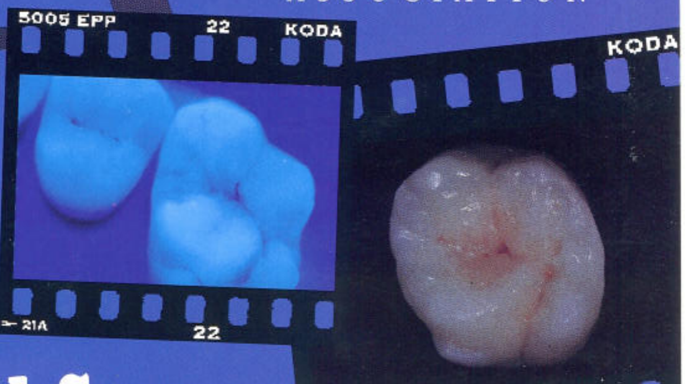
Biocompatibility ▪ CAD/CAM ▪ Materials

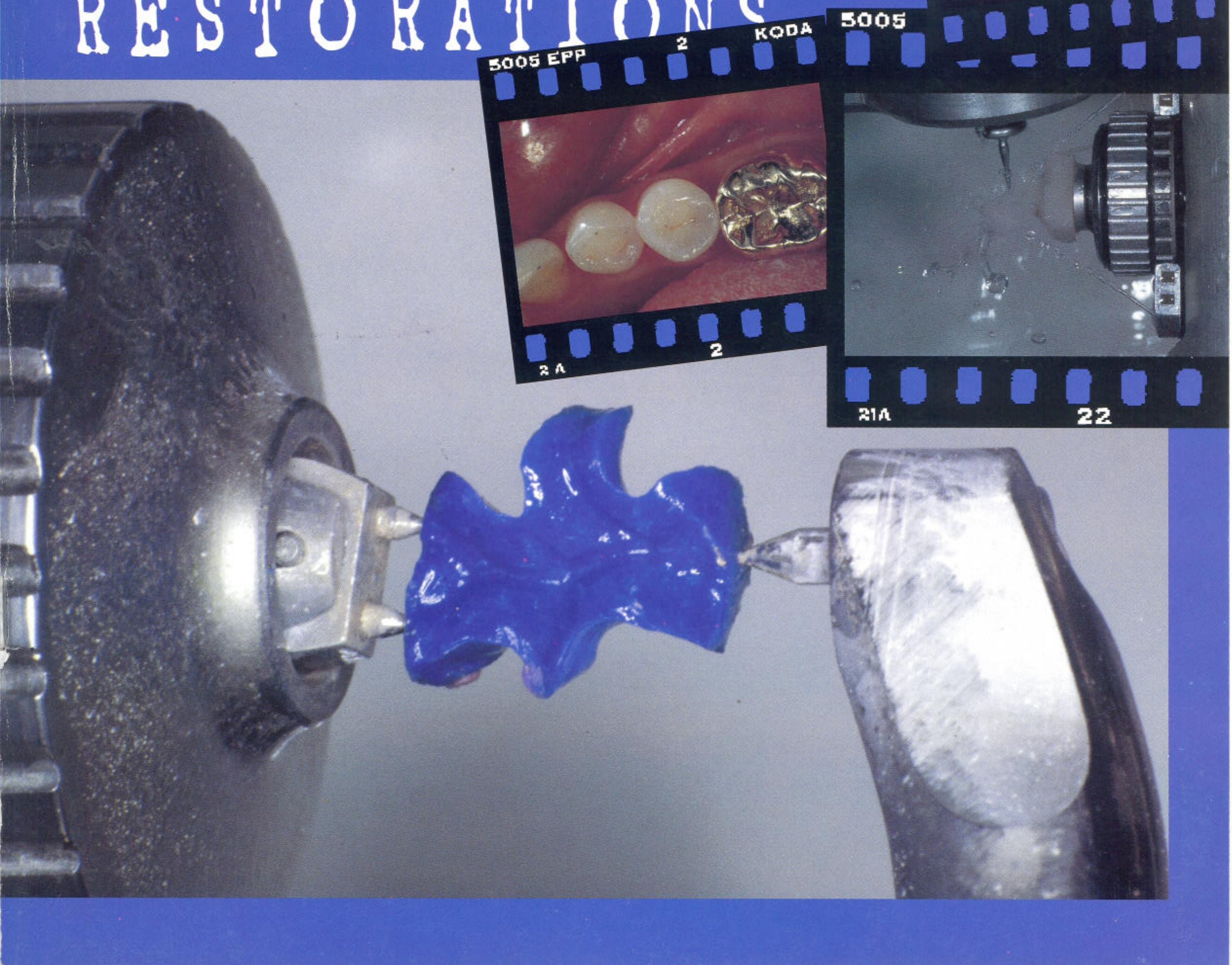
CDA

September 1996
JOURNAL OF THE CALIFORNIA DENTAL ASSOCIATION



Shane N. White, BDentSc

POSTERIOR RESTORATIONS



Performance of CAD/CAM Crown Restorations

François Duret, DDS, PhD; Jack Preston, DDS; and Bernard Duret, DDS

ABSTRACT

This research paper documents the current performance of an advanced CAD/CAM system. Patients with CAD/CAM Empress glass-ceramic or Aristeé composite machined complete crowns were retrospectively evaluated using U.S. Public Health Service criteria at least two years after placement. The composite restorations had unacceptable wear and surface loss. Development continues.

Single crowns remain one of the most important dental restorations. There are many specifications regarding the physical properties for restorative materials for complete crowns and evaluation criteria. There is also a volume of material establishing parameters for tooth preparations to receive complete crown restorations. Although such criteria are broadly available and basic to dental education and practice, the quality of any completed restoration is essentially dependent upon how skillfully the practitioner uses recognized, scientific data. The clinical practitioner and the dental technician are expected to do what is best for the patient.

Dental CAD/CAM (computer-assisted design/computer-assisted manufacture) techniques[1] can introduce to the profession measurable and reproducible criteria for establishing the quality level of a restoration. It is, of course, necessary to know how to measure the capacity of a machine to apply these scientific data. It is no longer a question of describing a specific waxing technique and having to rely on the artistic abilities of a technician to create a restoration. Rather, the clinician's specifications for the axial contours, proximal and occlusal contacts, and internal adaptation must be determined. These specifications are themselves derived from an individual's knowledge and subjective bias. The machine must be able to accommodate individual preferences and be adaptable to varying patient needs. However, once criteria are specified, they should be predictably and reproducibly accomplished by the CAD/CAM system. Such a requirement seems simplistic, but achieving it is extremely complex.

Whenever criteria for acceptability are discussed, the central topic is usually marginal accuracy. Most clinicians agree that the marginal gap should not be greater than 50 to 80 micrometers.[2-5] After marginal accuracy, the next concern is often occlusal contact. There are many disparate theories of occlusion, most largely unproved in spite of

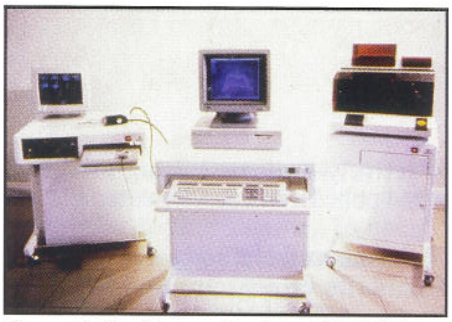


Figure 1. The three units of the CAD/CAM system: from left to right, the image acquisition station, the CAD system, the CAM unit

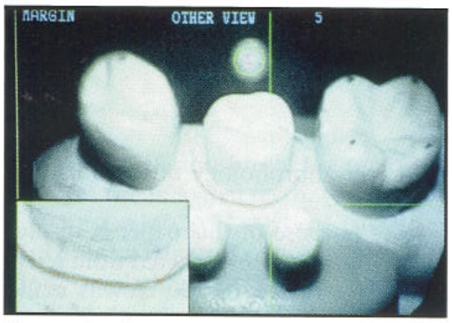


Figure 2. The image of a prepared tooth with three orientation spheres placed to allow correlation of multiple images.

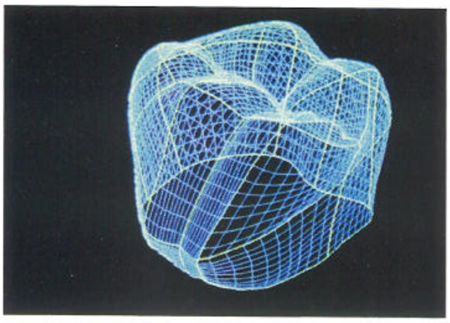


Figure 3. A "wire mesh" computer representation of a complete crown restoration.

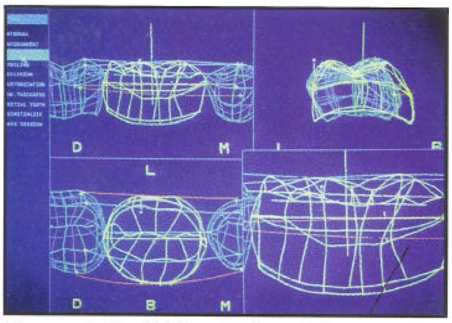


Figure 4. The CAD rendering of the restoration with adjacent teeth.

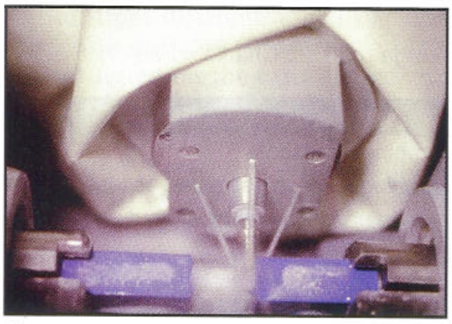


Figure 5. The CAM system machining a complete crown.

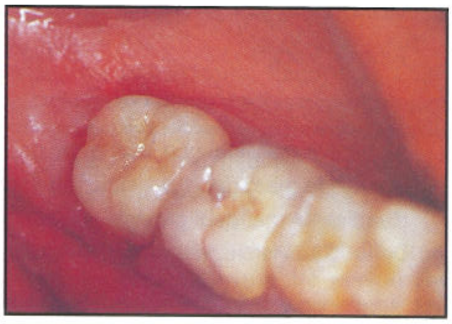


Figure 6. The completed molar crown restoration immediately after luting and cement removal.

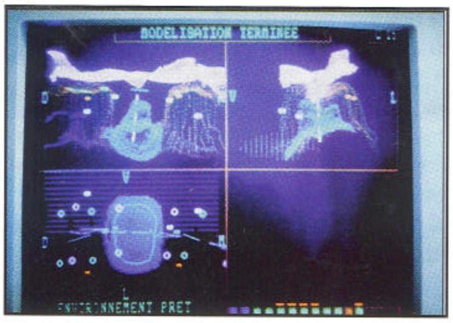


Figure 7. The CAD development of a restoration in relationship to adjacent and opposing teeth.

Figure 8. A maxillary premolar, trial placement prior to shading.

Figure 9. Twelve images of the maxillary second premolar and first molar preparations.

Figure 10. Trial placement of completed crowns before shading.

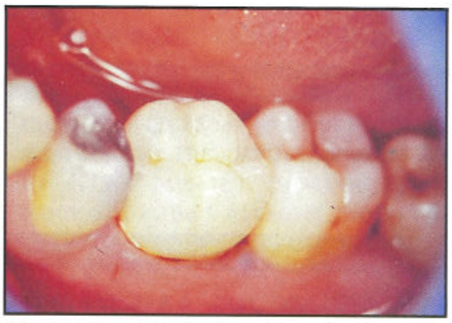


Figure 11. A mandibular molar restoration after placement and cement removal.

all the rhetoric about occlusion, dictating that the occlusal contacts should be tripodized, or cusp in fossa, precisely limited, or ranging within an area. It is difficult to find reference criteria for other areas of the tooth, other than to follow, as closely as possible, the morphology of the adjacent teeth.[6]

The purpose of this paper is to present clinical results gathered from a retrospective review of 300 crowns made using a CAD/CAM system in private practice from 1989 and 1994 and retrospectively evaluated using modified U.S. Public Health Service criteria.[7]

Materials and Methods

All the crowns involved in this study were made in the private dental practice of one of the authors (BD;

Table 1: Criteria for Evaluation

Alpha = Very Good | Bravo = Average | Charlie = Fair | Delta = Remake indicated

Criteria
Marginal Accuracy (evaluated using mirror and No. 17 explorer)
Alpha: No marginal gap visible, no gap on probing, no excess
Bravo: No marginal gap visible, no gap on probing, excess estimated as less than 100 micrometers
Charlie: No marginal gap visible, minimal gap on probing, with or without excess
Delta: Gap visible, with or without fracture
Morphology
Alpha: Surface morphology deemed correct
Bravo: Surface morphology slightly over- or undercontoured (less than approximately 250 micrometers)
Charlie: Surface morphology substantially over- or undercontoured (more than 250 micrometers)
Delta: Surface distorted
Proximal Contact Zone (evaluated using mirror, explorer and dental floss)
Alpha: No visible space, correct contact when probed, tight to floss
Bravo: No visible space, incorrect contact upon probing, floss passes easily
Charlie: Contact at correct height relative to adjacent teeth, space visible
Delta: Contact height incorrect, space visible
Occlusal Surface (Evaluated using mirror, articulating paper and explorer)
Alpha: No visible space, no interference, good markings from articulating paper
Bravo: No visible space, good markings, but interference in excursion(s).
Charlie: No visible space, markings irregular
Delta: Visible space, abnormal wear
Color Matching (Evaluated using mirror and shade guide)
Alpha: No color loss
Bravo: Color loss without apparent surface alterations
Charlie: Color loss with surface alteration
Sensitivity (Evaluated by interrogation)
Alpha: No abnormal sensitivity
Bravo: Incipient sensitivity to cold
Charlie: Abnormal pain, indication for restoration removal

Grenoble, France) using the Hennson-Sopha CAD/CAM system (Hennson-Sopha; Vienne, France).[8,9] This system was the only commercially available one capable of producing complete crowns in 1989. The system, derived from the work of Dr. F. Duret, (from which the name "Duret system" evolved) was commercially available from 1991 to 1993. The CAD/CAM units from Hennson (version 1) and Sopha (version 2) corporations were commercially available from 1991 to 1993 but are no longer being marketed because of the dissolution of the parent companies. However, research and revision are continuing. Among the 500 anterior and posterior crowns made in the cited office and placed in the mouth, 300 posterior units were able to be recalled as part of a documented clinical study. The patient pool ranged from 18 to 63 years of age, and the subjects had no chronic or acute occlusal pathosis. All units had been in place at least two years. Because this study was retrospective, some of the data that would have been desirable are lacking. It would have been preferable to have had a prospective study with better defined criteria and evaluations at the time of placement and at regular intervals thereafter. This study was conducted in an effort to objectively evaluate the results of the CAD/CAM procedures.

All the preparations were made using a short chamfer finishing line approximately 0.5 to 1.0 mm deep. The impressions were made using reversible hydrocolloid and were poured immediately using a quick setting white plaster that had good reflection characteristics (Matieres Plastiques; Lille, France) necessary for the optical impressions. To allow correlation of the various images of the prepared teeth, three correlation spheres (Cephanex; Grenoble, France) were placed around the preparation. An interocclusal record (Blu Mousse, Parkell; Farmingdale, NY) was made to record the relationship of the opposing teeth to the prepared teeth.

The CAD/CAM system includes three units (**Figure 1**): the imaging station, the design station (CAD), and the milling station (CAM). Optical impressions were made using a specially designed laser camera system with a resolution of 512 x 512 pixels. After recording several images of the preparation from different angles of view, and one view of the interocclusal record seated on the cast, the margins were outlined on the screen image (**Figure 2**), and the position of the contact zones and cusps and the maximum height of contour were defined.

The information was processed by the computer and the designed crown displayed on the screen after approximately 10 minutes. The computer created a cement space, designed the external shape of the crown (**Figure 3**) using a library of theoretical teeth in memory, and then adapted the occlusal surface to the opposite teeth according to the preferred occlusal theory, gnathologic or functional (**Figure 4**).

Upon completion of the CAD portion, the three-dimensional information was sent to the CAM unit where the restorations were milled (**Figure 5**). Restorations were created in either a specialized composite (Aristeé Spad; Quetigny, France) or ceramic (EPS-Empress ceramic Ivoclar; Shaan, Liechtenstein) material. Most of the units placed during the early part of the period covered were made using the composite material. After milling, the crowns were surface colored to complete the shading and luted following a conventional technique recommended for the particular material used. No specific procedure was required by the CAD/CAM process for these last two procedures.

The prepared teeth were conditioned (EDTA 17 percent, Hypochlorite 5.25 percent), and dried. A nonfilled adhesive resin (Scotch Bond, 3M; Minneapolis, MN) was applied to the preparation and the inside of the crown before luting using a dual polymerizing microfilled cement (Resilient, RTD; Grenoble, France).

All restorations were evaluated using the U.S. Public Health Service regulations[7] modified to accommodate the CAD/CAM procedures. These parameters allow subjective evaluation of restorations and the criteria are outlined in **Table 1**. All observations were made under the control of a neutral operator (Christophe Benamish, DDS; Grenoble, France). All the CAD/CAM work was performed by laboratory technicians who had no relationship with the manufacturer during the project. Different technicians with varying degrees of familiarity with the system were involved during the period the restorations were placed. Ethics dictate that it must be emphasized that the authors' opinion is subjective[10] inasmuch as the CAD/CAM system evolved from one author's design, and the study was undertaken to further the system's development.

Results

The combined results are presented in **Table 2**. Of the 300 units evaluated, 223 (74 percent) had no detectable marginal gap, but 41 percent had a minimal marginal excess. Forty-one units (13.7 percent) had a marginal gap that was explorable but not visible to the unaided eye, while 36 units (12 percent) had a visually detectable marginal deficiency. One hundred and ninety-nine (66 percent) had good occlusal contact in centric occlusion, but nearly one-half were deemed to have interferences in lateral excursion. Sixty-seven (22 percent) had markings that were considered minimal occlusal contact, while 11 percent had a visible lack of occlusal contact resulting from abnormal wear.

Two hundred and thirty-eight units (79 percent) were considered to have correct proximal contact position, and 45 percent of the units had positive occlusal contact to dental floss. The proximal contact was considered inadequate in amount and/or location for 62 (20 percent) of the units. Axial morphology was considered acceptable or very good for 80 percent of the units, while 19 (6 percent) had morphology the evaluator considered distorted.

More than one-third of the units had no loss of color, 47 percent had some color loss without detectable surface alteration, while fifty-five (18 percent) had detectable surface alteration. Placement of 245 of the restorations had not resulted in any sensitivity, while 22 units (7 percent) elicited incipient sensitivity to cold. Sixteen of the restorations required removal because of continued sensitivity.

Table 2

Location	Alpha	Bravo	Charlie	Delta
Marginal integrity				
Maxillary premolar	22	43	7	5
Mandibular premolar	13	18	11	10
Maxillary molar	30	44	13	9
Mandibular molar	34	19	10	12
Occlusion				
Maxillary premolar	8	34	32	3
Mandibular premolar	6	22	18	6
Maxillary molar	19	57	5	15
Mandibular molar	17	36	12	10
Axial morphology				
Maxillary premolar	34	25	14	4
Mandibular premolar	19	23	6	4
Maxillary molar	62	24	7	3
Mandibular molar	43	10	14	8
Proximal contacts				
Maxillary premolar	33	32	7	5
Mandibular premolar	15	23	11	3
Maxillary molar	51	32	9	4
Mandibular molar	37	15	16	7
Color				
Maxillary premolar	24	33	20	—
Mandibular premolar	19	28	5	—
Maxillary molar	36	48	12	—
Mandibular molar	25	32	18	—
Sensitivity				
Maxillary premolar	63	6	8	—
Mandibular premolar	49	0	3	—
Maxillary molar	85	8	3	—
Mandibular molar	65	8	2	—

Clinical Sample

Several examples of typical CAD/CAM restorations are presented to give the reader a better concept of basic procedures. These restorations could have been made using conventional techniques with either all-ceramic or metal-ceramic processes. The patients requested the CAD/CAM fabricated restorations after the advantages and disadvantages of the conventional and CAD/CAM options, as they were known at the time of treatment planning, were presented. Among the clinical restorations presented, the first was made using the Empress ceramic and the other three using the composite material designed for CAD/CAM fabrication.

Patient No. 1. The patient presented in April 1992 seeking restoration of the mandibular left second molar. Medical history was not contributory, while the oral health and oral hygiene were compromised. The optical impression, design and fabrication using an Empress ceramic blank followed conventional procedures as described previously. Upon completion of the CAM fabrication, the unit was shaded and luted (**Figure 6**).

Patient No. 2. This 48-year-old patient had good general and oral health and excellent oral hygiene. Restorations for the maxillary right second premolar and mandibular left first molar were fabricated in two appointments in March 1993. The optical impression of the maxillary premolar was made using eight views. The CAD restoration was designed in normal occlusion, and the restoration fabricated from Aristeé (**Figures 7, 8**).

Patient No. 3. This 39-year-old patient had poor home care and plaque retention. The maxillary second premolar and first molar required restoration and were prepared in one appointment in October 1989. An optical impression using 12 views (**Figure 9**) was made, and the restorations designed using a prototype software version that allowed sequential design of adjacent restorations. The two restorations were milled from Aristeé blanks (**Figure 10**).

Patient No. 4. This 20-year-old patient required a restoration of the mandibular left first molar. The unit was made in October 1989 (**Figure 11**). An optical impression using seven views was automatically designed without operator intervention.

Discussion

Today there are at least 12 systems termed "CAD/CAM" units, although only four of these are true CAD/CAM systems. More than 3,000 machines from various sources are now functioning in dental offices, and it is estimated that approximately 6,000 restorations are being fabricated daily. This indicates that a new paradigm is truly operating in the profession. This revolution will challenge some traditional techniques once thought impossible. CAD/CAM can change or circumvent procedures that are now routine, such as waxing, casting, firing, and occlusal adjustment on the articulator. However, the results of this evaluation clearly indicate that the development of an ideal system is a work in progress, and not a fait accompli.

The CAD/CAM process allows a wholly new approach to materials development. Traditionally, the parent material — metal, resin or ceramic — must be processed, invariably altering the physical properties of the manufactured material. The CAD/CAM process allows prestructuring and fabrication without changing the parent material. The authors have used several such products in their research, but many of the restorations in this study of 300 units were made from Aristeé. Aristeé is a true composite material developed especially for CAD/CAM and has some unique physical properties that in trials appeared to be indicative of clinical use. It was manufactured under high pressure and reinforced with dimensionally oriented glass fibers. The material differs substantially from more familiar restorative materials. However, it was seen in this study that many of the Aristeé restorations had unacceptable abrasion from oral function and were subject to surface alteration and color loss. Those restorations evaluated as "charlie" or "delta" (**Table 1**) were removed and replaced with ceramic units. Currently only ceramic materials are used for esthetic restorations. Nonetheless, the development of materials designed especially for CAD/CAM processing offers many possibilities and will undoubtedly be the subject of continued research. This study indicates the dependence of any technique on the continuing integrity of the restorative material and the luting system. It is the authors' opinion that the development of an ideal material for CAD/CAM restorations is the greatest challenge to obtaining the desired restorative results.

In general, a better result was obtained using a shallow chamfer rather than one that was deeper. However, with the shallow chamfer, there was frequently an axial marginal excess of approximately 100 micrometers that required adjustment prior to luting. This resulted from the programmed requirement of a marginal thickness of 300 micrometers using the software then available. Although the units could be reshaped on the die, it was obvious from the results of the retrospective analysis that not all the excess was removed prior to placement, inasmuch as 41 percent of the restorations had some marginal excess. This is clearly unacceptable, and the design has been changed in the current system. Such an excess was not present with shoulder finishing lines.

Regrettably, the optical impressions[11,12] were not made intraorally. Even though a number of patients have been treated with the system using intraoral impressions, such an operation has thus far proven difficult for both the patient and the operator. However, working from a cast of the prepared teeth has allowed the operator to check the restoration on the die and make any needed corrections prior to placing it on the preparation. In this way, the entire procedure, including the optical impression, may be performed by a trained operator. The dentist's traditional work is therefore not modified in any way. It is possible for the entire operation to take place in one appointment.

The design process has already been described several times,[13,14] and the basic software has been adapted by other systems. The CAD morphology is directly derived from the memorized shapes stored in the computer, following typical dental morphology. The "theoretical teeth"[14] are then adapted to the specific preparation environment. The axial contours did not require modification prior to placement. The position of the cusps and grooves for the restoration were derived from the position of these elements on the adjacent teeth. The resulting morphology greatly resembled that of the adjacent teeth and the authors believe it is quite attractive. The computer design may be applied automatically or may be modified by the operator. It was apparent from the result that some operators were more diligent or accomplished at altering the computer design to obtain the desired result.

The clinical review revealed a number of restorations that had interference in lateral excursion. During the early development of the Hennson CAD/CAM system from 1989 to mid 1990, the adaptation of the occlusal surface was more the result of manual adaptation than properly functioning occlusal software. At that time, the software was a rather primitive version.

Even though it was possible then to achieve an "optical waxing" of the centric occlusal contacts into the opposing central fossae, this could result in unwanted occlusal surface deformations. The software was performing a "computer" move somewhat removed from occlusal reality. After mid-1990 until 1994, the new software had automatic adaptation and corrections capabilities. Typically, intraoral occlusal adaptation has not required more than three to five minutes. Although the morphology recommended by several schools of occlusal philosophy has been incorporated, the system is still missing dynamic occlusal adaptation, although some prototype instrumentation, termed the "access articulator" has been developed.[15] Completion of this last step will then allow use of the CAD program to develop a complete CAD/CAM occlusion. The lack of a dynamic occlusion accounts for the interferences in lateral excursion that was found in this evaluation.

Proximal contact position and amount was generally satisfactory after placement However, it was frequently necessary to reduce the contact prior to seating. This usually resulted from the operator's tendency to encroach upon the adjacent teeth when designing the restoration. Such corrections required a minimal amount of time.

The success rates as retrospectively evaluated by the independent observer were far lower than one would desire. This was a combination of both the original software and the choice of restorative material. This is an indication of the rather rudimentary capabilities of the initial systems and reliance on a material that did not meet predicted standards. These clinical experiments have allowed the software to be progressively improved. It is now simple to use but extremely complex to engineer. A total of 35 systems working for four years (from 1989 to 1993) was necessary to adjust all the elements.[16] In spite of the initial optimism concerning the Aristeé composite material, it clearly produced far too many restorations rated charlie or delta, and its clinical use has been discontinued.

The processing time for a complete coverage posterior restoration averaged 10 minutes for the optical impression, 10 minutes for the CAD, and 40 minutes or one hour for the milling of resin composite or ceramic materials, respectively. For two adjacent crowns, the shading of the first is done during the milling of the second, thus considerably reducing the overall processing time of these restorations. Also, much of the total processing time is automatic, thus leaving ample time for the operator to shade the previously milled crowns. Overall, approximately 20 minutes of working time is required with 70 minutes of waiting time while the system works automatically. It is, therefore, possible for a dental office to schedule one-appointment restorations for a patient.

The precision possible today was not incorporated into the earlier units.[17,18] Measurements made on more than 3,000 crowns for typodont preparations have enabled progressive improvement in marginal accuracy. The most recent measurements on 50 crowns found the marginal gap to average 35 micrometers. These data were derived from crowns luted on their parent dies, embedded, and sectioned faciolingually and mesiodistally.

The numerous tests performed during a five-year period have allowed progressive modification and re-evaluation. It has required patient development and correction to overcome the shortcomings of the early systems documented here. The complexity of the software and the machines themselves has demanded perseverance and diligence. The authors believe that satisfactory performance of the CAD/CAM system regarding the quality of the restoration, the precision at the margin, and the respect of the occlusal morphology have been achieved in the laboratory studies.

CAD/CAM is rich in new ideas for the daily practice of dentistry. System development is demanding, and clinical proof is needed to justify the optimism derived from laboratory data. The future will arise from the union of CAD/CAM and biology. This study indicated the need for ongoing evaluation and improvement to recognize and correct inherent deficiencies and to temper in vitro optimism with in vivo reality.

Conclusions

From an independent review of 300 restorations fabricated using the Hennson-Sopha CAD/CAM system during the period from 1989 to 1994 and within the limitations of the potential bias of the authors, several conclusions may be made:

- The restorations fabricated using Aristeé composite material had unacceptable occlusal wear within the period of observation.
- Seventy-four percent of the restorations had no marginal gap, whereas 26 percent had marginal deficiencies that were explorable or visible.
- The CAD program required progressive refinement to produce a restoration that was clinically acceptable and biologically correct.

Summary

There are at least 12 systems termed "CAD/CAM" units, although only four of these are true CAD/CAM systems. More than 3,000 machines from various sources are now functioning in dental offices, and it is estimated that approximately 6,000 restorations are being fabricated daily. This indicates that a new paradigm is truly operating in the profession. This revolution will challenge some traditional techniques once thought impossible. CAD/CAM can change or circumvent procedures that are now routine, such as waxing, casting, firing, and occlusal adjustment on the articulator. This paper presented a candid, retrospective review of 300 restorations placed from 1989 to 1993 using a single CAD/CAM system. Marginal integrity, occlusion, axial morphology, proximal contacts, color and postoperative sensitivity were evaluated. The study demonstrated the routine use of a CAD/CAM system in a private practice in France. However, the results of this evaluation clearly indicate that the development of an ideal system is a work in progress, and not a fait accompli. CDA

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