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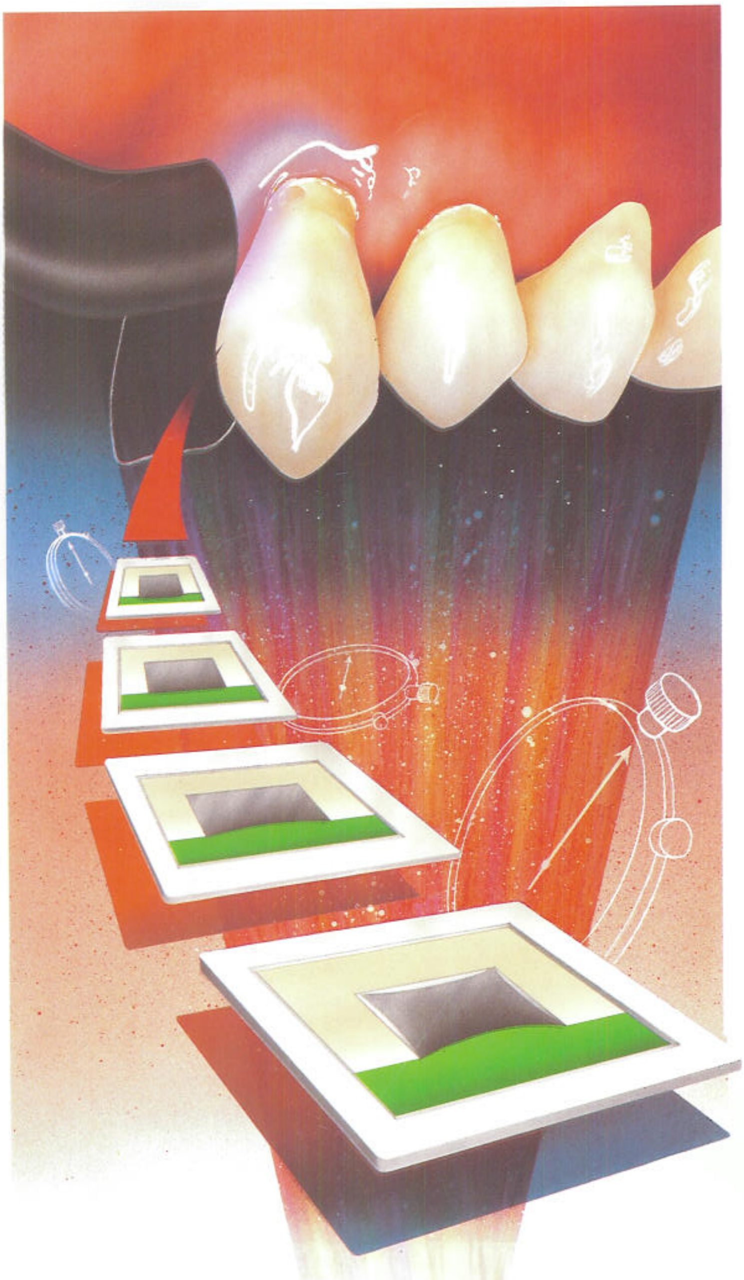

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Current Concepts

Current Concepts provides the opportunity for invited individuals to express their opinions on selected current topics of interest in the field of dentistry. The comments expressed herein represent personal opinion and not the positions of *Quintessence International*.

CAD/CAM in Dentistry: Present and Future Applications

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Did you ever wonder where all of the CAD/CAM units went that stormed the US markets in early 1990s? There has been a series of instant revolutions of technology in dentistry—CAD/CAM, lasers, air-abrasion units, imaging systems, etc. At a recent symposium at IADR in San Francisco, the real importance of this technology was discussed. Revolutions are exciting! Postrevolution realities are not. In every case, new technologies promised far reaching solutions to major dental problems. A few brave souls jumped on the bandwagon immediately. There were many excited bystanders. At the same time, the perpetual skeptics shouted loudly about the need to return to the past. When the shouting was over, any real value of the technology was greatly diminished by the disappointment. Dentistry rarely advances by leaps and bounds. Rather, like everything else, it is a series of small steps, ebbing forward only a little bit at a time.

So where is CAD/CAM? An honest view is that it is moving steadily along the path. While the fanfare occurred during the early 1990s, the ideas developed much earlier, and the ultimate impact will be realized farther down the line. Bruce Altschuler and other early pioneers of this technology remember the real beginnings much more clearly. CAD/CAM in the United States has its origins in the late 1940s. Engineers recognized that someday it would be useful to dentistry, once the equipment underwent considerable refinement for the small scale of dental applications. It is quite a different task to mill a crown rather than an engine block.

An early conceptual view of the technology, its potential, and proposals for dentistry were offered in a manuscript submitted by Altschuler to the *Journal of the American Dental Association* in 1972 as a view of the future. The article was rejected outright as folly. This rejection was evidence that the dream was less important than the corporate vision of the profession. Yet, the dream did not die. By the early 1980s, Duret had begun to assemble the first practical CAD/CAM unit.[1] He was followed quickly by Moermann and Brandestini[2] and Rekow.[3] Each had different application goals for their work. Rekow focused on acquiring direct intraoral images and milling crowns. Others touted applications such as inlays, onlays, and veneers, with future potential for crowns and bridges. Ultimately, everyone ran into certain real problems in fulfilling the dream. These limitations continue to define the state-of-the-art for CAD/CAM today.

When examining the dream for CAD/CAM in dentistry, you realize quickly that the name connotes only part of the challenge. "CAD" refers to "computer-assisted (or aided) design," and "CAM" represents "computer-assisted (or aided) machining." But the real dental operation is more complex. As proposed several years ago,[4] there are five stages that would occur with the ideal CAD/CAM system: *(1)* intraoral image acquisition (or indirect image acquisition from an impression or die); *(2)* computer-assited design; *(3)* computer-assisted machining; *(4)* computer-aided esthetics (or production of internal or external characterization of the milled material); and *(5)* computer-aided finishing (and polishing) to create the final restoration that would be ready for cementation.

The complete system does not exist. What we have instead is equipment that fulfills most of the first three steps, creating rough milled restorations as alternatives to castings. However, after initial manufacture, restorations still require many adjustments and are monochromatic in color. Small or thin portions of restorations can acquire sufficient light from scattering in adjacent tooth structure to look remarkably realistic. However, larger or thicker portions exhibit relatively poor esthetics without additional characterization, such as staining or glazing. While there are a variety of tricks to compensate for esthetic shortfalls, the overall process of CAD/CAM in dentistry currently requires more time and effort on the part of the dental team than is desirable.

Materials for use with CAD/CAM equipment have evolved slowly. Early milling units used either highly filled, pre-cured composites, or dental porcelains. Modified ceramics that were more machinable (Dicor MGC, Dentsply; Vita Mark II, Vita Zahnfabrik) were developed later. This solved the problems of production but did not change the problem for dentists. Materials were still relatively brittle. Extensive tooth preparation with shoulder-type margins and sufficient bulk were required to resist cracking. Only recently are there hints of new, tougher materials that might allow thinner margins. Milling of metal-alloy crowns never became popular, despite options to use gold alloys or titanium. Traditional dental ceramics have pores that predispose them to cracks. Pore-free materials, such as Dicor MGC, have displayed good short-term clinical performance but are still somewhat brittle. In situations in which cavity preparation principles have been carefully followed to insure that restorations possess adequate thickness, the long-term clinical performance for inlays and onlays has been good.[5,6] Some wear of the luting cement has been noted, but this has not been shown to compromise the restoration and is theoretically repairable.

CAD/CAM may be a strong option for large amalgam replacements.

Since the initial use of these restorations, the key question has been the quality or degree of fit. Actual measurements of fit are quite variable depending on the approach to the measurement, but cement thickness at the margins is the real point of interest. Despite the highly touted ADA ideal cement width of 25 to 40 µm,[7] most crowns and bridges in clinical practice appear to have cement thicknesses at the margins that average well above these levels. Many are much wider. A practical target for CAD/CAM has always been about 100 µm. The earliest CAD/CAM restorations varied significantly, averaging from 150 to 250 µm. Equipment refinements improved the fit to 90 to 120 µm.[8,9] Current equipment produces 50 to 75 µm at the margins. Therefore, by the 100-µm standard, one would conclude that CAD/CAM is competitive with conventional fabrication procedures.

Impetus to shift dental practice toward adopting CAD/CAM techniques has been strongly coupled with interest in amalgam alternatives and a strong bias toward esthetic restorations. CAD/CAM equipment sales have been strongest in Germany and Switzerland, where concern over dental amalgam use contributed greatly to this popularity. Meanwhile, in the United States, pressures to consider dental amalgam alternatives were just beginning. CAD/CAM use was limited to specialty practices where the equipment fees were less of a barrier. At the moment, future markets demand less expensive equipment. Chairside CAD/CAM procedures are simple and capable of producing high-quality restorations. However, the current cost-benefit ratios are high. Actual materials costs and dentist costs are small compared to the equipment amortization.

During the early 1990s, interest in CAD/CAM helped to open the door for copy milling, which can be conducted without expensive computer support. Excellent crowns and bridges can be produced by this technology.[10] To date, use of copy milling has been mostly in the dental laboratory, but the interest is strong and continues to grow. Still, there is no evidence that copy milling will replace CAD/CAM.

The future of CAD/CAM systems lies with ingenious reduction of technology into a simple, inexpensive chairside and/or laboratory unit. The future equipment must be *(1)* under US$ 10,000, compact; *(2)* capable of acquiring cavity preparation information readily from intraoral surfaces, impressions, or dies; *(3)* fully automated for inlays, onlays, and crowns; *(4)* rapid in production of restorations (less than 10 minutes); and *(5)* easily upgraded. The challenges for the next generations of equipment are price control and accurate acquisition of information about subgingival margins. Subgingival margins are difficult to identify with intraoral camera systems, necessitating contact digitizers or image acquisition from impressions. In light of the outstanding computer software that exists and the relatively low computer costs for today's technology, these characteristics seem to be within range for dentistry. Then, the final market will be driven by the developing interest in cost-effective amalgam replacement technologies.

While CAD/CAM may be a strong option for large amalgam replacements or crowns, most practitioners still desire a direct restorative technique involving esthetic materials. The pressure for the moment seems to be for a condensable, moisture-tolerant, direct-bonding esthetic material that can be quickly bulk-cured without shrinkage (ie, advanced composites). These types of materials probably will enter the dental market at the same time as the newer versions of CAD/CAM equipment (about 1997 to 2000). It will be interesting to see how the two technologies complement one another. One might imagine ultimately that inlays and onlays may become common applications for advanced composites, while crowns and bridges may be manufactured mostly by CAD/CAM. In either case, both technologies will be enhanced significantly by the development of new, tougher materials. Is CAD/CAM going away? No, but the ideal system is still down the road.

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Today, it would be unreasonable to doubt the CAD/CAM system. This procedure is about to cause a total upheaval in the manufacturing of prostheses, and dentistry in general, in spite of the "everyman for himself" reaction. For those who defend a "zero development" policy and the traditional methods, we will be obliged to review our daily work for the well-being of our patients. One thing is certain: that since the first CAD/CAM crown was placed in 1985 in front of 800 dentists, dentistry has changed and will never be the same again.

Today, the CAD/CAM instruments are ancestors of technological dinosaurs. Of course, we can make inlays and onlays (Celay, Ceramatic, CAP System, Cerec, etc.), copings (Procera, DCS Titan, Intra-Tech, etc.), crowns, and even fixed partial dentures (CAP System, Nissan, etc.). We also know that these instruments, in general, are precise enough for daily practice (margin widths, on average, of 40 ± 20 µm for the most precise and 120 ± 40 µm for the least), more rapid than the traditional method (30 minutes for the quickest and 2 hours for the slowest), and reliable in everyday work.

However, they are still too expensive (between US$ 40,000 for the least sophisticated and US$ 350,000 for the most sophisticated) and too sophisticated, and there are far too many (we are lost among the 12 different systems that are available or will soon be on the market).

Each potential user who considers his work seriously is aware that with CAD/CAM he can manufacture rapidly and precisely 80% of his fixed prostheses, according to the standards of the American Prosthetic Society, but at cost higher than that of the traditional method. Each potential user is also aware that CAD/CAM systems have become archaic, are no longer original, and are about to undergo a new lease of life.

To understand this new generation of CAD/CAM and its application possibilities, a global analysis of the change in 21st-century dentistry is necessary, as these two points are and will become inseparable. But, attention: words such as "application" must be used carefully, as computerization has a large default. It transforms not only the methods in practice, but also its needs and therefore its applications.

By studying the changes in the concept of dentistry, we will try and foresee what the CAD/CAM applications could be in the future.

It is true that we could make a list of the CAD/CAM methods and applications and stipulate what each machine can or will be able to carry out. The problem approached at this angle would limit the possibility of precisely defining a technology that will not cease to progress freely, and this limitation could be unknowingly projected into a future analysis. For these reasons, and a few others, we prefer a more general analysis and therefore outline the machine and its future applications.

To manufacture a prosthesis using traditional methods, we use the knowledge obtained during our training, at different congresses, and from articles. The manufacturing of a prosthesis by CAD/CAM is going to change completely our way of training and further knowledge acquisition.

At present, the know-how comes from a limited number of people, lecturers or teachers; and to attain such knowledge we have to study and then decide if we want to follow with continuing education or not. This makes the fabrication of a prosthesis complex and uncertain.

The CAD/CAM, by its computerized tool, transforms, brings up to date, and simplifies the method of prosthesis fabrication. Apart from the basic knowledge that must still be obtained to make a prosthesis, the CAD/CAM offers all the information instantly, accessible through servers equivalent to the Internet. This way the user can have instant access to the broadest scope of knowledge without any effort.

This information will then be directly used by the computer (intentionally, by updating of the software; or unintentionally, by loading at a distance). It will no longer be necessary to have long training for each innovation. The CAD/CAM should have standards for acquisition and use of its data.

Moreover, each prosthesis will be collected by an information center, which, after filtering, will give essential information leading to the creation of an expert system more and more sophisticated and enable complete success in the fabrication of all prostheses—individual and future.

Through this, each operator, whether a dentist or a prosthodontist, would become an actor in an immense world that could be called "Prosthetic World or Space."

Like any craft, partly artistic or scientific, dental practice is dependent on numerous repetitive tasks, like the mixing of impression plaster or denture paste, wax, or metal casting. This manual work limits creativity in a number of ways, causing lassitude, tiredness, and mistakes that can be made through manual work.

The CAD/CAM eliminates the majority of these repetitive acts so dentists can concentrate exclusively on the conception of the mouthpiece. We arrive finally at a "pure, intellectual, and virtual" conception of a prosthesis, which can become functional. But it is obvious that this power of calculation, allocated at present to the construction of a prosthesis, will no longer be so limited in its future applications. The CAD/CAM system was never meant to be exclusively for the manufacture of prostheses, but for the conception and/or manufacture.

The CAD station will be advantageous in determining diagnoses and prognoses.

Finally, in our professional reports, whether it be with the patient or between dentists and prosthodontists, the CAD/CAM comes forth as a system that limits the distances. If the apparatus is currently confined to the laboratory, in the future the decentralization of the manufacturing will no longer be necessary because communication will take place through waves.

It is not impossible to imagine that a prosthodontist will be able to order and supervise the manufacturing of a prosthesis from a distance or machining next to the patient, just as it is also not impossible to imagine a diagnosis made from a specialized center. The patient need not make the journey and can even stay at home.

This time reduction would allow higher-quality prostheses to be made at a reasonable price and in an acceptable amount of time. The CAD/CAM is without any doubt the only way of imposing good quality at the same price as a few prostheses manufactured with cheap human labor and escorted by plane in record time.

Research and the differences between CAD/CAM and traditional methods should now allow us to pinpoint accurately the future of this method.

Logically, in respect to what we have seen, a CAD/CAM system will be composed of a captor (image acquisition), a computer-aided design unit, and a performance system. The machine can be used in part or as a whole. The applications will not necessarily oblige the use of three units.

The image acquisition system could function from an image of a three-dimensional camera, radiograph, or any other source (ie, magnetic resonance or any new-information collecting system). It could be used simply for obtaining an image of the prepared (prosthesis) or unprepared (orthodontics, diagnostics, etc.) teeth. It could also be used to determine bone outline, allowing deeper impressions and precise diagnosis of the relation between bone and tooth (research of intraosseous pockets). The three-dimensional captor would therefore permit information about the studied element to be transferred to the CAD unit.

The diagnosis could be based not only on the image from the CAD, but also on a cast made by duplication methods (ie, stereolithography). This instrument could also be used to manufacture specific tools for the improvement of the observed therapy. It would be considered a form of diagnosis and image therapy, using a model that would allow a solution to the problem.

The numerous applications of the CAD station bring into action *the whole chain* and are well identified. Considering all the systems, all prostheses, including removable prostheses, can be manufactured with CAD/CAM. Therefore, it is not necessary to raise the manufacturing standard that exists and will only improve. Today, a good CAD station can design a four-element fixed partial denture in less than 1 second.

The extensive advantage of future applications would be the use of dynamic occlusion, followed by the integration of the occlusion for each patient and a multitemporal analysis—the creation of a prosthesis after presimulation. (It will be possible to simulate a 10-year life of a prosthesis in the stomatognathique system and therefore possible to foresee and construct this model, taking into account its evolution, which also is simulated).

The use of x-rays and surface modelizers permits the fabrication of made-to-measure implants, in respect to the endobuccal bone environment. (This is not new as it was described and carried out in 1984.) However, this modelization will be associated with new factors such as general esthetic or biochemical metabolisms (the control and follow-up or the bone remodelization commanded by the local phosphocalcium metabolism and studied by beta camera and the Doppler effect). The actual prefabricated implant would no longer make sense on the medical basis.

New prosthetic realizations, that we do not yet know, would appear, and these would be the result of the analysis made by expert systems.

The applications that bring into action *part of the chain* will be more and more numerous. It goes without saying that the integration of managing systems will be obligatory, if only used to manage the stock or analyze the real prosthetic profitability (sometimes 80% of the activity).

The most interesting advantage of the CAD station will be diagnostic help. To give an example, let's remember what I have often stated in congresses and in respect to orthodontics: "We are carrying out a 3-D global image of a child's mouth before treatment. Each tooth passes on the screen so that it is correctly positioned. This action will, of course, be verified, controlled, and even modified by a parallel analysis made with x-rays—digital or by a special center (via Internet). Once the modification is made, the computer analyzes the route made by each tooth (ideal route), controls the bone density in order to estimate the time necessary for the displacement, and then commands the machining of the grooved bracket, tooth by tooth, so that the arc directs the defined movement. A simple optical control will inform the dentist if the route taken is conformed to the analysis and prognosis."

On the other hand, the association of CAD/CAM, without the captor, will permit the station memory to reproduce indefinitely a prosthesis already manufactured, or to transfer the information through the modem to a colleague treating the same patient—with their broken crown in hand.

Finally, the important applications in respect to the manufacture station will be linked to the material. This will be one of the essential points of CAD/CAM in dentistry. At present, we can use only 2% of the materials available in the world, simply because we use casting. With CAD/CAM, more than 80% of the materials would be accessible in dentistry. This would revolutionize our work and transform it economically.

CAD/CAM will bring dentistry nearer to an exact science.

Moreover, instead of placing homogeneous materials (ie, gold, ceramic) in a universe uniquely composed of a heterogeneous-oriented structure, we could have heterogeneous materials respecting the dynamic analysis of the forces used in the mouth. The first preoriented material of this type in the history of dentistry was Aristee from Spad laboratory in Quetigny, France. This was the prototype of the 21st-century material.

It is possible that shading will be performed by the machining center. The machining tool will be replaced by the energetic system (ie, thermic and photonic effects), which will activate specific pigmentations predisposed in the materials and according to a cartography made by a spectrocolorimeter.

However, as you may well think, one must act cautiously, as anything is possible, including premature diagnosis, which would mandate a review of the use of the CAD/CAM.

The CAD/CAM will be a professional revolution and will lead to a new way of learning and working. From this will develop new applications, which we are still unable to imagine.

Finally, and it is because of this that I have liked this technique for more than 25 years now, it will inevitably bring our work, which is based purely at a statistical angle, nearer to exact science (through the expert systems).

It will be difficult to imagine how we have managed without it.

The CAD/CAM is not a machine but a concept.

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Although the development of computer-aided design (CAD) and computer-aided manufacture (CAM) technology and the benefits of increased productivity became obvious in the automobile and aerospace industries in the 1970s, investigations of this technology's application in dentistry did not begin until the 1980s. Only recently have we begun to see the advantages of this work with the commercial availability of some systems; the potential for this technology seems infinite.

The use of computers for designing and fabricating restorations is one of the most sophisticated and creative dental applications of electronic technology. CAD/CAM is a science adapted from industry where practically every manufacturer and production line relies on this process for product design and fabrication. Most industrial CAD/CAM applications are associated with the fabrication of replicas of a product. In dentistry, each restoration (product) is designed and formed only once.

For preparation of a dental restoration, an image of the prepared tooth or die must be procured and stored in the computer. This image must be transferred to the CAD station, where it is designed using computer-imaging software and display. The design data are used to operate a numerically controlled milling machine (CAM). Presently, CAD/CAM systems are used to produce inlays, onlays, crowns, or laminate veneers. These systems have the potential to be used for more complex restorations, such as fixed partial dentures, in the future.

In conventional restorative procedures, an impression is made to form a stone cast, and a wax pattern is created on the resulting die. The wax pattern is invested, sealed within a mold, and the hollow cavity is filled with metal or a castable ceramic material. With CAD/CAM processes, the impression and die procedures are replaced by image acquisition, and the waxing process is replaced by the CAD process. Just as a wax pattern may be manipulated to achieve the desired functional and esthetic form, the virtual restoration (image) may be designed using the CAD software.

Images may be procured either by tracing the surface of a tooth with a surface probe linked to a computer or by using a laser-based camera. For either procedure, the computer processes the data to develop a three-dimensional image of the prepared tooth and subsequent contiguous or adjacent surfaces. These reference points are located in three-dimensional space and represent a "virtual die," upon which the restoration is designed.

The development of some dental CAD/CAM systems has led to the creation and financial ruin of several companies. This complex computer application requires a substantial investment to design and produce. Furthermore, the intraoral imaging constraints preclude easy adaptation of industrial technology. A number of companies are developing dental applications, but only a few commercial systems are available today. There are currently three systems available.

CEREC System (Siemens). The CEREC System is the most widely available CAD/CAM system for fabrication of inlays, onlays, and veneers. CEREC is an acronym for ceramic reconstruction. The system consists of a laser-imaging probe, a monitor for viewing the image, and an electronic milling machine. This system has been available since 1985, and clinical results have been promising.

A single image is made using the laser camera. The system is not designed to accept more than one image or to incorporate multiple images. The margins of the preparation are outlined using a track ball to move the cursor, defining both the internal and external extent of the cavity. A diamond disc then machines the surfaces of the restoration from a ceramic block. The occlusal surface is only grossly developed, and the anatomy must be ground by the dentist.

The CEREC CAD/CAM system is an efficient, self-contained unit that has no design capability beyond that described. The use of diamond discs for machining the restoration limits its use, and the system is not adaptable for fabrication of crowns. Nonetheless, it is a well-designed compact unit that allows for in-office fabrication of ceramic inlays, onlays, and veneers.

Siemens recently introduced an improved version of the CEREC system, which incorporates dual milling mechanisms that provide enhanced efficiency. The unit is awaiting FDA approval in the United States. No data are currently available on performance.

The Procera System (Nobelpharma). Titanium and titanium alloys have become well established as materials for endosseous implants. As a result, there has been interest in developing a restorative system using titanium as a substructure for resin or ceramic veneering. The Procera system was developed for such a purpose. The system uses spark erosion and copy milling to shape the titanium. Carbon electrodes shaped like the die are formed by copy milling, ie, tracing the die with a pantographic device connected to a milling machine, much in the same way keys are duplicated. The electrodes are used to electromill the internal surface of the titanium workpiece. Computer-aided design is used to design the exterior of the coping and to control the electromachining of that surface. The titanium coping may be veneered with resin or porcelain, and studies in Sweden have shown the process to produce clinically satisfactory results.

The Duret System. The system developed by Francois Duret uses a laser-imaging camera to acquire multiple views of the prepared tooth and equate them into a true three-dimensional image. The system currently operates from a cast of the prepared tooth rather than directly on prepared teeth in the mouth. Multiple images are acquired, correlated by the software, and displayed so the user might define the margin and other landmarks. The occlusal relationships are established by imaging an interarch record placed over the die. After the necessary information has been input, a three-dimensional image is formed and passed to a CAD station, where the restoration is designed. Although the system may be used in an automatic mode, it is best used as an interactive system. All aspects of the design, from die spacing to controlling the occlusal surface, are under the operator's control. The system uses a library of tooth forms from which the restoration may be customized. The operator may selectively expand the die as desired to provide cement space; to alter the cusp height, ridge height, or groove direction; and to modify all external contours as desired.

When the desired form has been achieved, the information is sent to the CAM unit. The system uses a five-axis milling machine with diamond and carbide milling tools. All tool manipulation is automatic, and the finished piece is completed, requiring only minor modifications to remove the areas where it was retained in the original block.

A significant research effort is presently being devoted to the development of materials for CAD/CAM systems rather than using those adapted from other technologies. All of the processing techniques in dentistry have required reformulation (melting and casting or firing) of the initial material. The use of a CAD/CAM system changes this perspective and offers the prefabrication of materials without the current limitations of conventional dental laboratory processing. A distinct limitation of CAD/CAM technology is the lack of materials available for fabricating esthetic and multiple units. There is much opportunity for innovative design and development. Some research has been directed toward preparing improved formulations of intrinsically colored microcrystalline glass ceramics for use in CAD/CAM restorations. Research is also being conducted on analysis of milling effectiveness and machining damage in ceramic structure.

The amount of interest in research and development throughout the world indicates that CAD/CAM will have a definite place in routine dentistry. Japanese researchers have a number of fascinating projects, and marketable products are expected soon. CAD/CAM technology can be applied to both intraoral and indirect laboratory use. It will find widespread acceptance when intraoral applications are made practical and cost-effective. The potential for time and labor savings, including elimination of the temporary restoration and a reduced number of patient visits, provides an economic incentive in the quest for improved and affordable patient care delivery systems.

Although dental CAD/CAM technology is in its early stages, it holds the potential for numerous applications that are readily apparent. To optimize its potential, CAD/CAM systems will need to be eventually integrated with other computer-based dental applications, such as mandibular movement recording, expert systems, decision-making programs, digital radiography, and video imaging. One major limitation of CAD/CAM technology is the inability to produce variable shading and translucency. Thus, veneering and stain characterization will still be required except, perhaps, for posterior restorations.

The use of CAD/CAM technology is becoming a clinical reality in modern dentistry. There is great promise that this will help to provide a higher level of quality service to the patient by allowing the dentist to spend more time on patient needs than on the mechanical production of restorations. This technology is not suited for every dental office but will play a major role in the future of clinical dentistry.

CAD/CAM will allow dentists more time for patient needs.

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Manuscripts

- Manuscripts must be submitted to Richard J. Simonsen, DDS, MS, Editor-in-Chief, Quintessence International, Dental Research Institute, School of Dentistry, University of Minnesota, 515 Delaware Street SE, Minneapolis, Minnesota 55455
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For periodicals:

1. Denehy GE, Swift EJ Jr. Single-tooth home bleaching. Quintessence Int 1992;23:595-598.

For books:

1. Jeffcoat M. Imaging techniques for periodontium. In: Wilson TG Jr, Kornman KS, Newman MG (eds). Advances in Periodontics. Chicago: Quintessence, 1992:47-57.

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