Computer-Aided Design and Computer-Assisted Manufacturing in Prosthetic Implant Dentistry

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Purpose: *The aim of this systematic review was to evaluate the existing scientific evidence on human clinical studies describing the application of computer-aided design/computer-assisted manufacturing (CAD/CAM) technology in restorative implant dentistry.* ***Materials and Methods:*** *Electronic searches for clinical studies from 1966 through May 2008 focusing on long-term follow-up were performed using the PubMed search engine. Concentrating on the restorative aspect of the CAD/CAM technology applicable to implant dentistry, pertinent literature was divided into articles related to implant abutments and implant frameworks.* ***Results:*** *Of the 885 articles initially reviewed, 5 articles (3 CAD/CAM framework and 2 CAD/CAM abutment) satisfied the search criteria of the literature search performed. Combining the results from the framework clinical trial studies, there were a total of 189 prostheses supported by 888 implants. The follow-up varied between 12 and 60 months. Four implants were lost prior to the insertion of the prosthesis and 46 after the insertion. One prosthesis failure was reported. Similarly, in the 2 abutment clinical trial studies there were a total of 53 ceramic abutments supported by 53 implants. The patients were followed between 12 and 44 months. No significant failures or complications were reported in association with the implants and their restorations.* ***Conclusions:*** *Based on a systematic review of literature concerning CAD/CAM used for fabrication of frameworks and abutments, preliminary proof of concept was established. Clinical studies on the use of these techniques were too preliminary and underpowered to provide meaningful conclusions regarding the performance of these abutments/frameworks.* Int J Oral Maxillofac Implants 2009;24(suppl):110–117

Key words: *CAD/CAM, implant dentistry, implant-supported abutment, implant-supported framework*

Restoration of dental implants remains one of the most challenging aspects of implant dentistry. Since its introduction in dentistry almost 22 years ago, CAD/CAM technology has played an important role in the evolution of dental technology.[1]

Implant abutments and frameworks are required to fulfill biological, functional, and esthetic demands.[2] For this reason, the implant abutments and/or frameworks should be made from biocompatible materials with adequate mechanical properties.[3] Even more, they should accurately and passively fit on their mating implants to prevent complications such as screw loosening, bone loss, and abutment fracture during function.[4] Finally, for optimal mucogingival esthetics, implant abutments should have the appropriate emergence profile needed to support the surrounding soft tissue, and preferably be made from a tooth-colored material to prevent the bluish translucency of the overlying mucosa.[3–5]

Implant abutments can be either stock or custom abutments. There are two types of custom abutments: cast custom and CAD/CAM custom abutments.[6] According to their fabrication technique, implant frameworks are of four types: *(1)* conventional cast frameworks, *(2)* frameworks made from carbon/graphite fiber-reinforced polymethylmethacrylate,[7]

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(3) laser-welded titanium frameworks,[8] and most recently, *(4)* CAD/CAM milled frameworks.[9–11]

CAD/CAM technology was incorporated in the production of implant abutments and frameworks in the early 1990s[6] with the aim to facilitate their fabrication. While scientific evidence for CAD/CAM implant-supported restorations has been widely validated with in vitro studies, the clinical outcomes of such protocols are still being investigated.

Several in vitro studies have investigated CAD/CAM-fabricated implant frameworks and abutments. A study by Jemt et al reported a comparable fit of CAD/CAM-fabricated implant frameworks and conventional cast frameworks,[10] whereas a few other studies found the fit of CAD/CAM-fabricated implant frameworks to be statistically superior to that of the conventional cast frameworks.[12–14] Vigolo et al[15,16] assessed the precision at the implant-abutment interface of CAD/CAM abutments. In one study all three types of abutments—zirconia, alumina, and titanium—were connected to external hexed implants and showed less than 3 degrees of rotational freedom.[15] In a more recent study, a CAD/CAM titanium abutment was compared to a gold-machined abutment (UCLA abutment, University of California, Los Angeles, CA, USA), with both showing 1 degree of rotational freedom in cases of external-hexagonal connection and internal-hexagonal connection.[16] Yuzugullu and Avci compared the microgap values at the implant-abutment interface of ceramic abutments and titanium abutments subjected to dynamic loading. They found values to be comparable between the two groups, indicating that ceramic and titanium abutments possess similar tolerance to functional loading.[17]

The objective of this systematic review was to evaluate the existing scientific evidence in human clinical studies describing the application of CAD/CAM technology in restorative implant dentistry. These applications include CAD/CAM-fabricated abutments and/or frameworks.

MATERIALS AND METHODS

Search Strategy

Electronic searches for clinical studies published between 1966 and May 2008 were performed using the PubMed search engine. The search terms used were controlled subject vocabulary terms. These terms were identified after searching the MeSH database. Once their definition was approved, the vocabulary terms were inserted into the PubMed search box. The terms were combined in the following ways:

- *cad cam* AND *dental implants*
- *cad cam* AND *dental prosthesis*
- *cad cam* AND *dental prosthesis, implant-supported*
- *cad cam* AND *dental prosthesis design*
- *cad cam* AND *dental abutments*

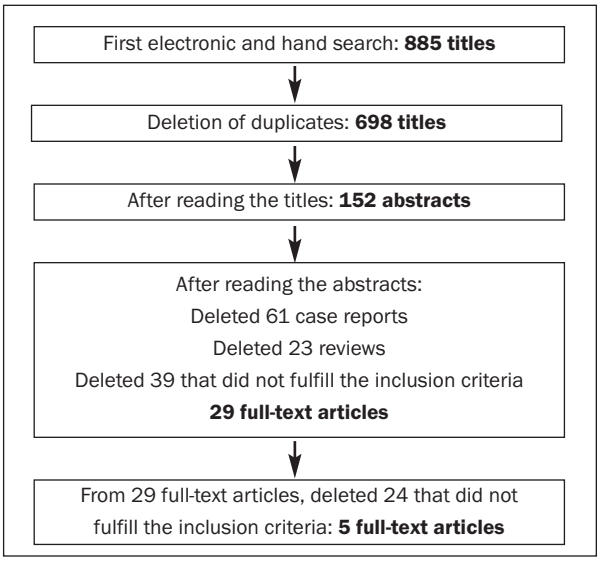

Fig 1 Literature search and selection of articles.

In addition, all offline journals relevant to the topic and relevant bibliographies of reviewed articles were hand searched. The following inclusion criteria were used to identify the publications of interest:

- All levels of the hierarchy of evidence except expert opinion and case reports
- Studies with 10 case series or more
- Studies reporting a minimum of 12 months of follow-up

Selected publications were collected in a reference manager software (Endnote XI, Thomson Research Soft), and duplicates were electronically discarded. All titles obtained from the electronic search for inclusion in the study were assessed to narrow down the list of studies matching the selection parameters. A full-text analysis was performed for the final articles selected.

Search Results

The electronic and hand searches provided a total of 885 titles. Duplicates were deleted, which resulted in 698 titles. Of those, 152 scientific publications were selected based on their titles. Of the 152 abstracts, 123 did not fulfill the inclusion criteria and were excluded from the study. More specifically, 61 articles were case reports with fewer than 10 patients, 23 articles were reviews, and 39 were either in vitro/finite elements studies, restorations on natural teeth, technical notes, or expert opinions. The full texts of the remaining 29

Table 1 Articles That Satisfied the Inclusion Criteria of the Performed Literature Search

Study	Year	Journal	City/Country	Study design
Engquist et al[19]	2004	CIDRR	Linkoping, Sweden	Prospective cohort
Henriksson and Jemt[20]	2003	IJP	Göteborg, Sweden	Prospective cohort
Ortorp and Jemt[21]	2004	CIDRR	Göteborg, Sweden	Prospective control
Sanna et al [22]	2007	JPD	Leuven, Belgium	Prospective cohort
Canullo[18]	2007	IJP	Rome, Italy (private practice)	Prospective cohort

CIDRR = *Clinical Implant Dentistry and Related Research*; IJP = *International Journal of Prosthodontics*; JPD = *Journal of Prosthetic Dentistry.*

Table 2 Clinical Trial Studies Included Under the CAD/CAM Framework Category

Study	Framework	No. of patients	No. of prostheses	No. of dropouts	No. of implants after dropout	No. of prostheses after dropout	Age range (y)	Mean age (y)	Follow-up period (mo)	System
Engquist et al (2004)[19]	Ti	108	108	0	418	108 (108/108 or 100%)	25–75	NR	12	Procera, Nobel Biocare
Ortorp and Jemt (2004)[21]	Ti	65	67	12	287	55 (55/67 or 82.1%)	49–85	68	60	All-in-One Procera, Nobel Biocare
Sanna et al (2007)[22]	Ti	30	30	4	183	26 (26/30 or 86.7%)	38–74	56	26.4 (mean)	Procera, Nobel Biocare
Total	—	203	205	16 (16/205 or 7.8%)	888	189 (189/205 or 92.2%)	—	—	—	

NR = not reported.

Table 3 Patient Characteristics of the Reviewed CAD/CAM Framework Studies

Study	Single tooth	Partially edentulous	Completely edentulous	Maxilla	Mandible	Implant type	Immediate restoration (< 1 wk)	Early restoration (1 week to 2 mo)	Conventional restoration (> 2 mo)
Engquist et al (2004)[19]	N	N	Y	N	Y	Nobel Biocare (Brånemark)	N	3 wk (24 d mean)	12 wk
Ortorp and Jemt (2004)[21]	N	N	Y	Y	Y	Nobel Biocare (Brånemark)	NR	NR	NR
Sanna et al (2007)[22]	N	N	Y	Y	Y	Nobel Biocare (TiUnite)	Y	N	N

N = no; Y = yes; NR = not reported.

articles were reviewed, and 5 articles satisfied the inclusion criteria for this search (Fig 1).[18–22] The 5 articles of interest are summarized in Table 1.

RESULTS

CAD/CAM Frameworks

Three articles were included under clinical trials of CAD/CAM frameworks. Two of them were prospective cohort studies and the third was a prospective controlled study. These articles were published between 2004 and 2007.

Engquist et al[19] reported on 108 patients who received 108 prostheses and were followed for up to 12 months. Ortorp and Jemt[21] presented a prospective study with 65 patients receiving 67 prostheses; of those, 12 were dropouts. The remaining 53 (55 prostheses) were followed up for a period of 5 years (60 months). Similarly, Sanna et al[22] performed a cohort study in which they restored 30 patients. The patients were followed up for a mean period of 2.2 years (26.4 months). Four of them dropped out, bringing the final number of patients to 26 (26 prostheses).

In all studies, the implant-supported prostheses were made of titanium frameworks using CAD/CAM technology. All restorations were made by Procera, Nobel Biocare (Table 2).

No studies were found that described CAD/CAM framework applications in partially edentulous patients. All three investigations used CAD/CAM technology to restore completely edentulous patients. In two studies, both the maxilla and the mandible were restored (Ortorp and Jemt[21] and Sanna et al[22]), and in one study only mandibles were restored (Engquist et al[19]) (Table 3).

Table 4 Complications and Failures of the Reviewed CAD/CAM Framework Studies

Study	No. of implant complications prior to insertion	No. of implant failures	No. of implant complications	No. of prosthetic failures	No. of prosthetic complications
Engquist et al (2004)[19]	NR	24	NR	0	0
Ortorp and Jemt (2004)[21]	4	13	0	1	19
Sanna et al (2007)[22]	0	9	NR	NR	NR
Total	4 (4/888 or 0.45%)	46 (46/888 or 5.2%)	0	1 (1/189 or 0.53%)	19 (19/189 or 10.1%)

NR = not reported.

The loading time of the prostheses varied significantly in the three articles. Sanna et al[22] restored their patients using immediate loading protocols, whereas Engquist et al[19] applied both early (mean 24 days) and conventional (12 weeks) restoration protocols as a restorative option. Finally, Ortorp and Jemt[21] used both two-stage (58 patients) as well as one-stage (7 patients) surgical protocols but did not report the restoration protocol that was used (Table 3). The definitions of the terms *immediate loading*, *early loading*, and *conventional loading* are based on the 2007 Cochrane Review.[23]

From a total of 287 implants, Ortorp and Jemt[21] reported 4 failures prior to the insertion of the prosthesis. The remaining studies either did not report any (Engquist et al[19]) or did not have any (Sanna et al[22]). The number of implant failures rose after the delivery of the prosthesis, with Engquist et al[19] reporting 24 out of 418, Ortorp and Jemt[21] 13 out of 287, and Sanna et al[22] 9 out of 183.

Two studies—Engquist et al[19] and Sanna et al[22]—failed to report any implant complications after the delivery of the prosthesis. Concurrently, Ortorp and Jemt[21] did not find any implant complications after the prosthesis was delivered. One prosthetic failure was described by Ortorp and Jemt[21]: one patient lost all six of his implants, which also resulted in the failure of the prosthesis, although there were no issues with the prosthesis itself. Engquist[19] and Sanna[22] did not mention any failures.

Nineteen prosthetic complications were reported by Ortorp and Jemt.[21] Seventeen patients presented with 19 occurrences of prosthodontic complications involving resin veneer fractures (12) and loss of access hole fillings (7). Engquist et al[19] and Sanna et al[22] did not report any prosthetic complications (Table 4).

The numbers of implants used to restore the edentulous patients also varied among the three studies. Engquist et al[19] concluded that 4 implants were enough to support full fixed prostheses in the mandible even in early loading. Ortorp and Jemt[21] placed an average of 6.6 implants in the maxilla (153 implants in 23 patients) and 4.8 in the mandible (215 implants in 44 patients). Sanna et al[22] placed an average of 7 implants per arch (212 implants in 30 patients).

When Ortorp and Jemt[21] compared the titanium framework test group with a control group restored with cast alloy frameworks, they found no significant difference in the survival of implants between titanium and cast frameworks. Furthermore, the titanium framework group had fewer complications and maintenance appointments, with the exception of veneer fracturing, which was greater in the test group. Finally, there were more failures in the maxilla than the mandible.

Engquist et al[19] described no statistically significant differences between the early loading (after 3 weeks) and delayed loading (after 3 months) patient groups.

Combining the results from the three clinical trial studies, there were a total of 189 prostheses supported by 888 implants. The patients were followed from 12 to 60 months. Four implants were lost prior to the insertion of the prosthesis and 46 after the insertion. Only 1 prosthesis failure was reported, and the failure was due to the fact that the patient had lost all the implants that supported the prosthesis.

CAD/CAM Abutments

Two articles on CAD/CAM abutments satisfied the search criteria. The study by Henriksson and Jemt[20] is a prospective cohort study of 20 patients who received 24 single-implant restorations with CAD/CAM customized alumina abutments (Procera, Nobel Biocare). The study reported 1 dropout over the 1-year follow-up period, which reduced the number of patients from 20 to 19 and the number of implants from 24 to 23. Canullo,[18] in another prospective cohort study, reported 25 patients who received 30 single-implant restorations. The abutments were customized titanium-zirconia complexes (Zirkonzahn). The mean clinical follow-up period was 40 months, and the number of dropouts was not reported (Table 5).

Patients in both studies received single implants and single-unit restorations. No edentulous or partially

Table 5 Clinical Trial Studies Included Under the CAD/CAM Abutment Category

Study	Abutment	No. of patients	No. of prostheses	No. of dropouts	No. of implants/ restorations after dropout	No. of prostheses after dropout	Age range (y)	Mean age (y)	Follow-up period (mo)	System
Henriksson and Jemt (2003)[20]	Aluminum oxide abutments	20	24	1	23	23 (23/24 or 95.8%)	18–62	29	12	Procera Nobel Biocare
Canullo (2007)[18]	Ti-Zirconia abutment complexes	25	30	NR	NR	30 (30/30 or 100%)	25–70	52.28	36–44	Zirkozahn
Total	-	45	54	1	23	53	-	-	-	-

NR = not reported.

edentulous patients were included in either study. Henriksson and Jemt[20] placed the implants in the maxillary anterior region using the two-stage surgical protocol. Nine patients (13 implants) received ceramic crowns cemented on ceramic abutments (Procera crown [PC] group) and 11 patients (11 implants) received ceramic crowns that were directly fused onto the abutments (fused crown [FC] group). The prosthetic treatment started about 2 weeks after the second-stage surgery. Similarly, Canullo[18] used the submerged surgical protocol, and each implant was restored following the second-stage exposure surgery. Eighteen implants were placed in the maxilla and 12 in the mandible in both anterior and posterior regions. The abutment complexes were made of titanium posts (ProUnic abutment, Impladent) with CAD/CAM-fabricated zirconia abutments. In group 1, the lower margin of the zirconia abutment was positioned directly on the implant margin, while in group 2 the metallic structure was positioned on the implant neck and the zirconia margin was more coronally positioned on the titanium post.

No screw loosenings or fractures (prosthetic complications) were recorded in Canullo's study, which resulted in a survival rate of 100%. However, a single case of marginal porcelain chipping was observed at the 1-year follow-up. The periodontal indices mPI and mGI indicated healthy soft tissue conditions at neighboring teeth and zirconia abutments.

In the study of Henriksson and Jemt, all crowns remained "stable during the 12-month period, with no severe problems reported." One patient in the PC group (cemented crowns) developed a buccal fistula, which healed after recementing the crown. In addition, two patients from the PC group presented with soft tissue recession in association with the crown-abutment margin. The authors suggested that these results might raise concerns regarding the "unfavorable biologic effect of a cement margin and possible cement remnants in the implant area."[20] One more interesting observation is that even though all abutment screws of the FC group were tightened by hand when inserted, the authors reported similar crown stability and lack of porcelain fracture in the groups. This clinical investigation reported encouraging results for the use of alumina oxide custom abutments that were followed for 1 year. In addition, it provided some data that presented similar complications and survival rates for two different delivery techniques of CAD/CAM custom abutments.

Combining the results from the two clinical trial studies, there were a total of 53 ceramic abutments supported by 53 implants. The patients were followed from 12 to 44 months. No significant failures or complications were reported in association with the implants and their restorations.

DISCUSSION

Clinical trials describing the performance of CAD/CAM implant abutments and frameworks in the literature are scarce. However, the interest in CAD/CAM technology for implant restorations is substantially increasing, for several reasons. First, CAD/CAM-produced implant frameworks are made from a solid block of material. With this specific fabrication technique, the material is more homogeneous and has high mechanical properties. Second, inaccuracies are largely minimized since there is no waxing, investing, or casting. This fact translates into reduced production costs overall. Furthermore, with CAD/CAM technology the unfavorable implant angulations can be corrected and the proper emergence profile can be achieved. Finally, CAD/CAM ceramic abutments provide the optimal optical properties of a natural tooth and a predictable esthetic result for the surrounding soft tissues.

An important point concerns the prosthesis that is opposing the CAD/CAM restoration. Engquist et al[19]

Table 6 Summary of Currently Available CAD/CAM Systems for Dental Implants

CAD/CAM system	Provider	Implant restoration type	Restoration material
Procera	Nobel Biocare	Abutments Fixed partial denture frameworks Milled bars	Titanium Alumina Zirconia
Atlantis	Astra Tech	Abutments	Titanium Titanium with gold coating Zirconia
Encode	Biomet 3i	Abutments	Titanium Titanium with gold coating
CAM StructSURE	Biomet 3i	Milled bars	Titanium
CARES	Straumann	Abutments	Titanium Zirconia
Etkon	Straumann	Frameworks Abutments	Zirconia Titanium
BioCad	BioCad Medical	Abutments Milled bars	Titanium

stated that "most of the patients used a full upper denture with acrylic teeth." Ortorp and Jemt[21] reported that the titanium framework restorations were opposing 26 complete dentures, 1 overdenture, 8 removable partial dentures, 12 implant-supported prostheses, 19 fixed prostheses with natural teeth, and 1 implant-supported prosthesis that was combined with natural teeth. Sanna et al[22] failed to describe the patient's opposing arch at the time of implant placement or later.

In addition to the survival and failure rates of the CAD/CAM restorations, equally interesting are the complications of the final CAD/CAM restorative outcome. In the literature, numerous systematic reviews have evaluated "biological," "technical," as well as "esthetic" complications of dental restorations/implants.[24–26] We would like to see a similar effort for the CAD/CAM restorations reported in long-term prospective studies. These complications need to be presented in greater detail, in a systematic manner, and with an adequate follow-up time.

To determine if there is a difference regarding the influence of CAD/CAM design on the tissues, the "biological" complications could be subdivided into peri-implant mucosal lesions, gingival inflammation, soft tissue dehiscence, formation fistulas, and marginal bone height. Similarly, the "technical" complications could be separated into groups such as abutment/screw loosening, fracture of the veneer material, fracture of the CAD/CAM framework/abutment, and loss of retention due to cementation.

Although the esthetic outcome has become a main focus of interest in implant dentistry, none of the included studies evaluated the esthetic appearance of CAD/CAM-fabricated prostheses. This is a difficult task, since there is a lack of standardized esthetic criteria. Hence, there is a need for widely accepted and reproducible esthetic scores, not only for the evaluation of CAD/CAM restorations, but also for the peri-implant soft tissues.[27]

Currently, several CAD/CAM systems are available for dental implants. The following are a few examples reported in the literature, listed according to their fabrication capabilities (abutments versus frameworks). Table 6 summarizes information about these currently available CAD/CAM systems.

CAD/CAM Custom Implant Abutment Systems

The ***Procera*** system (Nobel Biocare) provides custom abutments in titanium, alumina, and zirconia. A master cast is developed after making an implant-level impression. The master cast is then scanned and the custom abutment is designed by a 3D CAD program.[2,20,28] Alternatively, a machined base cylinder is screwed to the implant analog and the abutment is waxed up. The pattern is then removed from the master cast and scanned by the Procera scanner.[29,30] The design is sent to the production facility for the abutment fabrication.[2,20] The abutment can be further digitized, and finally a titanium or ceramic coping is produced using the same system.[6]

The ***Atlantis*** abutment (Astra Tech) is milled in titanium alloy or zirconia. Gold anodized coatings can be added to mask the silver color of the titanium abutment, giving natural shades through all-ceramic restoration.[31] In this system an implant-level impression is made and then both the diagnostic model and the master cast are scanned. In this way a computer

accurately captures the implant location, orientation, angle, and depth. The abutment is then designed on a software system known as VAD and precision machined by a computer-controlled milling machine from a solid block of titanium alloy.[32]

The ***Encode*** Restorative System (ARCHITECH PSR, Biomet 3i) is a CAD/CAM system limited to a specific implant (Biomet 3i).[33] In this system the clinician needs to make an intraoral impression of a special healing abutment. This abutment has notches on its occlusal surface that serve as codes. When these embedded codes are scanned they give information about the implant platform diameter, the position of the hex, and the collar height of the healing abutment. The CAD/CAM abutment is designed on the computer and is milled from a solid block of titanium alloy.[6,33,34]

CARES (Computer Aided Restoration Service; Straumann) offers exclusively customized implant prosthetics for the Straumann dental implant system. It provides two types of abutments: zirconium oxide and titanium RNSynOcta custom abutments. After fabrication of an implant-level impression, a duplicate model of the master cast, known as a scan model, is made from a scanable plaster. A scan body, which is used to record the implant position during the scanning procedure, is attached to the implant analog on the master cast before the duplication or to the scan model after the duplication. The scan model is digitized using laser scanners from Sirona. The custom abutment is designed on-screen using 3D software. Generated data are electronically transmitted to the Straumann production center, where the custom abutment is manufactured. Intraorally, the ceramic custom abutment needs to be fixed to the SynOcta 1.5 abutment, whereas the RNSynOcta 1.5 is not required if the titanium custom abutment is used, as the titanium custom abutment is screwed directly into the implant.

Etkon is another system that supports the prosthetic portfolio of the Straumann dental implant, among others. Using the laser light-band principle to scan, it can fabricate abutments made of zirconia or titanium. After an implant-level impression is made, a master cast is produced. A plastic cylinder is placed into the implant analog and the abutment is waxed up. The generated pattern is then removed and scanned. The resulting design is sent electronically to a manufacturing facility to produce the final custom abutment.

CAD/CAM Custom Implant Framework Systems

Procera implant partial prostheses are available in zirconia or titanium. CAD/CAM custom Procera partial prostheses are screw-retained implant-supported restorations that can be used with a wide range of implant systems. The zirconia implant prosthesis is available at the implant level, while the titanium implant prosthesis is available at the implant and abutment levels (www.nobelbiocare.com). Using acrylic resin, a framework pattern is fabricated directly on temporary implant cylinders.[9] The acrylic resin framework pattern is then laser scanned, and the framework is milled in a CNC-milling machine with 5 degrees of freedom.[9–11]

CAM StructSURE precision milled bars (Biomet 3i) are available in Hader and Dolder designs for overdenture bars and primary bars and in fixed hybrid designs. With this system, the technician does not need to wax or resin design the framework; instead, the design is made on-screen with a sophisticated software program.[35]

BioCad milled bars (BioCad Medical). BioCad software permits the design of bars for most implant systems. They are made from a surgical grade titanium alloy milled on industrial machines. BioCad implant bars are available in Hader, Dolder, fixed, and round styles.

The ***Etkon*** system can produce frameworks[36] up to 16 units from a variety of materials, such as zirconia and titanium.

CONCLUSIONS

Based on a systematic review of literature on the use of CAD/CAM for fabrication of frameworks and abutments, preliminary proof of concept was established.

Clinical studies on the use of these techniques were too preliminary and underpowered to provide meaningful conclusions regarding the performance of these abutments/frameworks.

The influence of the implant CAD/CAM abutment on peri-implant tissues as well as the effect of the CAD/CAM-fabricated frameworks on the survival of veneered porcelain has not yet been assessed in the scientific literature. There is a need for long-term prospective studies that examine:

- Survival outcomes of CAD/CAM abutments (alumina oxide, zirconia, titanium)
- The influence of the abutment material (zirconia/titanium) on the peri-implant tissues (shade, tissue color)
- The effect of zirconia versus titanium on the porcelain veneer material survival rate and on long-term clinical performance

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