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Review

A review of dental CAD/CAM: current status and future perspectives from 20 years of experience

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In this article, we review the recent history of the development of dental CAD/CAM systems for the fabrication of crowns and fixed partial dentures (FPDs), based on our 20 years of experience in this field. The current status of commercial dental CAD/CAM systems developed around the world is evaluated, with particular focus on the field of ceramic crowns and FPDs. Finally, we discuss the future perspectives applicable to dental CAD/CAM. The use of dental CAD/CAM systems is promising not only in the field of crowns and FPDs but also in other fields of dentistry, even if the contribution is presently limited. CAD/CAM technology will contribute to patients' health and QOL in the aging society.

Key words: CAD/CAM, Crowns and fixed partial dentures, Digitizing, Network, Zirconia

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INTRODUCTION

In dentistry, we have a long history of contributing to the needs of patients by offering dental restorative and prosthetic devices such as inlays, onlays, crowns, fixed partial dentures (FPDs), and removable dentures, to recover patients' oral function and maintain their health. In contrast with other ordinal industrial products, such dental devices were originally tailor-made to the patient's individual condition. During the 20th century, both dental materials and dental technologies for the fabrication of dental devices progressed remarkably. The lost-wax precision casting of gold alloys, dough modeling and curing of acrylic resins, and powder sintering of dental porcelains were originally developed for dentistry and are well established as conventional dental laboratory technologies. There is no doubt that high quality dental devices can be routinely fabricated through the collaboration of dentists and dental technicians. Nevertheless, dental laboratory work still remains to be labor-intensive and experience-dependent.

Owing to the increased demand for safe and esthetically pleasing dental materials, new high-strength ceramic materials have been recently introduced as materials for dental devices[1, 2]. Since these materials have proved to be inimical to conventional dental processing technology, new sophisticated processing technologies and systems have been anticipated for introduction into dentistry. One solution to this is the introduction of computer-aided design and computer-aided manufacturing (CAD/CAM) technology.

In relation to the rapid progress being made in computer-assisted processing technology in various industries since the 1970s, research and development of dental CAD/CAM systems has been actively pursued worldwide since the 1980s, including in Japanese academies[3-13]. Recently, commercial dental CAD/CAM systems have been introduced for specific fields such as all-ceramic restorations. In this article, we describe the recent history of the development of dental CAD/CAM systems for the fabrication of crowns and FPDs, based on our 20 years of experience in this field. We also summarize the current state of commercial dental CAD/CAM systems that have been developed around the world, with particular focus on the field of ceramic crowns and FPDs. Finally, we discuss the future perspectives applicable to dental CAD/CAM.

A BRIEF HISTORY OF DENTAL CAD/CAM

When we started research and development in the 1980s, the design and processing of dental devices using CAD/CAM technology was generally believed to be simpler and easier than for industrial products. However, in reality, dental CAD/CAM is neither simple nor easy for the following reasons:

1) Total cost, operation time, and manipulation of the systems for processing dental devices using CAD/CAM technology should be at the levels found in conventional systems, or be superior, to replace the conventional individual tailor-made restorations and ensure that new systems are practical in daily laboratory work and clinical practice.
2) Morphology of the abutment teeth, related adjacent teeth, and related opponent teeth

should be accurately digitized prior to designing the restoration to adjust crowns and FPDs to abutment teeth and dentitions. However, it was difficult to recognize the delicate margin prepared by dentists using the compact digitizers available at that time. Therefore, the development of an accurate and compact digitizer and related sophisticated software was necessary for high-precision digitizing of complex and delicate targets.

3) Numerical representation of the shape of crowns and FPDs is complex in comparison with the typical industrial products that are expressed using functional equations. In addition, because the restorations not only have to be adjusted for abutment teeth but must also harmonize with adjacent and opposing teeth, once again, the development of sophisticated CAD software of restorations was necessary.
4) Accurate processing, including mechanical milling of sharp corners and delicate margins of crowns and FPDs, was difficult with brittle ceramic materials. Therefore, the development of a stiff processing machine and sophisticated software to control the tool path were necessary. In addition, the size of the machine needed to be limited for installation in a normal dental laboratory office.

In dentistry, the major developments of dental CAD/CAM systems occurred in the 1980s. There were three pioneers in particular who contributed to the development of the current dental CAD/CAM systems.

Dr. Duret was the first in the field of dental CAD/CAM development[4]. From 1971 he began to fabricate crowns with the functional shape of the occlusal surface using a series of systems that started with an optical impression of the abutment tooth in the mouth, followed by designing an optimal crown considering functional movement, and milling a crown using a numerically controlled milling machine. Later he developed the Sopha® System, which had an impact on the later development of dental CAD/CAM systems in the world.

The second is Dr. Moermann, the developer of the CEREC® system[3]. He attempted to use new technology in a dental office clinically at the chair-side of patients. He directly measured the prepared cavity with an intra-oral camera, which was followed by the design and carving of an inlay from a ceramic block using a compact machine set at chair-side. The emergence of this system was really innovative because it allowed same-day ceramic restorations. When this system was announced, it rapidly spread the term CAD/CAM to the dental profession.

The third is Dr. Andersson, the developer of the Procera® system[7]. At the beginning of the 1980s, nickel-chromium alloys were used as a substitute for gold alloys because of the drastic increase of gold prices at that time. However, metal allergies became a problem, especially in Northern Europe, and a transition to allergy-free titanium was proposed. Since the precision casting of titanium was still difficult at that time, Dr. Andersson attempted to fabricate titanium copings by spark erosion and introduced CAD/CAM technology into the process of composite veneered restorations[8]. This was the application of CAD/CAM in a specialized procedure as part of a total processing system. This system later developed as a processing center networked with satellite digitizers around the world for the fabrication of all-ceramic frameworks. Such networked production systems are currently being introduced by a number of companies worldwide.

Meanwhile, a number of Japanese universities started research and development of dental CAD/CAM systems in the latter half of the 1980s[9-13] and several CAD/CAM systems have been available on the domestic Japanese market. However, there was the unfortunate situation in Japan that, even though there was abundant research on dental CAD/CAM at universities and companies during the past 20 years, dental service was largely provided by the health insurance system, which have resisted the routine application of dental CAD/CAM in clinics. Nevertheless, considering the globalization of dental services, it appears promising that dental CAD/CAM will obtain approval for the application of all-ceramic crowns and FPDs in Japan in the near future.

AN OVERVIEW OF DENTAL CAD/CAM

A variety of CAD/CAM systems have been applied to the total process for fabricating restorations. An overview of the current dental CAD/CAM systems used for the fabrication of crowns and FPDs is given in Fig. 1.

After the abutment teeth are prepared, the mainstream work-flow for conventional metal restorations is first obtained by taking an impression followed by model production, wax up, and then casting. When this work is performed with the aid of computer-assisted technology, abutment teeth are directly digitized inside the oral cavity instead of taking conventional impressions. Restorations are designed on a computer monitor using CAD software based on the digitized data as a virtual wax-up. Finally, restorations are processed by a computer-assisted processing machine, usually a milling machine. This process was investigated and practically developed by the pioneer Dr. Duret. However, direct digitizing of abutment teeth in a mouth with a camera for crowns and FPDs was technically difficult because of the restricted measuring conditions in the mouth, including the presence of adjacent teeth, gingiva, and saliva, which made accurate recognition of the margin of an abutment difficult. This has been a critical limitation of the system to fabricate final precision restorations.

On the other hand, Dr. Moermann succeeded in his efforts to produce a ceramic inlay restoration using computer-assisted technology. Digitizing of the inlay cavity was performed directly in the mouth using a compact intra-oral camera, which was technically less difficult compared with crown abutments. Design and fabrication of the ceramic inlays were performed using a compact machine set at the chair-side in a dental office.

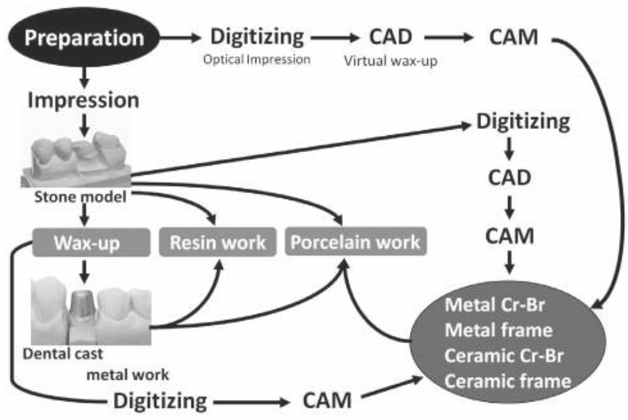

Fig. 1 An overview of current dental CAD/CAM systems using for the fabrication of crown-bridge restorations.

Currently, a stone model of crowns and FPDs is first produced, as was done with conventional methods, and this serves as the starting point for the CAD/CAM process to ensure digitizing accuracy. After the stone model is digitized, restorations can be designed on the monitor and fabricated by various processing machines. Dental laboratory technicians can use this system as a laboratory tool. This flow is most commonly followed by the current commercial dental CAD/CAM systems available for crown and FPD restorations. There are also systems that complete the wax up, as in the conventional method, and then digitize the wax patterns followed by automatic processing.

Recently, networked CAD/CAM systems that were originally based on the Procera® system have garnered attention, especially for the fabrication of high-strength ceramic frameworks. The role of digitizing a stone model and that of CAD/CAM processing are separated in this system. Data for the abutment that are digitized at the satellite office are transferred via the internet to a processing center based anywhere in the world. Frameworks fabricated at the center are then delivered to the satellite office to complete the restorations by layering porcelains. This is an application of CAD/CAM technology to a specialized field within a total process. This application holds promise for the fabrication of zirconia frameworks.

DIGITIZING

Most of the current commercial CAD/CAM systems

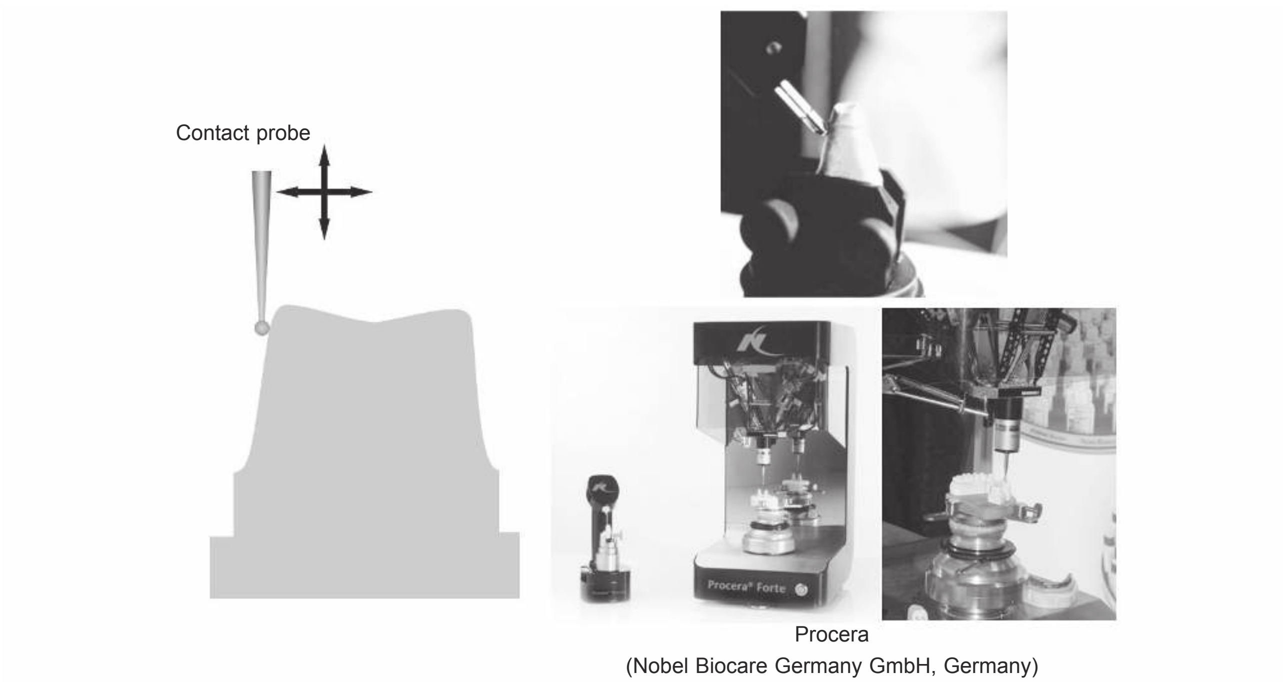

Fig. 2 Currently available digitizing method using a contact probe.

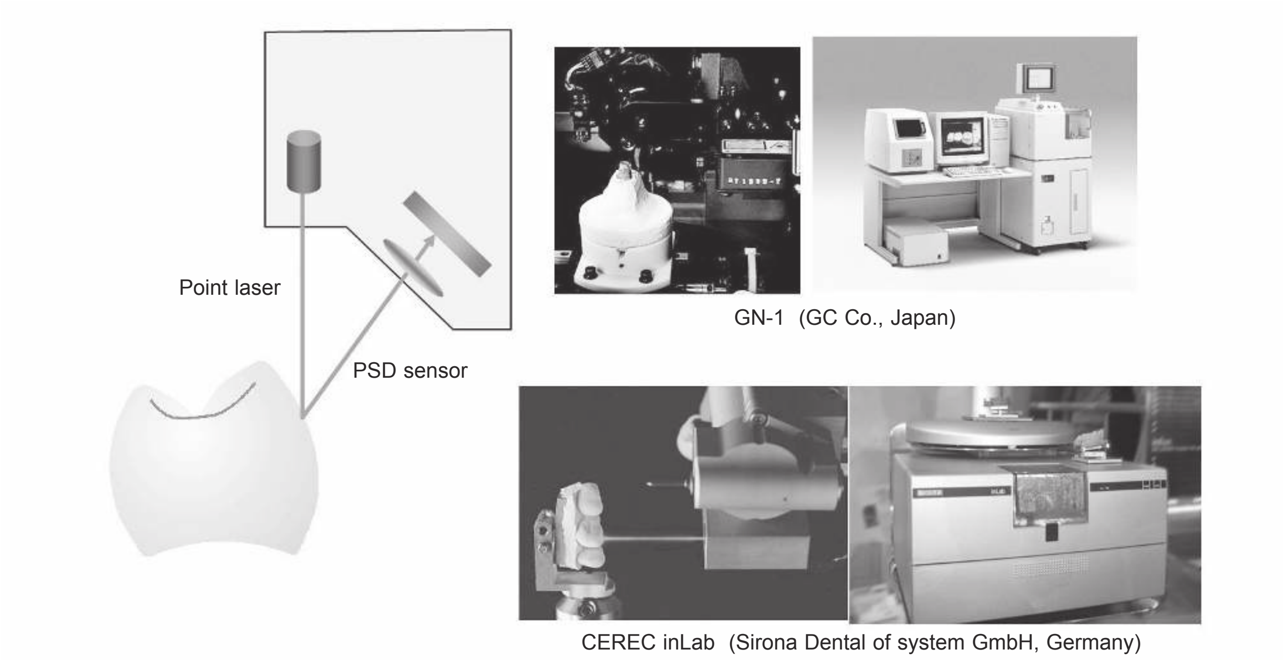

Fig. 3 Currently available digitizing method using a laser displacement gauge.

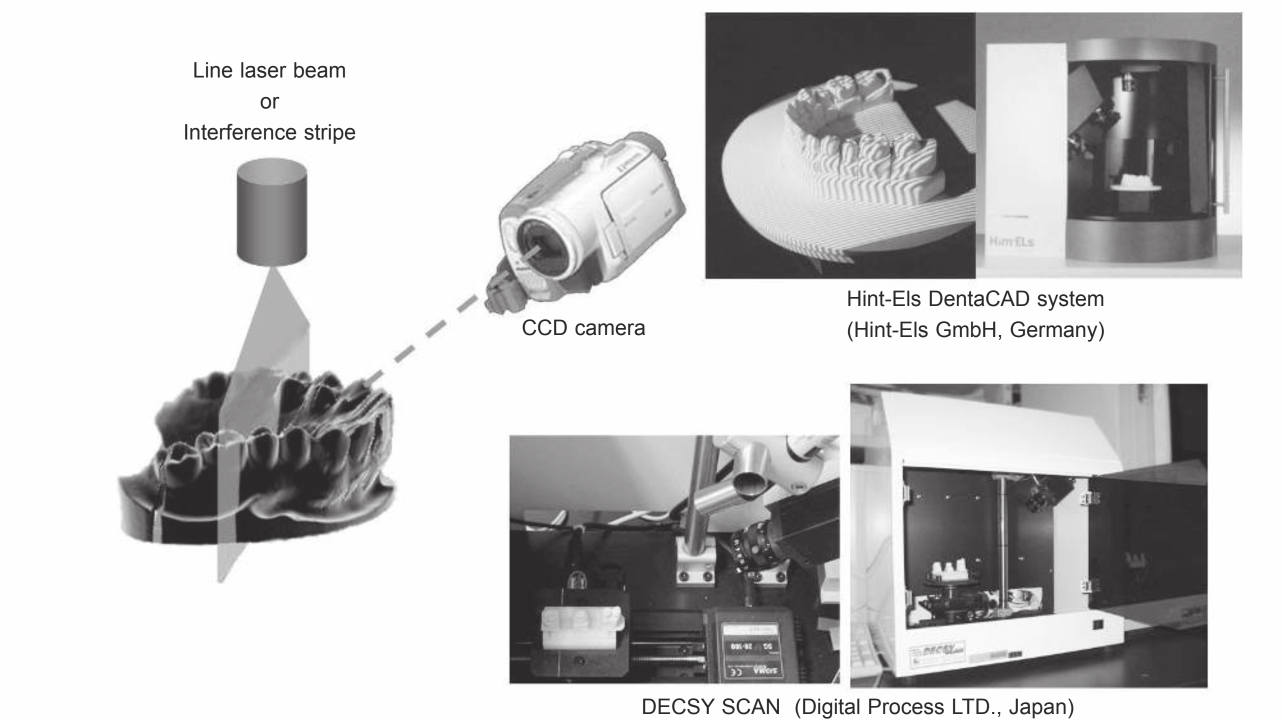

Fig. 4 Currently available digitizing method using a line laser beam or interference stripe with a CCD camera.

available for the fabrication of crowns and FPDs use a stone model as their starting point. The surface of a stone model is measured using various measuring tools to obtain the digital data that represent the morphology of the target tooth. These measuring tools are called digitizers and scanners. A variety of methods of digitizing have been investigated and developed. The methods currently available for practical use are a contact probe[14] (Fig. 2), a laser displacement gauge (Fig. 3) and a line laser beam with a CCD camera (fig. 4).

When a fine-tipped probe is used as the contact probe, even if it is very precise, it takes time to scan the entire model surface. A laser displacement gauge is relatively inexpensive and measurement takes less time than with a contact probe. However, because the reflected light of the projected laser beam is recognized by a PSD sensor, the precision decreases with the effects of diffusion. Corner precision was particularly difficult to obtain[15,16]. When a line laser is used, the scanning time is greatly reduced, but the resolution of the CCD camera affects the precision. Since none of the methods allowed for measurements of undercuts of tooth, multi-axial control of the stage of the stone model and the projection beam was needed. As described later, small digitizers that could be used separately in both a dental office and a laboratory networked to the processing machine and the processing center are very popular.

APPLICATION OF CAD/CAM AT THE DENTAL CHAIR-SIDE IN A CLINIC

Dr. Moermann succeeded in his efforts to develop a CEREC® system that would simply produce a ceramic inlay restoration at the dental chair-side in a short time. However, the occlusal surface of the inlay had to be prepared by manual grinding[3]. On the other hand, marginal fit of the prepared inlay was initially unsatisfactory because of limits to the camera's digitizing accuracy. Nevertheless, this system has gained acceptance in clinics when used with recently developed adhesive composite luting materials, and has helped increase popularity of CAD/CAM within the dental profession.

The CEREC® system has been continually improved in terms of both apparatus and software. Numerous reports have been published on this system, with satisfactory long-term results[17-19]. A recent iteration of the system can fabricate not only original inlays and onlays, but also crowns and the cores/frameworks of FPDs in both clinical and laboratory settings.

APPLICATION OF CAD/CAM FOR THE FABRICATION OF CROWN-BRIDGE RESTORATIONS IN A DENTAL LABORATORY

Spurred on by Dr. Duret's developments, research and development has been actively conducted to fabricate crowns and FPDs with the anatomical shape of the occlusal surface using CAD/CAM technologies. Unfortunately, there are few published reports regarding the development of both software and hardware for the currently available systems because of corporate trade secrets related to the rapid progress and model-changes for commercial products. Judging from the latest exhibitions at IDS in 2006, the final development goal for the current systems all seem to be heading in a similar direction. Therefore, in this section, our research strategies over the past 20 years of developing a dental CAD/CAM will be described.

In 1985, we initially applied CAD/CAM technology to several steps and parts of a total fabrication system for removable prostheses using numerically-controlled electric discharge machining[20-24]. Then in 1990, we started research and development into the direct application of CAD/CAM technology for crowns and FPDs. At that time, there were already several CAD/CAM systems developed or under development to fabricate crowns and FPDs practically. However, it took considerable time to reproduce the digitized data three-dimensionally using computer graphics (CG) and to design an appropriate crown on a monitor by undertaking the so-called virtual wax-up operation. We succeeded in developing software to automatically design crown morphology in a short time instead of the time consuming CG process on the monitor. In addition, the structural mechanics of an optimally shaped crown was also evaluated (Fig. 5). On the other hand, CAD/CAM systems in development at that time appear to have consisted of three components: measuring equipment (digitizer/scanner), relatively large processing machine, and a large computer workstation to realize the CG of digitizing images related to the CAD process. Installation of these large systems at regular dental offices and laboratories in Japan was limited not only because of the price but also space limitations. Furthermore, even if the advantage of production using a computer was emphasized by the developer, essential quality data such as the fit of the restorations were lacking at presentations and in publications. Therefore, we established the following development strategies and started the development of a small and integrated CAD/CAM machine for a dental use[25-32].

1) Developing an operator-friendly CAD/CAM system as a supplemental tool for dental laboratories.

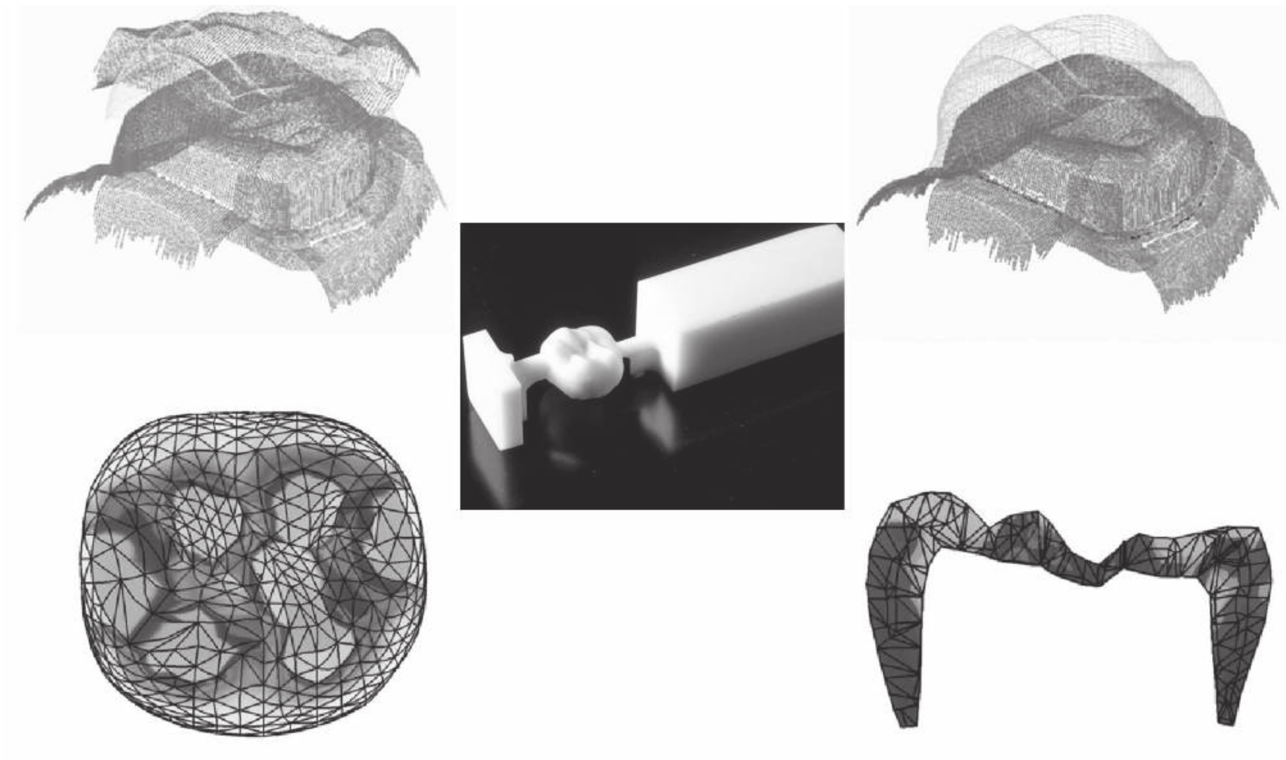

Fig. 5 An optimally shaped crown designed and fabricated under the evaluation of structural mechanics.

2) Devising a compact and integrated machine that could be installed in regular Japanese laboratories.
3) Providing and displaying the operation using a personal computer instead of an expensive and large workstation.
4) Developing simple but high-performance measuring equipment.
5) Providing an operator-friendly CAD process by fully automating the design of crowns and FPDs including the occlusal surface.
6) Fabrication of high-precision crowns and FPDs using both metallic and ceramic materials.

As shown in Fig. 6, an initial prototype of a compact and integrated CAD/CAM machine was developed in 1994. The device used a touch screen and could even be operated by those with limited keyboard skills. It incorporated a small laser displacement gauge and a milling device that allowed measurement and processing to take place in the same chamber. This machine was probably the world's first integrated dental CAD/CAM machine. A second machine was exhibited at the Japan Dental Show held during the 1995 general meeting of the Japanese Association for Dental Science. We investigated the accuracy of digitizing and the milled products. After a series of modifications of both the hardware and the software, a smaller, third-generation machine was developed in 1996 and data were collected to facilitate the release of the system into the market. Finally, in 1999, this machine was marketed under the product name DECSY®[29]. Its basic specifications and development philosophy have not changed.

It was operated by touching an LCD monitor. The site and type of restoration and material to be used were selected on-screen. Working models separated beforehand from a dedicated tray were placed on the measurement stage. When the button to start measurement was pressed, the measurement started automatically. Then, an occlusal record obtained in the oral cavity beforehand by FGP was placed on the occlusal surface of the model and measurement was performed again.

Once the measurement of the working model was completed with essentially a one-button operation and without any graphical imaging of the shape of abutment teeth, the design of crowns and FPDs was implemented automatically in principle by sophisticated software within 1 min. In addition, software to expedite minor corrections of the crown morphology was also developed and installed in the system. Therefore, crown morphology could be customized as desired by the operator.

After the design of the restorations was completed, data for processing were calculated automatically. The size of the block was selected on the monitor depended on the size of the restorations.

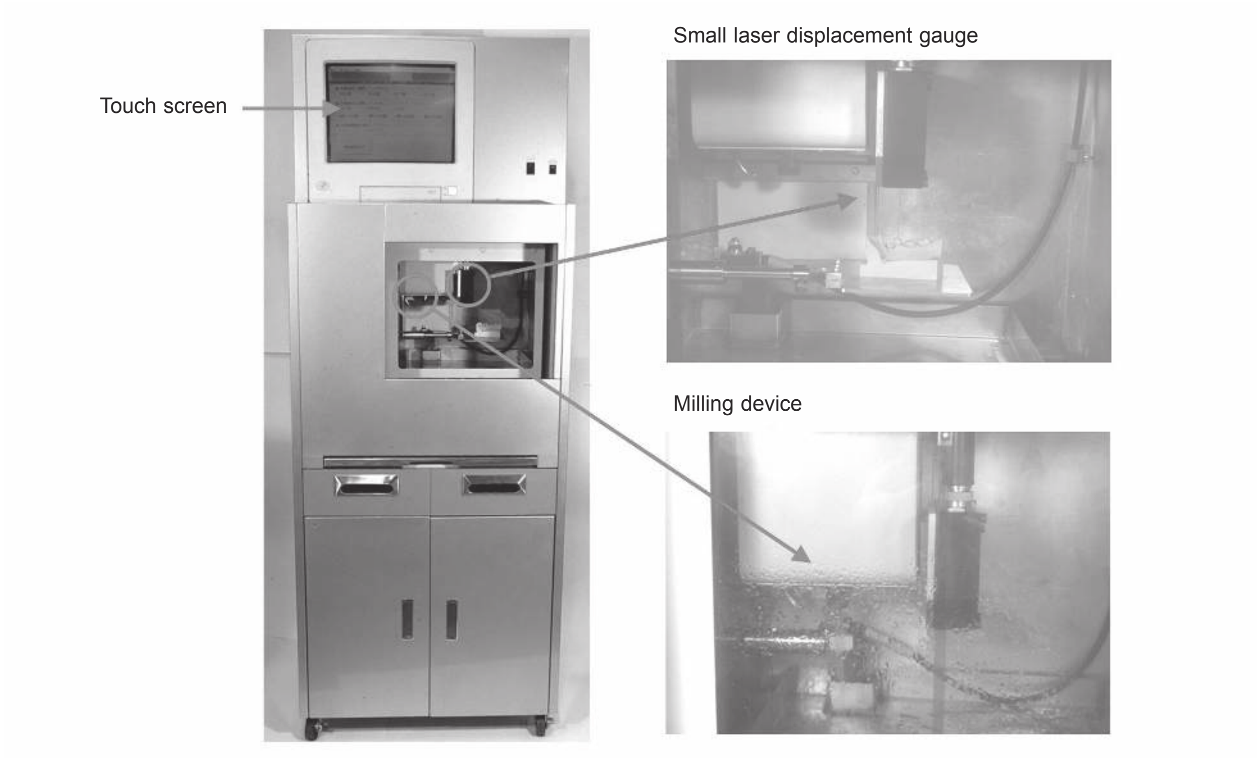

Fig. 6 Initial prototype of a compact and integrated CAD/CAM machine developed in 1994.

Processing was started automatically by milling the set block using a tool for rough machining (dia. 3.0 mm) and another for finishing (dia. 1.6 mm). The machine could change tools automatically and invert the work-piece automatically to mill both the outer and inner sides of the crown. In addition to titanium, ceramic materials that could be machined and ground, such as crystalline glass ceramics and porcelain, could be processed in 60−90 min. Once the completed restoration was separated from the remainder used as a grip by the device, final polishing was performed as is done with conventional methods.

Fitting tests performed for ceramic crowns with three different materials showed the cement thickness of the margin was 10−30 μm and that of the axial portion and occlusal surface were at the level of thickness designed by CAD, providing an excellent fit[25]. There was no significant difference in fit between the materials tested, guaranteeing a reproducible and reliable fit.

We continued to develop compact and high-performance measuring machines and released the DECSY Scan® in 2003. This machine consisted of a line laser and CCD camera that allowed higher-precision measurement at higher speeds. Measurements for an abutment and adjunct teeth that would take about 15 min. with the conventional DECSY® were reduced to only 2 min. with the DECSY Scan®. In addition, the projection of the line laser and imaging with the CCD camera were performed at an angle, and the measurement took place as the model itself was rotated. Therefore, the precision of margin measurement was drastically improved. Furthermore, digitized data currently being gathered with this machine could be transferred to DECSY® via a network for processing to increase the productivity. In Japan, single crowns of leucite-reinforced glass ceramics fabricated by the DECSY® system have been gaining increasing popularity in clinics. They offered all-ceramic crowns with excellent esthetics, fit, and mechanical durability with the combination of adhesive resin cements at a reasonable price for the patients.

APPLICATION OF CAD/CAM FOR OUTSOURCING DENTAL LABORATORY WORK USING NETWORKS

High strength ceramics have been developed as the core/framework material for all-ceramic restorations because of their improved esthetics and the eventual biological incompatibility risks of metals used for conventional porcelain-fused to metal restorations (PFM)[1, 33]. Because of the improved mechanical properties, especially flexural strength and fracture toughness, lithium disilicate (Empress II ®), glass-infiltrated alumina (InCeram Alumina®), glass-infiltrated alumina with partially stabilized zirconia

(In-Ceram Zirconia®), densely sintered high-purity alumina (Procera®) and yttria-stabilized tetragonal zirconia polycrystal materials (Cercon®, DCS-Precident®, and Lava®) have been used as framework materials for all-ceramic FPDs [34-42].

Since the design and fabrication of the framework for high-strength ceramics were technically sensitive and inimical to conventional dental laboratory technology, new technologies using CAD/CAM combined with a networked machining center, i.e. outsourcing the framework fabrication using a network, have been introduced positively in recent years.

The Procera system was the world's first practical application of outsourced fabrication of densely sintered high-purity alumina cores for all-ceramic crowns using a network between individual dental laboratories worldwide and a processing center in Sweden and the USA[7, 43]. A compact measuring machine was installed in the dental laboratory and once a stone model was measured, the digitized data were sent to the processing center via the Internet. A processing center was effectively a factory that made dental restorative and prosthetic devices. Using a large, and computer-controlled processing machine, the processing center efficiently

Table 1 Main dental CAD/CAM systems in the world available for zirconia

CAD/CAM system (Manufacture)	Dizitizing Method	Restoration type				Material						Central Machining center
		In	Veneer	Cr	Br	Resin	Titanium	Gold	Ceramic	Alumina	Zirconia	
Etkon® (Etkon AG)	PSD/ Laser			○	○	○	○	○	○		○	○
Everest® (KaVo electrotechnical work GmbH)	CCD/ White light	○	○	○	○		○		○		○	Available
Lava® (3M ESPE Dental AG)	CCD/ White light			○	○		○		○		○	Available
Pro 50, WaxPro® (SYNOVAD)	CCD/ Color light			○	○		○	○	○		○	○
Procera® (Nobel Biocare Germany GmbH)	Touch Probe		○	○	○		○		○	○	○	○
Hint ELs DentaCAD system® (Hint-ELs GmbH)	CCD/ White light			○	○	○	○				○	Available
KATANA system® (Noritake dental supply co.,LTD)	CCD/ Laser			○	○						○	Available
Cercon smart ceramics® (DeguDent GmbH)	CCD/ Laser			○	○						○	Available
CEREC3®/inLab® (Sirona Dental of system GmbH)	CCD/ Laser	○	○	○	○				○		○	Available
DCS Dental® (DSC Dental AG)	PSD/ Laser	○	○	○	○	○	○		○		○	Available
ZENO® Tec System (Wieland Dental & Technik GmbH)	CCD/ Laser			○	○	○	○			○	○	Available

Fig. 7 The KATANA® system currently available for clinics.

produces frameworks of crowns and FPDs and delivers them back to the laboratory that ordered them. In the laboratory, the esthetic restorations were completed by layering compatible porcelain on the framework.

Yttria-stabilized tetragonal zirconia polycrystals (Y-TZP), which have greater fracture resistance than conventional ceramics, are gaining increasing attention as a framework material for FPDs. Currently, most of the commercially available CAD/CAM systems in the world use Y-TZP to fabricate the frameworks of FPDs [39-47]. (Table 1)

There are two types of zirconia blocks currently available for distinct CAD/CAM applications. The first application is the use of fully sintered dense blocks for direct machining using a dental CAD/CAM system with a grinding machine with higher stiffness. The second application is the use of partially sintered blocks for CAD/CAM fabrication followed by post-sintering to obtain a final product with sufficient strength. The former has the advantage of a superior fit because no shrinkage is involved in the process, but has a disadvantage of inferior machinability associated with the wear of the tool. In addition, micro-crack formation on the material during the milling procedure might deteriorate mechanical durability[46, 50]. The latter has the advantage of easy machinability without wear on the tools or chipping of the material. However, because of the extensive sintering shrinkage during the post-sintering process, the fit of the frameworks must be compensated for by the dimensional adjustment of CAD procedures involving the frameworks[46, 47]. Through the use of a network, this system reduces labor from that needed with a conventional CAD/CAM system and completed final restorations in an individual dental laboratory.

The digitizing technology and software we developed for the Decsy Scan was applied to a new system for the fabrication of zirconia frameworks. This is currently available for clinics as the KATANA® system (Fig. 7). In this system, Y-TZP green blocks are available for milling. The size of the framework is increased by the CAD process to compensate for any prospective shrinkage that might occur during final sintering at 1350-1400°C. We have already investigated the marginal and internal fits of the frameworks with the KATANA system, and found satisfactory fits within clinically acceptable levels[53]. There were also reports on the marginal fit of zirconia frameworks fabricated by different commercial systems that also suggested satisfactory fits[54-56]. However, we also found sintering shrinkage of the bulky pontic during the post sintering processes that degraded the fit of the final frameworks. Therefore, we suggest delicate dimensional adjustment during the CAD process and management to prevent distortion of the long framework is necessary to guarantee the fit of CAD/CAM fabricated zirconia frameworks.

ADVANTAGES OF CAD/CAM USE

The advantages of using CAD/CAM technology for the fabrication of crowns and FPDs can be summarized as: 1) application of new materials, 2) reduced labor, 3) cost effectiveness and 4) quality control.

Materials and their processing technology have been intimately related to the fabrication of dental restorative and prosthetic devices throughout the history of dentistry. When new materials are introduced as candidates for the material of dental devices, the application of conventional technology is first tested. We sometimes overcome difficulties of processing new materials and succeed in routinely introduce new materials. However, high-strength ceramics that were expected to be the new materials for FPDs frameworks have been difficult to process using conventional dental laboratory technologies. Therefore, this challenged us to apply CAD/CAM processing, particularly at a processing center with large facilities. Overall, CAD/CAM technology was useful and effective in compensating for changes in dimensions that come with processing chalky material and post-treatment to obtain fit of crowns and FPDs to abutment teeth.

Conventional dental laboratory technologies are traditionally labor-intensive. On the other hand, the application of CAD/CAM technology, even within the total processing system, should reduce the labor involved. When a ceramic molar crown with leucite-reinforced porcelain were produced with DECSY®, for example, it took 4 min for the measurement, 1 min for the design, 2 min for the conversion of the processing data, and 90 min for the follow-on processing with ceramics. This total processing time was much shorter than that of conventional powder build-up and baking of porcelain. In addition, the operator attended the machine for only 5−6 min and most of the process was performed automatically by the CAD/CAM machine. Therefore, labor was vastly reduced using CAD/CAM machine. Furthermore, systems of outsourcing of some specialized procedures to a processing center using network connections allows for further reduction of labor time.

Conventional porcelain dental laboratory processing with powder build-up and baking required a degree of proficiency both in terms of reproducing natural esthetics and shaping because of the extensive sintering shrinkage during baking at high temperatures. Since productivity was ineffective, the cost of conventional porcelain restorations for the patients was also necessarily high. On the other hand, when porcelain crowns are milled from a prefabricated porcelain block using a CAD/CAM machine, for example, the cost of a block is inexpensive because of mass-production. In addition, even with regard to particular esthetic requirements, milled crowns could be completed merely by staining, using a conventional and simple method. This not only reduces labor costs, but provides financial advantages for the owners of dental laboratories and dental offices and, in turn, for patients. Furthermore, production of all-ceramic FPDs using a zirconia framework fabricated by a CAD/CAM process could provide even more financial benefits to owners of dental laboratories because they can invest in small measuring machines and not in large expensive facilities; thus they could concentrate on conventional porcelain processing.

The use of CAD/CAM technology can not only shape restorations by milling, but also allows for quality control of the dental devices by designing optimal shapes based on material characteristics by CAD; thus preventing degradations such as residual strain due to the effects of processing, and ultimately providing reproducible processing.

When milling a prefabricated ceramic block, the quality of which has been confirmed beforehand by the manufacturer, there are almost no internal defects in the milled products, whereas conventional powder build-up and baked porcelain products usually contain internal porosity.

According to clinical and in vitro studies using finite element and fractographic analyses, the primary causes of failure reported for all-ceramic FPDs differed from those reported for the metal-ceramic FPDs. Fractures of ceramic FPDs tended to occur in the connector areas because of the concentrated stress[57-61]. Therefore, the design of the connector, particularly the dimensions, must be made independently depending on the type of ceramic material used for the framework. CAD better guarantees the durability and reduces the risk of fracture.

Processing data can be saved and followed up during the functional period for the device. Even if evidence is required to predict the prognosis of restorations during the functional period, these features detailed here have not been available with the conventional production systems in general use. Therefore, quality control of dental restorative and prosthetic devices using CAD/CAM technology will be a factor with increasing importance in the future with an aging society because such restorative and prosthetic devices will need to function for longer periods as part of the body.

A FUTURE PERSPECTIVE FOR DENTAL CAD/CAM

There are no doubts that treatment technologies and materials in dentistry have progressively advanced over the past 50 years, especially in the field of restorative dentistry and prosthodontics. Some opinion leaders in dentistry have stated that dental service in these fields has reached its peak at the moment and that there is no need to develop higher technology in the future. However, we have an objection to this opinion. Restoring a patient's quality of life (QOL) through dental service is becoming more and more important to fostering the health of people in an aging society. We have to offer more comfortable and higher quality dental services to all patients to maintain their oral function and restore their QOL. Therefore, positive application of new materials and novel technology is essential for dental service in the future. We believe that CAD/CAM technology will contribute greatly to the healthy aging of patients.

As already mentioned in this article, there are several directions to apply CAD/CAM systems in dentistry. Among them, introduction of CAD/CAM systems directly into clinics is promising. Patients desire shorter treatment times and early functional recovery for the sake of convenience. Dentists are expected to offer esthetic tooth-colored restorations with one appointment and at reasonable cost for their patients. CAD/CAM technology applied at the chair-side has the potential to deliver this service. Compact, but high-precision, intraoral measurement systems available for use directly in the mouth at the chair-side must be developed. Additionally, tooth-colored materials that satisfy sophisticated esthetics, with excellent machinability, and the required mechanical characteristics are of course necessary to make this application popular.

Besides the demand for esthetic restorations, the demand for comfortable high-quality FPDs and removable dentures is also increasing in the aging society. These devices have traditionally been fabricated in dental laboratories but not at chair-side. We still need to collaborate with dental technicians to fabricate these devices. Considering the expected functional lifetime of these devices as part of the body, innovations in both materials and technologies for the fabrication of FPDs are needed to satisfy stringent safety and quality assurance standards. Structural design analyses during CAD process is promising and is expected to be a powerful tool for the design of dental ceramic frameworks of FPDs including the design of the connecting area to decrease the risk of fracture during function. To provide more sophisticated dental services using restorative and prosthetic devices, future devices are expected to be designed and fabricated with improved function related to jaw movements. The analysis of multiple-axis mandible movements for the purpose of recovering oral function of patients has already been widely investigated in prosthodontics. However, at the moment, CAD software only establishes static morphological reproduction of crowns and FPDs. Production of dynamic occlusal morphology of CAD process is still challenging but must be made practical in the near future to offer dental devices for the recovery of oral function.

In addition to the successful application of CAD/CAM technology to the fabrication of FPDs, CAD/CAM technology is also expected to be applied for the fabrication of removable partial denture frameworks[62,63], orthodontic devices and implant superstructures. Therefore, the application of CAD/CAM technology is promising for the delivery of high quality devices in all fields of dentistry. Additionally, dental CAD/CAM should also be available in educational settings and as training tools for daily dental practice, with explanatory materials for patients, diagnostic materials, and for simulations of surgical procedures[64, 65].

As shown in industrial fields, establishing global standardization of dental CAD/CAM systems will help make this new technology popular and replace conventional dental laboratory technology. We must not forget that CAD/CAM technology should be used to accumulate data for both fabrication and the functional period as these will be used to formulate evidence-based guidelines for dental devices. Such guidelines are anticipated but still are difficult to develop when using only conventional technology.

CONCLUSION

In this article, we reviewed the current state and future perspectives of the application of dental CAD/CAM systems, particularly in the field of the fabrication of crowns and FPDs restorations, from a perspective based on our 20 years of experience in this field. The application of dental CAD/CAM systems is promising, not only in the field of crowns and FPDs, but also in other fields of dentistry, even if its contribution is limited at present. We feel proud that we have been using dental restorative and prosthetic devices to recover and maintain the oral function and health of patients. There is no doubt that the application of CAD/CAM technology in dentistry provides innovative, state-of-the-art dental service, and contributes to the health and QOL of people in aging societies Therefore, we in the field of dentistry must not procrastinate in implementing new technology for the benefit of our patients.

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