is accomplished using traditional numerically controlled milling procedures for a micromilling machine. The space required for the entire system is smaller than a normal office desk top. 4

2. **Data Acquisition:** The DentiCAD miniature intraoral mechanical digitizer consists of a linkage with a computer interface and a mounting fixture to attach the linkage of the teeth during data acquisition. 4

To acquire data the mounting fixture is attached to a tooth somewhere in the arch, away from the prepared tooth. The linkage is attached to the fixture. The dentist touches the probe to an arbitrary point on the mesial, distal, occlusal, buccal, and lingual surfaces to register the general orientation of the tooth in space. The dentist then moves the probe at the end of the linkage over the surface of the tooth. Sensors record the position of the tip of the probe. Simultaneously the location of the data points is displayed on a graphics terminal. 4

There are no constraints in the order that data must be acquired. The entire surface of any prepared tooth (as well as the proximal contacts, opposing dentition, and functional movements) can be obtained in less time than it takes to make an impression. 4

Data acquired with the digitizer include the configuration of the prepared tooth, contact areas of the proximal teeth, and information about centric relation (or centric position) as well as working, nonworking, and protrusive movement. When these data have been acquired, a three-dimensional representation of the prepared tooth is created and displayed. This three-dimensional image can be rotated on the screen, providing multiple views to verify that the desired data have been captured and the preparation design is acceptable. 4

The mechanical digitizer offers at least two advantages over other data acquisition techniques. Perhaps the primary advantage is that it is a technology and procedure that is already familiar to the dentist. The activities involved in digitizing are essentially the same as those used to examine the teeth. Additionally, it is not necessary to place retraction cord to isolate the margins; the tip of the digitizing probe easily fits into the spaces created by the handpiece during preparation of the tooth. It is not necessary to visualize the margins, to coat the tooth before it is imaged (as is required by the optical data acquisition techniques used by other systems), or to displace the tissues and create a dry field (as is required for impressions). 4

3. **Restoration Design and Fabrication:** The design of the restoration is completely automatic. To begin the process, the user specifies the type of restoration to be created and the material from which it is be fabricated. This is all accomplished by touching points in a menu.

The restoration is designed automatically, without requiring any intervention by the user. An expert system designs the restoration fitting the internal surfaces to the configuration of the prepared tooth and the external surfaces to the margins and requirements for both centric and functional occlusion. 4

When the design is complete machine tool paths are automatically generated. The entire design process and generation of machine tool paths is completed within 2 minutes.

The restoration is fabricated with a standard numerically controlled milling machine. The configuration of this machine offers the rigidity necessary to permit a high-quality fit of the restoration. The restoration is machined from a blank of material. The entire internal and external surface can be machined. Currently the system is capable of machining complete coverage crowns and copings. Bridges and intracoronal restorations will be added in the near future. Restorations can be machined from an array of alloys (including type III dental gold and commercially pure titanium), diverse composites and various machinable ceramics. 4

4. **Restoration Fit:** Fit of any restorations is critical for its clinical success. Crowns produced with the DentiCAD system were tested for marginal fit. The distance between the surface of the die and the internal surface of the crown was measured. Measurements were made using a traveling microscope calibrated to an accuracy of 3.5μm. For the sections, the average distance between the die and crown was 23μm (SD = 23μm; range, 0 to 49μm). 4

   Machining operations are controlled to tighter tolerances around the edge of the margin. Measurements of the distance between the surface of the die and the internal surface of the crown were repeated for the first 100μm from the margin. In this region, the average fit was 12 μm. 4

V. THE CELAY SYSTEM

1. **Directly Milled Ceramic Inlays and Onlays CAD/CAM Systems:** An innovative system, the Celay technique (developed by Dr Stefan I. Eidenbenz at the University of Zurich), is a variation on the direct-indirect restoration concept but without the need for a laboratory technician. An inlay or onlay preparation is made for the compromised tooth, but, instead of a conventional impression, a direct process is used. A moldable, precision imprint material is modeled directly inside the mouth in the cavity preparation, where it is adjusted for occlusion, contact relations, and marginal integrity. The material then undergoes a light-hardening or curing process before it is removed from the tooth to serve as a prototype model to be copied and reproduced in ceramic on a unique milling system developed by Claude Nowak of Microna Technologie AG, Spreitenbach, Germany. 3

   The milling center has two distinct aspects. In one half the model to be copied is centered in a holder where it is manually scanned. A second part of the milling machine contains a rotary turbine with various cutting tools. The directly formed pattern in the vise is manually scanned with a sensor. This sensor is directly connected to the milling aspect. Any form scanned is thus simultaneously reproduced in all three dimensions in a block of ceramic by the rotary turbine. The gross form is developed with a diamond disk and refined with a diamond point. The ceramic blocks to be milled into restorations are available in various colors and sizes. An appropriately sized block is selected and inserted in the holder of the milling center. The system can also be used as a purely indirect process, in which an impression is made and a die developed in the laboratory. The composite resin imprint prototype material is precisely formed in the die to represent the desired restoration. The composite resin prototype inlay is then placed in the left side of the milling unit in a bipoint metallic vise. The surface of the prototype is then similarly scanned manually and reproduced in ceramic on the milling unit, which carves out an exact replica of the plastic prototype in ceramic. The occlusal scheme developed inside the mouth is reproduced identically, so that after completion of the milling process, the inlay is ready to be inserted into the mouth with, at best, minor corrections. Additional characterization or colorization of the inlay, if required, can be accomplished in the laboratory by refiring the inlay prior to final finishing. The fit of the restoration has a tolerance of less than 50 μm. 3

2. Advantages of the Celay System

- A precisely fitting ceramic restoration can be developed in one patient session.
- A ceramic restoration can be developed without the need for a laboratory technician.
- The restoration is developed in factory fired high-grade porcelain.
- The processing time required is very short. A small inlay can be milled in 3 minutes, a mesio-occlusodistal inlay in less than 8 minutes, and a complete onlay in 12 to 13 minutes. 3

VI. THE CEREC SYSTEM

Many patients prefer having esthetic natural-Looking restorations placed in their posterior teeth. Such restorations pose difficulties in selecting ideal materials and processing techniques. Esthetically acceptable posterior restorations must be resistant to oral abrasive and chewing forces. The materials and techniques currently available to achieve esthetic posterior restorations include (1) composite resins used as posterior restorations: light or chemical1y cured; (2) composite resin inlays: made immediately at chairside; (3) composite resin inlays: made in the laboratory; (4) glass ceramics and Dicor inlays (Dentsply International): made in the laboratory; (5) porcelain inlays: refractory die technique made in the laboratory; and (6) Cerec inlays (Brains Inc): computer-designed and made at chairside.5

Ceramics, in contrast to composite resins, more closely approximate the physical and chemical properties of enamel, and etched porcelain successful1y bonds to etched enamel when a composite resin-based cement is used. Both acid-etched porcelain and Dicor glass ceramic inlays cemented to etched enamel using a composite resin-based cement have excellent marginal qualities. The cuspal fracture resistance of etched porcc1ain-restored teeth is equivalent to the cuspal fracture resistance of unprepared maxillary premolars. 5

At least two visits are required to fit conventional1y fabricated porcelain and composite resin inlays. During these visits, impressions are taken, temporary restorations are placed, casts are made, and, after the firing and/or casting, the ceramic inlay is fitted. However, since 1971 optical scanning methods and computer-aided inlay fabrication techniques have been used in attempts to eliminate the current]y practiced impression, die, lost wax casting technique .The Cerec system (computer-aided ceramic reconstruction) was first presented to the dental profession in 1986, but has been repeatedly described since 1980. 5

The Step-By-Step Fabrication of an Onlay Restoration Using The Cerec System. (Chair side computer-aided direct ceramic inlays).

1. Technical and clinical procedures

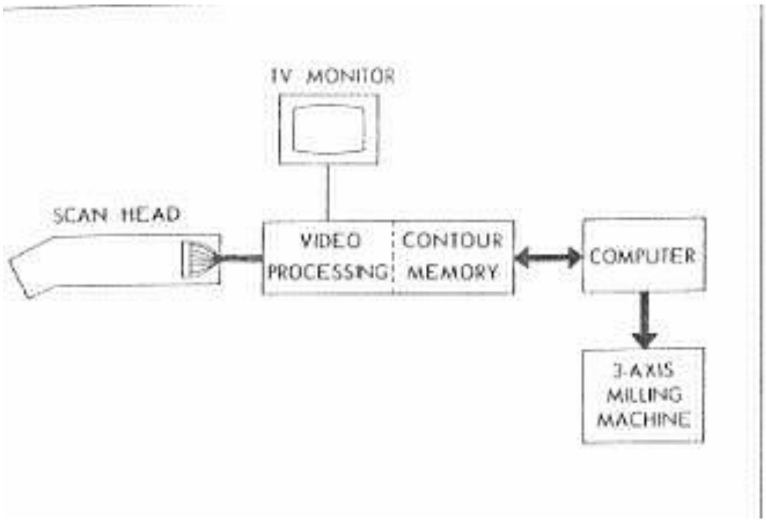

Figure 1: Flow diagram of Cerec system

Figure 1 presents a flow diagram of the Cerec system. It consists of a three-dimensional video camera (scan head), an electronic image processing (video processing) and memory unit (contour memory), and a processor (computer), which is connected to a miniature milling machine (three-axis milling machine).The recorded three-dimensional data are immediately displayed as a freeze-frame pseudoplastic video image on the monitor. The dentist now checks the preparation and its three-dimensional representation for corrections to be made, if necessary. The optical technique enables rapid repetitions and optimizing of the cavity preparation and its three-dimensional representation. The dentist designs the restorations by tracing frame lines on the optical impression while it is displayed on the monitor. 5

The dentist checks the cavity preparation displayed on the monitor (Fig 2). The cavity is detailed on the monitor by using the camera search mode while the three-dimensional camera is held by the dentist. The milling chamber is the unit

Simple, box-shaped preparations suffice for the Cerec three-dimensional scanning and fabrication process. Undercuts in cavity walls do not affect the optical scanning and are filled in with composite resin during the cementation. Straight walls with right angles are recommended. The 4- to 6-degree divergence required for cast inlays is not necessary using the Cerec system; parallel walls suffice, thereby ensuring maximal preservation of hard dental tissues. 5

The occlusal and proximal cavity margins are not beveled. Instead, the cavity walls and enamel edges are finished using diamond-coated finishing stones. 5

The gingival floor is horizontal or declines between 5 and 15 degrees toward the gingival margin. The optical scanning is facilitated by having clearly defined walls and cavity margins and by the use of rubber dam during the optical scanning and cementation stages. 5

2. **Quality of materials and the restoration:** The advantage of the Cerec system is that restorations is milled from prefabricated and optimized, quality-controlled ceramic porcelain, can be placed in one visit. The prefabricated ceramic is wear resistant. The optimized structure of the ceramic enables optimal polishability of the material and low abrasion of the cuspal enamel of the opposing tooth, A tight marginal fit is provided by the adhesive system used between the etched ceramic porcelain and enamel surfaces, The essential measures are (1) porcelain-ceramic etching (HF 5% for 60 seconds): microretentive adhesive bond between porcelain/ceramic and the bonding agent/composite resin cement; and (2) enamel-etching technique (H_3PO_4 35% for 30 seconds): microretentive adhesive bond between composite resin cement/bonding agent and enamel. 5

   The above adhesive bonding system ensures a stress resistant, hermetic seal, even in large mesio-occluso-distal restorations. 5

3. **Cementation:** The thin layer of composite resin, together with the microretentive bond within the ceramic and enamel, apparently minimizes the negative aspects of the polymerization shrinkage and the high thermal expansion of the cement. 5

4. **Construction on the video screen:** Clinicians require a two to three-day comprehensive course to produce and to interpret the ideal image on the screen and to understand the computer graphics5

5. **Advantages and disadvantages of the Cerec system:** In order to be accepted, new techniques must have distinct advantages over existing well-tried and tested techniques. Advantages of the Cerec system are:

   - Natural esthetics; excellent color matching because of its similar color and translucency to enamel. 5
   - Lasting esthetics because ceramic is resistant to the oral environment.
   - Optimal quality of the material because it is controlled by the manufacturer and not subsequently modified by conditions that vary from practice to practice and from laboratory to laboratory. 5
   - Glazing is not required, and Cerec inlays/onlays can easily be polished.
   - Minimal abrasion of the hard dental tissues of the opposing tooth occurs because of the homogeneity of the material and its abrasion does not exceed that of conventional and hybrid posterior composites resins. 5
   - High stability during chewing because of the microretentive adhesive bond among the etched and silanated porcelain, composite resin cement, and etched enamel. 5
   - It is thought to be an alternative to metallic restorations in posterior teeth because of its high resistance to abrasion and good marginal adaptation. 5
   - Cerec inlays/onlays are an alternative to complete crowns. 5

Following are some advantages of the Cerec system compared to conventional indirect restorations:

- One or more inlays or onlays, prepared from high quality material, can be placed in one visit. 5
- The cost of the porcelain material is similar to that of composite resin.
- Conventional impression taking is replaced by the optical three-dimensional scan. 5
- Casts, wax ups, investing, casting, and firing are no longer required.
- Corrections can be immediately carried out on the screen and the "laboratory stages" can be repeated any number of times. 5
- The mobile character of the entire system enables easy transport from one dental operatory to another. 5
- The construction and fitting of temporary restorations is not necessary; therefore time is saved and costs are reduced. 5
- Patients no longer require temporary restorations, which are often functionally inadequate, have poor gingival marginal adaptation, and may not provide true patient comfort. 5
- The number of local anesthetics is reduced to an absolute minimum.
- Because second or subsequent visits are not necessary, the savings in time and cost are high. 5

Following are some disadvantages of the Cerec system compared to conventional indirect restorations:

- Initial costs for the purchase of the Cerec unit are high. 5
- Time and cost must be invested to learn how to master the technique. 5
- Contouring of the occlusal surface must still be carried out by the clinician. 5

VII. ADVANCES IN CEREC SYSTEM

The first clinical investigation of computer-generated ceramic restorations was begun in 1986. The inlays were fabricated using the original CEREC 1 (a) hardware (BRAINS AG) and software (CEREC Operating System). Examination by scanning electron microscopy, or SEM, showed occlusal luting interfacial widths to be 140 to 265 micrometers. 6

Using the second-generation CEREC 1 (b) unit developed in 1988 (Siemens AG) and COS software developed in 1991 (Siemens AG), researchers clinically measured interfacial widths, which were a mean of 169 +/- 48 μm. In an in vitro study, lnokoshi and colleagues measured the marginal interfaces in Class II CEREC restorations using second-generation CEREC 1 (b) hardware and COS 2.1 software; they found that widths ranged between 50 and 99 μm. 6

The third-generation CEREC 1 (c) unit was introduced in 1992. An electric motor significantly increased the engine power as well as the service life of the grinding disks. The higher rigidity of the system and a smaller diamond grain diameter (64 μm) of the grinding wheel considerably improved the marginal integrity of the machined restorations. The precision of the margins was reported to be in the 80- to 120-μm range. 6

The completely redesigned CEREC system, called CEREC 2, is able to produce inlays, overlays, veneers and full crowns. Through improvements in the grinding process and optimized three-dimensional, or 3-D, scanning, it aims to achieve an even higher accuracy of fit than previous systems achieved. The further development of the intraoral 3-D camera was done in accordance with the original CEREC process. 6

The grinding precision and accuracy of fit of inlays in mesio-occlusodistal preparations produced by CEREC 2 CAD-CAM unit was examined. It was found that the interfacial width of the CEREC 1 and CEREC 2 inlays differed significantly in margin sections at the deep and very deep line angles of proximal preparations as well as at the gingival margins of deep proximal preparations. 6

The improved grinding precision of CEREC 2 vs. CEREC 1 can be attributed to the general improvement in electronics and engineering know-how accumulated during the developmental stages of CEREC 1. 6

The improvements in CAD-CIM technology, as represented by the CEREC 2 unit, provide dental practitioners and dental laboratory technicians with a fast and easy production method for ceramic restorations using industrially prefabricated Vita Mark II and Dicor MGC machinable ceramic materials. 6

VIII. WEAR OF CAD/CAM CERAMIC INLAYS: RESTORATIONS, OPPOSING CUSPS, AND LUTING CEMENTS

Cerec inlays (Siemens) are commercially manufactured out of porcelain or glass ceramic. Although these materials may be used for replacing amalgam, very little is known about their wear resistance. Ceramics are assumed to be wear resistant because of their enam-el-like physical properties.7

Wear is a natural process affecting practically every teeth and restoration in the mouth. Nevertheless, if wear of a restoration is significantly worse than that of enamel. decompensation of the occlusion may occur. This may be the case if the restorative itself is not wear resistant enough or if it abrades the opposing enamel cusps more than would natural enamel. In this study by. Krejci, F. Lutz and M. Reimer, the generally assumed good wear resistance of porcelain materials was confirmed. 7

The wear rate of all ceramic materials except Dicor MGC was less than that of human enamel. On other hand, the abrasivity against opposing en cusps was high with Dicor MGC and Cerec Vita ." and moderate with the new fine porcelain Cerec Mk II. This led to total wear values that were a able for the fine porcelain only, Therefore, as far; occlusal contact wear is concerned, fine porcelain seems to be the material of choice if ceramics are machined with the Cerec system. The composite cements were less wear resistant than were ceramics and enamel7

IX. CAD-CAM CERAMIC INLAYS AND ONLAYS: USING AN INDIRECT TECHNIQUE

An attempt to resolve some of the problems that are associated with conventional posterior ceramic restorations was made by Mormann and Brandestini. They used a CAD-CAM device to digitize and electronically store the cavity preparation parameters and then a computerized milling device to shape the restoration from a ceramic block. This method has been made commercially available as an integrated CAD-CAM unit for dental use (Cerec, Siemens AG). 8

However, the time required for these operations can be significant and is not always predictable. The patient must also have a rubber dam in place throughout the procedure. This extra time involved may interfere with other patients appointments and contribute to operator, patient and office staff stress. 8

In offices with multiple practitioners sharing the CAD-CAM unit (to control the cost), simultaneous appointments must be avoided. Buffer time should be allowed if the milling operation has to be repeated, and time provided to transport the machine between operatories. 8

To solve some of these limitations, a procedure using a Cerec CAD-CAM unit with an indirect technique has been developed by Dan Nathanson, Douglas N. Riis, Gennaro L. Cataldo, Nargess Ashayeri. This technique uses the fabrication of a simple die for construction and initial adjusting of the restoration. The technique allows use of the CAD-CAM unit during "free time." In fact, many steps may I be accomplished by the dental staff. In a way, the computerized unit becomes an automated "mini" dental lab. 8

The CAD-CAM inlay/onlay system using an indirect technique produces quality restorations comparable to CAD-CAM restorations with the direct method. Although it requires two visits and additional treatment steps, the indirect method has advantages in many clinical situations, including:

1. Rather than using "expensive" chair time for restoration design, milling, try-in, modification and seating, these procedures can be done with a stone die, during non-patient hours-a much less stressful situation. 8
2. Scheduling difficulties. Using the CAD-CAM device in the direct mode demands allowing enough time for corrective steps and repeated milling of the restoration if necessary. The indirect method requires a short initial appointment. 'A second "normal"

   Length cementing appointment is about one hour. This method provides restorations that are already tested and adjusted for fit on a die, reducing the likelihood that the second appointment runs overtime. 8
3. Situations limiting appointment length. Severe limitations in mouth opening may preclude placing the CAD-CAM camera over posterior teeth. The indirect method divides the procedure into two manageable sessions and obviates intra-oral use of the video camera. 8
4. Effective use of staff. Delegating the tasks of optical impression, restoration design and milling to the staff using dies and the indirect method can save a significant amount of

chair time. 8
5. Cost sharing. By using the CAD-CAM unit in an indirect method, several dentists can use one machine through "time sharing."
6. Clinical training in a teaching environment. The indirect technique is uniquely suited for dental school clinical training where it can offer the student sufficient time for practice without overburdening the patient with unusually long appointments. 8
7. Treating multiple teeth in a quadrant may require unusually long sessions. In these situations, milling the restorations through use of a die/cast can contribute to time savings and minimize patient discomfort. 8

Clinical results of the two treatment methods are comparable and the resulting restorations meet with high patient acceptance. The indirect method is an effective alternative to the primary (direct) method for specific clinical situations. Both options can be offered to patients. 8

X. THE CICERO SYSTEM

Dental porcelain, is the most difficult of all restorative materials with which to develop accurate occlusal surfaces. The dental technician not only has to contend with high firing shrinkages, but also the hardness of dental porcelain that makes the carving of occlusal surfaces more difficult. It seems common to see overcontoured and esthetically displeasing crowns. 9

Another problem is that careful registration of mandibular movements and its translation to the dental laboratory is too laborious for an economic and practical execution. With the help of the combination of optoelectronics, computer techniques, and sinter - technology, it is possible to morphologically shape crowns in a computer-automated way. Registration of mandibular joint movements or of the functionally generated path in the mouth provides the necessary data for an interference-free escape of cusps from their fossae. 9

The Cicero (computer-integrated crown reconstructIon) CAD/CAM system for the production of state of-the-art ceramic-fused-to-metal (CFM) restorations makes use of optical scanning, nearly net-shaped metal and ceramic sintering, and computer-aided fabrication techniques. Alloy sintering eliminates casting and therewith many processing steps in the fabrication of metal-ceramic restorations. This makes the fabrication process adaptable for automation. The Cicero system produces crowns, fixed partial dentures, and inlays with different layers, such as metal and dentin and incisal porcelains, for maximum strength and esthetics. It is to be used for the production of restorations with maximal static and dynamic occlusion. 9

Technique

1. **Computer surface digitization:** The first step in the automated fabrication of a metal - ceramic crown is the optical impression with computer surface digitization. 9

The Cicero CAD/CAM system makes use of a fast laser-stripe scanning method to measure the three-dimensional geometry of the preparation and its immediate surroundings and the opposing teeth (Fig 7). A straight laser stripe is deformed by the occlusal geometry. A charged-coupled device (CCD) camera scans the projected line and a computer calculates the points by triangulation. 9

The optical sensor consists of a helium-neon laser, a CCD video camera, acquisition and enhancement software, design software, and an error accommodation provision. 'The laser is expanded by a zoom line projector into a long, thin stripe and projected onto the gypsum cast. The light sections are captured by the CCD video camera placed at a known angle to the laser-preparation line. The video information of the consecutive sections is converted to three-dimensional xyz data under microcomputer control and is transmitted to the CAD system. 9

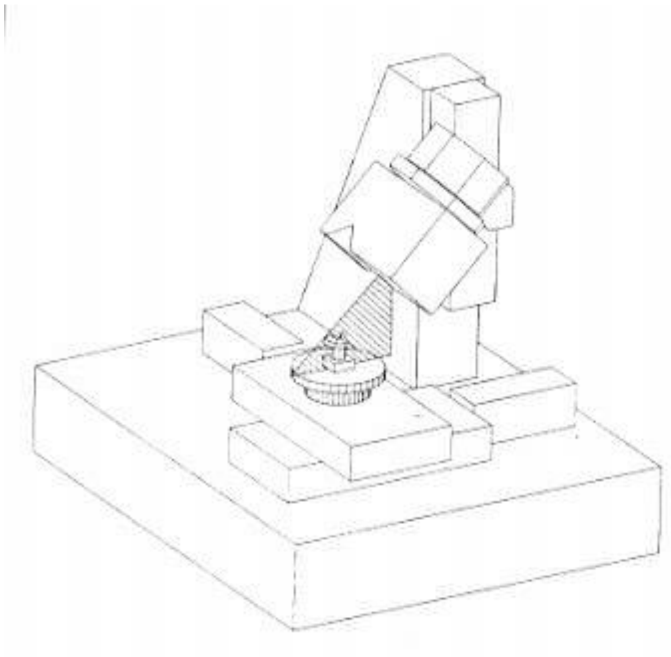

Figure 7: Set-up of the laser scanner

The 0.3-mm-thick focus laser and the 600 x 625, Pixel CCD camera will give a reproducibility of 0.02 mm on each point. 9

First an impression is made of the arch with the prepared teeth: This step must proceed with the greatest possible accuracy. Then a gypsum cast is obtained. The gypsum cast of the model that contains the preparation is prepared for scanning by indicating the preparation line on the cast with black and white contrast paints. This unique feature of the scanning method makes it possible for the computer to automatically "grab" the preparation line, instead of requiring the operator to trace it afterwards on the screen with an input device, such as a mouse, It also allows great freedom in the preparation method used. 9

Digitizing the information from a cast rather than directly in the mouth is a compromise, because direct scanning in the mouth stilI poses many problems.

The cast is placed in the scanner clamping device, which has a ball-and-socket table that can be tilted and locked in a direction. 9 To prevent a jitter effect during the scanning of both the preparation cast and the checkbite, a special gypsum and checkbite wax are used for optjmal reflectivity. 9

The system is rapid and can supply approximately 100,000 surface points per minute. A rough overall scan of the whole of the cast is made and converted to a multi-colored Z chart. From this information the position of the restoration in the masticatory system is known, and the Cicero scanner software can now generate an intelligent scanning protocol according to a special strategy. 9

2. **Computer-aided crown design:** A mandibular first molar (tooth 46) was designed on a die with a chamfer preparation. The preparation and its immediate surroundings, including a checkbite of the opposing teeth, were digitized with the Cicero scanner. The die, consisting of approximately 60,000 points, is converted to a meshed. spline surface of 5,000 control points or more if desired. 9

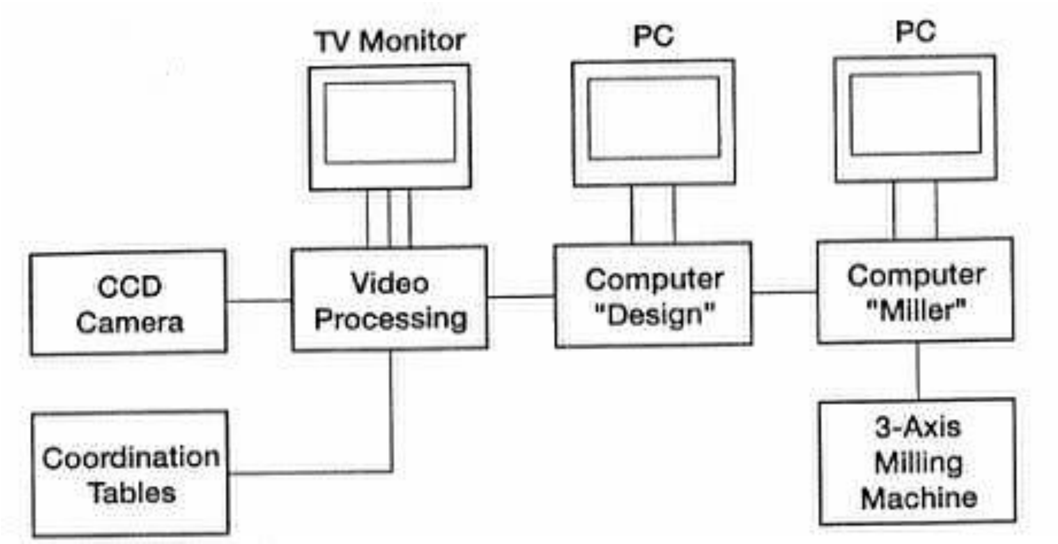

Figure 8: Flow diagram of the Cicero system.

The appropriate tooth is then chosen by the operator from an extensive collection of generic forms of theoretical teeth in the program's library (Fig 9). Between the major landmarks a certain number of splines are then interpolated on the surface of the scanned cast of the crown. 9

The distal and mesial contacts indicated by the operator in the occlusal and buccolingual views of the scan form the first step in the fitting of the generic tooth. The margin line of the new crown is adjusted to the preparation line that was isolated automatically from the scan of the die. The lingual and buccal boundaries are clicked in with the mouse, to shape the tooth so that it fits in a natural-appearing row with the adjacent teeth. A warping algorithm generates a deformation field and deformation vectors within the field to generate the new form as directed by the drag vector indicated with the mouse. This way the external contours of the new crown can be adjusted interactively with the mouse, in much the same way of the building up of porcelain by brush or spatula, to obtain maximum esthetics. 9

The new crown is then superimposed on the opposing tooth, which is displayed on the screen as a multicolored relief map. 9The core of the CAD program is formed by an expert system that deforms the generic tooth parametrically (wIth conservation of shape) according to gnathologic rules. 9

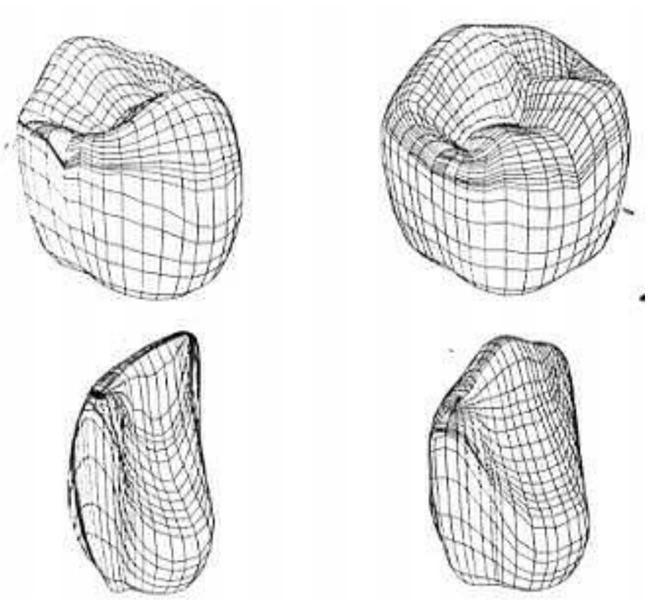

Figure 9: Examples of teeth in the generic tooth shapes.

3. **Mathematical articulation model:** The aim of tooth design is that cusps should escape . and return to their fossae without interferences. Mandibular movements in three dimensions have been simulated by dental articulator whose condylar and incisal guides define the maxillomandibular movement patterns. These can be obtained by registering the functionally generated path obtained by chewing movements or by registration of the movements of the mandibular joints. 9

   The three-dimensional pathways that the supporting maxillary or mandibular cusps follow during mandibular movements are computed mathematically. 9

   A model of the craniomandibular system was developed in a way that simulates the action of the human stomatognathic system. All elements of the biomechanic model are incorporated into the mathematical model and can be varied. Initial standard or default settings other than zero are selected for certain parameters. The default setting for the intercondylar distance is 110 mm, or 55 mm on either side of the midline. The standard medial wall configuration, or Bennett angle, is 10 degrees, and the standard antero-posterior condylar inclination is 35 degrees.

Other variables are related to the location of the dental arches within the model system. The standard location of the incisal edges of the mandibular incisors is 85 mm anterior to and 33 mm inferior to the horizontal (transverse) axis. The initial inclination of the occlusal plane is parallel to the horizontal. 9

Registrations such as electronic axiography can be used to change the default settings in the computer. 9

lncremental locations of the supporting cusp tips, guided by the simulated condylar guides, are computed and recorded in three dimensions. Working, balancing, and protrusive pathways for the new restoration are computed. 9

The registration of the movement envelope of the opposing teeth in the functionally generated path impression can be scanned, and the surface obtained can be used to determine the appropriate contacts. Of the occlusal contacts normally required by classic gnathologic concepts, about 50% are eliminated by using the functionally generated path technique. 9

Vertical contacts are made with the opposing tooth at the mesiolingual cusp, distobuccal cusp, distal marginal ridge, distolingual triangular ridge, mesial marginal ridge, and mesiolingual triangular ridge of the maxillary first molar. 9

After the interior and exterior tooth surfaces have been designed, this is followed by the definition of the different interface surfaces between cement and metal and between dentin and incisal porcelain. The Cicero software calculates the interior surface (corrected with marginal gap, overall cement thickness, and metal-die cement thickness) and the different interfaces between the material layers as specified by the operator. 9

4. **Computer-aided crown machining:** The tools are positioned in the tool exchange clamps. Standard diamond-coated grinding tools are used, and the exactly measured dimensions of each of the individual tools are entered into a dialog window of the Cicero Miller software on the screen through the keyboard. 9

Factory-standardized, prefonned Cicero refractory blocks for single elements, which have a precision fit in the milling machine clamping device, are made of material that resembles that of the refractory investments used in the fabrication of ceramic inlays and veneers. The blocks used for single crowns are cylindrical with a diameter equal to the maximal mesiodistal tooth diameter. 9

The refractory block is fixed in a high-precision vice in the milling machine and the inside surface of the crown is milled, with a diamond-coated disk and a round diamond-coated bur, within 10 minutes (Fig 14). 9

The next step is the sintering of a thin layer of Synthobond alloy powder (Elephant Industries) on the refractory block, where this is needed for strength purposes (Fig 15) The next material applied is Cicero porcelain, in the appropriate shade. This is a special fine-grained, lucite-strengthened ceramic in the form of a colloidal vacuum-kneaded paste. A paste porcelain tablet is simply cold-pressed on the metal-covered refractory shape and fired under standardized conditions under vacuum in a porcelain furnace. After it is fired, the porcelain has a high density and can be easily ground to a feather edge without chipping, because it adheres to and is supported by the refractory block and the Synthobond layer. 9

After firing of the porcelain, the refractory block is placed back into the precision vice of the milling- machine and the interface of dentinal and incisal porcelains is milled in 15 minutes (Fig 16). Then incisal porcelain is cold-pressed over the dentinal porcelain and fired, and the, external surface of the crown is milled in 20 minutes-;, including the characterization grooves of the fossae (Fig 17). The crown is milled along the primary fossae, the cusp line, the equator line, the margin line, and between these lines. This ensures a sharp but smooth marginal edge (Fig 18) with a marginal gap of up to 50 μm. Preliminary clinical investigations have shown that marginal gaps at least comparable to those of traditionally cast crowns can be obtained. 9

The last step in the fabrication includes individual staining and glazing of t!1e external surface at a low glazing temperature. Because the surface is finished to a fine texture, an extremely smooth porcelain surface is obtained. 9

The Cicero system deviates from the other CAD/CAM techniques developed recently in that it makes use of a layered crown for better strength and esthetics. Metal structure-sintering techniques will give a durable support to crowns, fixed partial dentures, and inlays made with this CAD/CAM system. 9

XI. COMPUTER MODELING OF OCCLUSAL SURFACES OF POSTERIOR TEETH WITH THE CICERO CAD/CAM SYSTEM

Although the strength and the esthetic demands of dental restorations can be met by automated production system, and such systems are less time-consuming and thus will help to reduce the expenses of dental treatment, the functional properties of the restoration will determine its overall quality, For this reason, the production of crowns that do not cause interference in dynamic occlusion and in which there is optimal contact in centric occlusion will be of great value to dental practice. 10

The software of CICERO system can use various input parameters to design a functional restoration by simulating 3-dimensional maxillo-mandibular movement patterns on the basis of this data. After the application of these values, the individual locations of the supporting cusp tip can be computed using software. 10

In this study, by Lambert W. Olthoff et al the CICERO CAD/CAM procedure was used to prepare a crown in static contact (STA), Because this crown disturbs normal functional movements, 3 methods were used to design crowns that avoided these disturbances during dynamic contact movements: (1) individual data transferred from KAVO-Condylocomp registration; (2) default values often used in semiadustable dental articulators; and (3) data obtained alter registration of the individual contact movements in an occlusal-generated path technique (OGP). 10

Occlusal generated path technique: The OGP technique was introduced to overcome the time-consuming procedures-of the String-condylocomp registration system, The OGP technique can be compared with the functionally generated path technique, which is used to register dynamic contact movement with dental registration wax. With the FGP technique, the registration wax will produce the movements in the TMJ and the gliding movements of the front and lateral teeth; These constraints in the TMJ and dynamic front contact are not measured with the OGP technique. 10

Although in essence the FGP method allows the incorporation of all determinants of of occlusion in the FPG wax registration procedure, this technique is not easy to perform accurately, even for trained dentists. For practical reasons, dentists do not favor this technique. For this reason, the OGP technique was introduced, which makes use of a computer program (CICERO). Computer calculations can now solve the practical problems of the FGP registration system. 10

Lambert W. Olthoff et al suggest that the OGP method used for the production of CICERO CAD/CAM crowns is an appropriate method for restorative procedures in which 1 or a couple of teeth are replaced. With this method, it is possible to gather information on the movements of the restoration with reference to the opposing teeth by making use of digitized models. The OGP technique was tested with occlusal determinants that could be considered extreme, i.e., without setting a value for the laterally directed movements. Even under these conditions, a crown with a well-modeled anatomic form could be generated. The OGP Technique was preferred to other techniques because of its simplicity for eliminating potential problems with opposing teeth during motion.10

XII. USE OF CAD/CAM SYSTEM TO FABRICATE DENTAL PROSTHESES

Most of the dental prostheses are produced manually, require considerable technical skill and consume a substantial amount of time. Recently there have been efforts to supplant the traditional process by using computer-aided design manufacturing (CAD/CAM) systems. The authors also have developed a trial CAD/CAM systems, composed of a component to measure the shape of the stone model, a CAD system to design the restoration and a CAM system to mill prostheses using the CAD data. In this system crowns or laminate veneer could be fabricated. However, this trial system was too complex to be practical. Furthermore, the form and preparation of the die and occlusion for a clinical restoration were too variable and complex for the system. This paper reports the development of an efficient and practical CAD system. 11

The goal of this program by Taiji Sohmura and Junzo Takahashi was the development of an inexpensive CAD/CAM system to lower the cost of fabrication. The system for measurement and CAD is composed of the following inexpensive Components. 11

A laser displacement meter with spot beam emitted, and double sensors was used to measure the height of the stone casts. Two sensors were used to compensate individual blind spots. A personal computer-controlled three-dimensional tooth model-scanning machine was used to automatically scan the model tooth. In the present study, a stone cast previously used 1 in routine clinical care was used instead of a model, as reported in the trial CAD/CAM system. The cast included a preparation with a chamfer buccal margin but with mesial and distal margins that were indistinct. 11

A wax interocclusal record that recorded the shape of the opposing teeth was placed on the die, and its shape was measured to establish the relative position between die and record. A functionally generated path record recorded using FGP wax was also placed on the cast and measured. 11

Initially, the shape of the standard crown was deformed and adapted on the die depending on the shape of the margin. Then, the measured occlusal record data were taken in the computer graphics, and the adapted crown was adjusted with these data to obtain the centric occlusion. The occlusal data were replaced with data obtained using functionally generated path record and the occlusal interferences eliminated. The ends of the adapted crown were connected with the margin. Thus, the entire crown was efficiently designed using the computer program developed. 11

Thus, all the crown CAD data that comprised the modulated occlusal surface, the inner crown, and the connective data between them were obtained. As a result of the present improvement of CAD with CG drawn from three directions, especially the procedure of margin determination and primary crown adaptation, the process was much more efficient, and the CAD process could be finished within approximately 40 minutes. In the former trial system, it took more than 4 or 5 hours with iteration of trial and error. 11

XIII. DENTAL CAD-CAM. WHAT IS THE STATE OF THE ART?

A review by Diane Rekow, describes six dental CAD-CAM systems and offers a framework for establishing their clinical value. Comparisons are made on the basis of system configuration, system capabilities, the learning curve required to use the system successfully, system costs and the fit of CADCAM-produced restorations. 2

1. **Comparison Of System Configurations:** The physical configurations of each of the six different systems are briefly described (references offer more detailed information).
   - The CEREC system, manufactured by Siemens Dental Corp. (Benshein,Germany), is one of the best known and widely available. This compact chairside system consists of an optical data acquisition camera, CAD-CAM software and a micromilling machine. 2
   - The Duret system in dental offices in France and at the University of Southern California. This system is produced by Sopha (Lyon, France). The Duret CAD-CAM system consists of three discrete units: a camera module for data acquisition, the CAD module used to design the restoration and the milling module. 2
   - The DUX system, also known as the Titan system (DCS Dental, Allschwill, Switzerland), consists of a miniature contact digitizer a central computer and a milling unit. The digitizer consists of a table that shifts a die or model beneath a contact stylus. The central computer includes limited CAD capabilities. 2
   - The Celay system (Mikrona Technologie, Spreitenbach, Switzerland) is a very small unit consisting of a contact digitizer that "reads" the shape of an acrylic inlay (fabricated directly in the mouth) and directly transfers that shape to a miniature milling machine. The system is similar to a key copying or pantograph machine. 2
   - The Procera system (Nobelpharma, Inc., Goteborg, Sweden) is a copying and

fabrication system using a pantograph and electric discharge machining. The shape of the die and the wax pattern of the restoration are "read" by a pantography stylus that transmits these shapes to a milling machine to produce electrodes in these shapes. These electrodes are used to produce a restoration with EDM. 2

- The DentiCAD system (BEGO, Bremen,Germany, and DentiCAD USA Waltham, Mass.) system consists of miniature robot arm digitizer, CAD-CAM software with an expert system for fully automated design and a milling machine. The robot arm digitizer can be used intraorally or on traditional models and dies. The CAD-CAM software and expert system. reside in a personal computer. The milling machine is directly controlled by the computer. 2

2. **Comparison of System Capabilities:** Perhaps the greatest difference among the systems is the type of restorations that can be produced. The CEREC and Celay systems can produce only inlays and a few onlays. The cutting tool used to fabricate restorations with these systems is a flat disk with a diameter of approximately 20 millimeters. It is impossible to have access to the internal portions of a crown. 2

The DUX arid Procera systems produce only copings; they have insufficient CAD capabilities to design the occlusal surface of the restoration. The Duret and DentiCAD systems can produce Crowns and copings. The Duret system can also produce inlays (intracoronal restorations and bridges will be available in the DentiCAD system in 1992). Various materials are available for fabricating -CAD-CAM restorations. Many systems, however, can use only a few. The CEREC and Celay System provide an. alternative to amalgams; they produce inlays from ceramic materials. The two most widely used ceramic materials are Machinable Glass Ceramic (Dicor, Dentsply International, York, Pa.) and Vita Porcelain (Vita Zahnfabrik, Germany). 2

Machinable ceramics, metals (including titanium), and composites. The Duret system also offers an organaceramic material (Aristee, Spad Dijon, France). Another major system difference is the degree of automation. The Celay and Procera systems have very little automation. Each requires a pattern to be produced by a clinician or technician.

That human—created pattern is then digitized and simply reproduced by the fabrication methods available for that system. With the DUX system, a die is digitized and a constant thickness coping is designed by the CAD software. Both the CEREC and Duret systems provide a moderate level of automation; both, however, require the user to be involved interactively with the design of restoration. The user must identify selected points around the margin and provide intelligent input for the restoration design. 2

The DentiCAD system is the most completely automated; the user need only digitize the teeth required (prepared, opposing and contact areas of the proximal teeth) and load the milling machine. Everything else is done automatically. The degree of automation has implications in the time required to produce a restoration. The DentiCAD and Duret systems produce similar types of restorations. But with the automation available in the DentiCAD system, the design requires less than three minutes. The Duret system's design requires an expert user who understands occlusion and restoration design and, because so many interactive commands are necessary, the design requires nearly 50 minutes to complete. One primary advantage provided by CAD-CAM technology is the fast turnaround time for restoration production. Even the slowest systems can produce a restoration easily within three hours (including the time to produce models and a die). The CEREC and Duret systems can produce a restoration within 90 minutes. Much of the time required with the CEREC system is spent creating the occlusion of the inlay after it has been seated in the patient's mouth (the restoration, in its as-milled form, does not include any occlusal anatomy). Most of the time required by the Duret system is the result of the demands for interactive design of the restoration. The fastest system, the DentiCAD, can produce a full crown in less than 30 minutes. 2

3. **Comparison of Learning Curves:** With any new system, sometime is required to learn how to use it. The same is true with the CAD-CAM systems. Major influences in the amount of training required are the number of new technologies and how those technologies differ from the user's experience or knowledge. The CEREC and Duret systems both use an optical data acquisition system. Optical "impressions" are at least as difficult to obtain as tradition impressions. Indeed, the optical "impressions" are less forgiving-the margins must absolutely be isolated and visible to capture their entire periphery. The optical systems also require a powder layer placed on the tooth surface (to optimize reflections and color consistency). If that layer is not thin and even, the information captured with the optical systems will include a distortion. 2

   The DUX, Celay and Procera systems all use mechanical pantographic-type digitizers that are easy to use. The DentiCAD digitizer is new technology but easy to learn. The digitizer consists of a linkage and a mounting post. The post is attached, using compound, to a tooth or teeth at any arbitrary position away from the tooth being restored. A probe at the end of the linkage is moved over the areas where data need to be collected (the prepared tooth, for instance).

   Contact with the tooth need not be maintained throughout the entire digitizing process, If the probe tip is lifted off the tooth surface, data points are collected only when the two are in contact. There is no need for retraction and isolation of the margins. The probe tip is smaller in diameter than burs used to create a preparation so there is no problem with access the probe can easily obtain data subgingivally. From a clinical perspective, using the probe is similar to examining with an explorer. 2

   The CEREC and Duret systems require the user to become familiar with CAD commands. All systems require the user to learn some fundamentals of milling, though these are similar to concepts currently used with a dental handpiece. Additionally, the Procera system requires familiarity with EDM processing. 2

4. **Comparison Of System Costs:** Costs of the various systems range from under $25,000 (Celay) to over $200,000 (Duret). Factors other than initial cost for acquisition also need to be considered. The cost of operating the system may be important. Some systems require an expert user (CEREC and Duret, for instance); only the DentiCAD system can be operated without any special expertise. 2

   The materials cost must be factored into the comparison. At this time, incomplete information is available concerning the materials cost for each restoration for all systems. Another factor is the cost and replacement rate of cutters. Again, incomplete information is available so no fair comparisons can be made. 2

5. **Comparison of Quality of Fit:** There is little agreement concerning the acceptable quality of fit for CAD-CAM restorations. There is little agreement, indeed, about how measurements should be made to determine the quality of fit. For crowns, the fit at the margins (especially subgingival margins) should be better than around an inlay's occlusal periphery since more tissue reaction is likely to occur in those areas. Holmes found that excellent full coverage castings typically have a gap between the margin of the preparation and the margin of the restoration of about 40 to 60 microns. 2

   Marginal fit for the CEREC, Duret, Procera and DentiCAD systems are listed separately (values for Celay and DUX are not yet known). Clinical experience with the CEREC inlays-all with supragingival margins-suggests that the 100μm fit may be adequate for this type of restoration. 2224The only clinical data reported to date on the performance of CAD-CAM crowns is from Procera-produced Titanium crowns. Unfortunately, those reports do not quantitate the misfit between the restoration and the preparation at the margins; they report only the tissue response. No clinical data are yet available from the Duret or DentiCAD systems. Laboratory data suggest that the DentiCAD system can provide crowns with marginal fit at least as good as that achieved with excellent castings. 2

FIT OF CAD-CAM RESTORATIONS

SYSTEM	MARGINAL GAP AVERAGE	(MICRONS)	SD RANGE	REFERENCE
DENTICAD	23	28	0-49	22
	12	15	0-37*	
CEREC	79	46	(at proximal boxes)	23
	71	16	(at cervical margin)	
	134	16	(at shoulder)	
	88	14	(at occlusal cusp)	
	172	28	(at occlusal fissure)	
PROCERA	Surface, color:	90.3% E or A†		15, 16
	Anatomic form:	93.4% E or A		
	Marginal index:	100% E or A		
DURET	Average 200			9

XIV. A CAD/CAM TECHNIQUE FOR FABRICATING FACIAL PROSTHESES

The primary objective of prosthetic rehabilitation in patients having congenital or surgically acquired defects of the maxillofacial region is restoration of function and appearance. The surgical treatment of malignant disease in the maxillofacial and orofacial region may result in considerable morphologic deformity and psychologic disturbance. It is essential to provide appropriate prosthetic treatment for patients with facial defects to improve their quality of life. 12

For the conventional method of prosthetic design, a physical impression using fast-set dental irreversible hydrocolloid impression material is made and a master plaster-cast is produced from the impression. A wax model is prepared on the plaster cast and the final prosthesis is processed with silicone material after disclosing the wax. However, making an impression of the complete face is not only difficult but may cause the patient distress and discomfort. Moreover, the conventional method is not satisfactory because considerable skill, experience, and laboratory work are required. 12

Computer technology is an important tool in modern medicine. Three-dimensional imaging acquired from computed tomography scans or laser surface scanning can provide Superior visualization and has been accepted for studies of tooth, skeletal, and facial morphology. The three-dimensional data can then be fed to a computer aided design (CAD) program to simulate surgery and has been shown to be useful in the preoperative planning and post-operative evaluation of maxillofacial surgery. 12

This approach eliminated the necessity of laboratory work and provided a simple and efficient procedure in contrast to conventional methods. Lianq-Horng Chen, Sadami Tsutsumi, Tadahiko lizuka describe this technique. 12

Technique

1. **Acquisition of the "Facial Impression":** A laser surface-scanning unit (Surflacer VMR-301, UNISN) was used to acquire three-dimensional image data of the patient's facial defect. Two CCD cameras, positioned at an oblique angle, synchronously recorded the resulting slit-line images projected on the face. 12

   The slit-line images of the cameras were then sequentially transferred into an image processor to generate three-dimensional coordinate data of a cloud of points. The point image was then transmitted to an engineering workstation (Titan Vistra 800ex, Kubota Computer) to provide a three dimensional surfacing image using interactive CAD software INURBS software, Kubota Computer). After three-dimensional CAD data were completed, data images were then transferred to a CAD/CAM system for successive mathematical processing, design simulation, and model production. 12

2. **Production of the Wax Model:** Two alternative CAD/CAM three-dimensional modeling techniques, the laser lithographic model and numerically controlled (NC) milling model, were connected to fabricate the prototype wax model of the defect to complete the facial prosthesis. 12

   The interactive editing capabilities allow the clinician to design the restorative three-dimensional shape on the computer screen as desired. Modification of the computer-design processing can be continued until a satisfactory result has been achieved. Once the computer-designed shape of defect restoration has been completed, the CAD image files were processed further to generate computer milling control data. The milling data message was then linked to a numerically controlled three-axis milling machine (CAMM-3, Roland DC) that milled the required wax model from a wax block.

3. **Completing the Final Silicon Facial Prosthesis:** The prototype wax model was then applied to the patient for fitting and adjustment. When an optimal wax shape had been determined, the wax model was then invested in an appropriate flask. Boiling out, packing, and processing in a conventional manner were performed to produce the silicon facial prostheses. 12

In the present study, two distinct advantages were demonstrated: (1) an electro-optical unit was used to acquire the three-dimensional data needed to generate a processing image model without touching the patient; and (2) three-dimensional data was integrated directly into the CAD/CAM machines, which performed the labor and thus eliminated all the hand work except for the silicon fabrication and coloration. 12

Two alternative CAD/CAM three-dimensional modeling techniques, the laser lithographic and NC milling models, were used to prepare the wax model for fabrication of a prosthesis in the present study. In the laser lithographic modeling approach, which was similar to the modeling approach used in the conventional plaster-cast method, an intrinsic resin model was prepared prior to fabrication of the wax model. The r< in model was built and solidified in layers by laser lighting; therefore, complex anatomic construction that included surface and inner bony components was produced. Although some hand work was necessary to form the wax model on the resin model, an intrinsic resin model is helpful in the design of internal fixation devices, such as dental implants, for the prosthesis, particularly for a prosthesis for an extensive and complex facial defect. 12

Using the NC milling model approach, the wax model could be fabricated automatically from the data acquisition arid image processing to the milling of the device. This approach can simplify and reduce the laboratory work to a greater extent than the laser lithographic method. The NC milled model approach may be appropriate if the defect is localized or simplified; however, current limitations in the diameters and axes of the milling tools caused difficulty in cutting the delicate wax pattern. 12

Using the mirror-image technique of the patient's unaffected side to superimpose directly on the contralateral side is a simple technique for reconstruction of the defect. This technique was applied for maxillofacial reconstruction using three-dimensional computerized tomographic images to plan bone implants. In contrast to the procedure for preparation of bony tissue, the procedure for preparation of the tissue for a facial prosthesis would need to be more sophisticated. In addition to the facial asymmetry, healing of the soft tissue surrounding the defect will also cause shrinkage after surgery. These factors will cause the mirror image, created directly from the computer, to fail in properly matching the skin surface. To ensure a good surface match between the correlative mirror images, a least-square method was applied for minor compensations to smooth the margins during the image processing in this preliminary application. 12

In this preliminary study, the prototype wax model was initially formed. The wax model was fitted and adjusted during the try-in stage to improve conformity and then was replaced with silicon material to complete the final restoration. The research goal of this study was the development of a CAD/CAM technique that would make it possible to fabricate facial prostheses automatically. In the future, both improvement of the accuracy of the imaging processing and development of a suitable biomaterial will probably allow the CAD/CAM technique to more effectively fabricate facial prostheses. 12

XV. CONCLUSION

The advent of computer graphics and CAD-CAM have revolutionized dentistry. It is now possible to provide the equivalent of a cast restoration with a single appointment. Several systems are under development, each providing different characteristics and advantages. Some permit the clinician to be actively involved in the design process; others provide complete automation, freeing the clinician for other tasks. 2

Some use technologies similar to those already used in dentistry; others draw technologies that are state-of-the-art in engineering or manufacturing but not dentistry. Some aspects, like optical "impressions," are fairly technique sensitive. Others like the DentiCAD digitizer are forgiving and easy to use. Some systems are easy to use; others require expert users. Some are initially expensive; others are relatively less so. 2

Exciting changes are occurring in producing restorations. CAD CAM systems are available and more are being introduced continually. Clinicians must decide if and when it is cost effective to integrate this technology into their practice and which system is the best for their practice. 2

Results achieved must be analyzed with caution, but the extraordinary speed of development of this technology in industry affirms that it will be rapidly and definitively accepted in the dental profession. Its future evolution could be spectacular considering its numerous possibilities. 1

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