A Systematic Review of the Clinical Performance of CAD/CAM Single-Tooth Restorations

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Purpose: This systematic review sought to determine the long-term clinical survival rates of single-tooth restorations fabricated with computer-aided design/computer-assisted manufacture (CAD/CAM) technology, as well as the frequency of failures depending on the CAD/CAM system, the type of restoration, the selected material, and the luting agent. ***Materials and Methods:*** An electronic search from 1985 to 2007 was performed using two databases: Medline/PubMed and Embase. Selected keywords and well-defined inclusion and exclusion criteria guided the search. All articles were first reviewed by title, then by abstract, and subsequently by a full text reading. Data were assessed and extracted by two independent examiners. The pooled results were statistically analyzed and the overall failure rate was calculated by assuming a Poisson-distributed number of events. In addition, reported failures were analyzed by CAD/CAM system, type of restoration, restorative material, and luting agent. ***Results:*** From a total of 1,957 single-tooth restorations with a mean exposure time of 7.9 years and 170 failures, the failure rate was 1.75% per year, estimated per 100 restoration years (95% CI: 1.22% to 2.52%). The estimated total survival rate after 5 years of 91.6% (95% CI: 88.2% to 94.1%) was based on random-effects Poisson regression analysis. ***Conclusions:*** Long-term survival rates for CAD/CAM single-tooth Cerec 1, Cerec 2, and Celay restorations appear to be similar to conventional ones. No clinical studies or randomized clinical trials reporting on other CAD/CAM systems currently used in clinical practice and with follow-up reports of 3 or more years were found at the time of the search. *Int J Prosthodont 2009;22:466–471.*

The past decade's increased demand for all-ceramic restorations in both anterior and posterior teeth has expanded the search for materials with improved properties.[1–4] Consequently, requirements for modern dental restorations with predictably efficacious outcomes demand materials of high strength and durability, biocompatibility, fit, and esthetic appearance.[1,5]

The need for a uniform material quality, reduction in production costs, and standardization of the manufacturing process has encouraged researchers to seek to automate the conventional manual process via the use of computer-aided design/computer-assisted manufacture (CAD/CAM) technology since the 1980s.[6] More recently, the development of CAD/CAM technology in restorative dentistry has dramatically evolved.[6]

The introduction and promotion of such techniques into clinical practice should ideally be based on related scientific evidence; regrettably, very few and limited randomized clinical trials (RCTs) are currently available.

This systematic review of the available literature sought to establish a starting point for reconciling current viewpoints regarding a possible estimate for clinical survival rates of single-tooth restorations fabricated with CAD/CAM technology following more than 3 years of functional service.

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Materials and Methods

Systematic Search Design and Article Selection

An electronic search of publications from 1985 to 2007 was established from two electronic databases: Medline (PubMed) and the Embase Library. The search included only English-language articles published in peer-reviewed dental journals. The keywords were selected listing the following six combinations: *(1)* "CAD or CAM," *(2)* "CAD and CAM," *(3)* "computer aided design," *(4)* "computer aided manufacturing," *(5)* "computer dentistry," and *(6)* "computer milled prosthesis." All data from both electronic databases were collected and the duplicates deleted.

In general, all selected articles contained well-defined inclusion and exclusion criteria as shown in Table 1. The search strategy is outlined in Fig 1.

Following an electronic search, all nondental and in vitro studies were excluded and a title search of the remaining articles was performed by two independent reviewers. The selection of included titles was followed by an abstract search and a review, which were conducted by the same two reviewers. After agreeing on abstract inclusion, a full text search followed. Subsequently, the full text search was performed by the same two reviewers until an agreement was reached. Data of each individual restoration were extracted from the selected studies and broken down on an Excel spread sheet by author, year, type of study (prospective/retrospective), restoration type, tooth location (anterior/posterior), CAD/CAM system, survival time (months), material, luting cement, and failure (yes/no).

The restorations were categorized as either inlay/onlay, core crown, crown, "endo" crown, "reduced" crown, and veneer. An "endo" crown was defined as a restoration for endodontically treated posterior teeth with a complete loss of coronal hard tissues that is prepared with a circular equigingival butt margin and central retention cavity of the entire pulp chamber.[7] A "reduced" crown was defined as a crown with a preparation with a stump height of less than 3.0 mm and a defect-oriented surface.[8]

The selection for the inclusion of the studies in this systematic review was based on the inclusion and exclusion criteria determined by both reviewers and measured by the data extraction list. When data were missing, authors were contacted via email. The examiner calibration was assessed via κ score at two different intervals.

Table 1 Inclusion and Exclusion Criteria

Inclusion criteria
Clinical trials
Prospective studies
Retrospective studies with patient recall
Written in English
Minimum follow-up of 3 y
Exclusion criteria
Not written in English
Minimum follow-up < 3 y
Studies that were based on patient's charts
Studies that were based on questionnaires
Case reports
Animal studies
In vitro studies

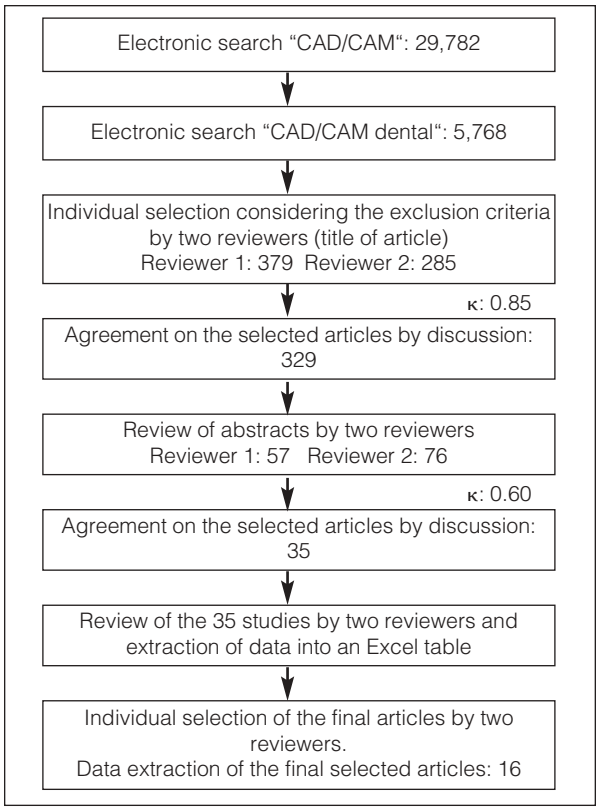

Fig 1 Search design and strategy.

Statistical Analysis

Failure rates were estimated by dividing the number of events by the total exposure time of the restorations. Statistical analysis included the estimated failure rates at 95% confidence intervals (CIs) per study per 100 restoration years. The overall failure rate of all studies was calculated by assuming a Poisson-distributed number of events. Random-effects Poisson regression was used to estimate the overall failure rate attributing specific weight to each of the selected studies.[9]

Failure rates of restoration type (inlay/onlay, core crown, crown, "endo" crown, "reduced" crown, veneer), CAD/CAM system (Cerec 1, Cerec 2, Celay), restoration material (feldspathic, glass-ceramic, oxide ceramic with aluminum oxide [In-Ceram Alumina],

Table 2 Descriptive and Failure Analysis: Overview of Exposure Time, Study Type, Location, and Failure Rate of Included Studies

Study	No. of restorations	Total exposure time (y)	Study type	Tooth location	Mean exposure time (y)	No. of failures	Estimated failure rate (per 100 restoration years) (%, CI)
Isenberg et al[11]	121	347	Pro	Posterior	2.9	7	2.02 (0.96–4.23)
Mörmann and Krejci[12]	8	40	Retro	Posterior	5	0	–
Heymann et al[13]	42	168	Pro	Posterior	4	0	–
Bindl and Mörmann[7]	19	41	Pro	Posterior	2.2	1	2.42 (0.34–17.18)
Thordrup et al[14]	30	84	Pro	Posterior	2.8	4	4.79 (1.8–12.76)
Molin and Karlsson[15]	20	94	Pro	Posterior	4.7	2	2.12 (0.53–8.48)
Pallesen and van Dijken[16]	32	239	Pro	Posterior	7.5	9	3.77 (1.96–7.24)
Reiss and Walther[17]	1,010	10,241	Retro	Posterior	10.1	81	0.79 (0.64–0.98)
Bindl and Mörmann[18]	43	136	Pro	Posterior	3.2	2	1.47 (0.37–5.89)
Otto and De Nisco[19]	187	1,892	Pro	Posterior	10.1	15	0.79 (0.48–1.32)
Bindl and Mörmann[20]	36	131	Pro	Anterior	3.6	2	1.52 (0.38–6.09)
Reich et al[21]	54	162	Pro	Anterior and posterior	3	2	1.23 (0.31–4.94)
Sjögren et al[22]	61	578	Pro	Posterior	9.5	7	1.21 (0.58–2.54)
Bindl et al[8]	208	919	Pro	Posterior	4.4	32	3.48 (2.46–4.92)
Fasbinder et al[23]	71	213	Pro	Posterior	3	3	1.41 (0.45–4.37)
Thordrup et al[24]	15	143	Pro	Posterior	9.5	3	2.11 (0.68–6.53)
Total summary	1,957	15,428	Pro: 48% Retro: 52%	Anterior: 2% Posterior: 98%	7.9	170	1.75 (1.22–2.52)

Pro = prospective; Retro = retrospective.

oxide ceramic with aluminum and magnesium oxide [In-Ceram Spinell], resin-based composite), and luting cement (chemically, light-, or dual-cured) were estimated by random-effects Poisson regression. In addition, a multivariate random-effects Poisson regression was used to estimate the effect of these factors on the failure rate.

Five-year survival rates were calculated for all factors as the relationship between event rate and survival function S, S(T) = exp (-T * event rate), assuming constant event rates were given.[9,10] The statistical analyses were performed using Stata 10.0 (StataCorp LP) and the significance level was set at .05.

Results

A total of 16 articles representing 14 prospective and 2 retrospective studies were selected for data analysis with κ agreement scores of 0.85 for titles and 0.60 for abstracts. The total of 1,957 restorations included 48% that were prospectively analyzed and 52% that were studied retrospectively. The majority of the studied restorations (98%) were on posterior teeth (ie, premolars and molars) while only 2% were on anterior teeth (Table 2). Table 3 presents an overview of all included studies and restorations, the mean exposure time in years, *P* values, and the estimated failure and survival rates for each CAD/CAM system, different types of restorations, and material and luting agents used in the selected studies.

Based on the random-effects Poisson regression analysis, the analyzed 1,957 restorations revealed a mean exposure time of 7.9 years. A total of 170 failures occurred, resulting in an overall survival rate of 91.6% after 5 years (95% CI: 88.2% to 94.1%). This represents a calculated failure rate of 1.75% per year, estimated per 100 restoration years (95% CI: 1.22% to 2.52%). The failure rates per study are presented in Table 2 and Fig 2, in which the weight of each of the selected studies is listed as well.

There were no significant differences between the failure rates of Cerec 1 ($P = .178$) and Celay ($P = .427$) when compared to Cerec 2 (Table 3).

Glass-ceramic restorations exhibited a significantly higher failure rate than feldspathic porcelain ($P < .001$, 18.18% versus 1.19%). Restorations composed of ceramic with aluminum oxide, ceramic with aluminum and magnesium oxide, and a resin-based composite were not significantly different from the feldspathic restorations (Table 3).

Regarding type of restoration, "endo" crowns showed a significantly higher failure rate than inlay/onlays ($P = .026$, 3.90% versus 1.47%), while the other restoration types did not differ significantly. Outcomes with light-cured and dual-cured restorations were not statistically significantly different (Table 3).

Discussion

New technologies and materials are routinely introduced into dental practice. Ideally, clinicians should regard evidence-based dentistry as an essential guide in the planning of successful treatment. However, scientific evidence from well-controlled investigations in different aspects of prosthodontics, including single-tooth restorations, is rarely available.[25]

Table 3 CAD/CAM System, Restoration Type, Material Type, and Type of Luting Agent Effects on Failures

	No. of restorations	% of all studies	Mean exposure time (y)	*P* value*	Estimated failure rate* (per 100 restoration years (%, CI))	Estimated survival rate after 5 years* (%, CI)
CAD/CAM system						
Cerec 1	1,420	72.6	9.2	.178	1.29 (0.42–3.94)	93.8 (82.1–97.9)
Cerec 2†	522	26.7	4.5	–	2.06 (1.33–3.18)	90.2 (85.3–93.6)
Celay	15	0.8	2.9	.427	3.95 (0.51–30.46)	82.1 (21.8–97.5)
Restoration type						
Inlay/onlay†	1,619	82.7	8.7	–	1.47 (0.96–2.27)	92.9 (89.3–95.3)
Core crown	61	3.1	3.3	.994	1.48 (0.25–8.71)	92.9 (64.7–98.7)
"Endo" crown	114	5.4	3.9	.026	3.90 (1.07–14.13)	82.3 (49.3–94.8)
Crown	106	5.4	4.1	.867	1.60 (0.39–6.58)	92.3 (72.0–98.1)
"Reduced" crown	54	2.8	4.4	.348	2.47 (0.55–11.16)	88.4 (57.2–97.3)
Veneer	3	0.2	3	–	–	–
Material type						
Glass-ceramics	147	7.5	4.1	< .001	18.18 (5.77–57.28)	40.3 (5.7–74.9)
In-Ceram Alumina	42	2.1	2.9	.285	2.58 (0.35–19.23)	87.9 (38.2–98.3)
In-Ceram Spinell	40	2.0	3.4	.590	0.65 (0.04–10.52)	96.8 (59.1–99.8)
Composite resin	37	1.9	3	.607	1.97 (0.16–24.38)	90.6 (29.6–99.2)
Feldspathic†	1,691	86.4	8.5	–	1.19 (0.66–2.15)	94.2 (89.8–96.7)
Luting agent						
Chemically cured	37	1.9	8.7	–	–	–
Light-cured	261	13.3	4.2	.232	2.72 (0.79–9.33)	87.3 (62.7–96.1)
Dual-cured†	1,659	84.8	8.4	–	1.64 (1.09–2.47)	92.1 (88.4–94.7)
Summary	1,957	100	7.9	–	1.75 (1.22–2.52)	91.6 (88.2–94.1)

*Based on random-effects Poisson regression.
†Reference variable.

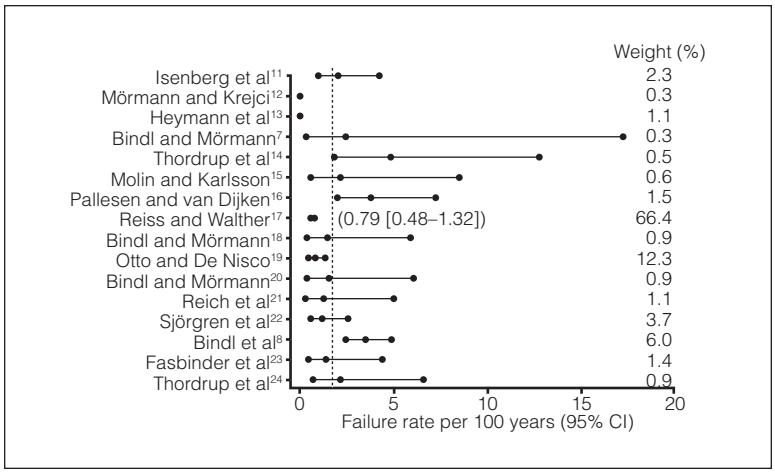

Fig 2 Random-effects Poisson regression of failure rates, confidence intervals, and the weight of each study.

The aim of this investigation was to conduct a systematic review on the performance of single-tooth restorations fabricated with CAD/CAM technology. It also sought to underscore the absence of robust evidence to support the routine use of well-accepted dental treatment restorative protocols. Nonetheless, the advantages of a standardized manufacturing system are self-evident: industrially prefabricated and controlled materials; increased quality, efficiency, and reproducibility; electronic data storage of various treatment and production steps with a standardized chain of production; and, especially, the use of high-strength ceramic and titanium materials as well as the possibility of chairside treatment manufacturing.[6,26–28]

The opacity of this type of restoration remains a disadvantage in the comparison of different systems as they relate to the resolution and precision of scanning technologies, software design, and milling procedures. Additional disadvantages include the high investment costs for equipment and the lack of scientific background, since RCTs are not especially common.[6,26,27]

This systematic review evaluated the long-term clinical survival rate of single-tooth restorations fabricated with CAD/CAM technology in the context of strict inclusion and exclusion criteria and a minimum follow-up of 3 years. In the absence of RCTs, prospective and retrospective studies were selected with a clearly defined patient recall system (Table 1), and

studies based on patient charts and questionnaires were excluded.

None of the analyzed studies reflected an RCT protocol design. It is therefore apparent that the study of single-tooth restorative materials does not include patient control groups and patient-based randomization. This fact suggests concern regarding the clinician's ability to make evidence-based decisions regarding CAD/CAM restorations. According to Kelly, systematic review papers should include patient and provider factors.[29] Both considerations were absent from the papers selected for this particular review. Other limitations included the fast development of new materials and technologies, differences in study design, authors, and the weight of each investigation (Fig 2). The greatest weight of all of the included articles was the study by Reiss and Walther,[17] which reported clinical long-term results with Cerec restorations. Consequently, this study had an impact on the statistical analysis. It should also be mentioned that those authors were experienced Cerec system users. Hence, their results were not affected by a steep learning curve.

In the present report, a mean exposure time of 7.9 years was apparent, based on the random-effects Poisson regression analysis. A total of 170 failures occurred, resulting in an overall survival rate of 91.6% after 5 years (95% CI: 88.2% to 94.1%) and a calculated failure rate of 1.75% per year, estimated per 100 restoration years (95% CI: 1.22% to 2.52%) (Tables 2 and 3).

The most common technical failures were fractures of the restoration or tooth and the most common biologic failures were secondary caries and endodontic problems.

To analyze and define failures, different types of standardized criteria systems for failures were utilized among the studies. The United States Public Health Service criteria were predominantly used (12 studies), along with the California Dental Association criteria (3 studies) and the Kaplan-Meier method (1 study). In this systematic review, the effect on failure was assessed by the CAD/CAM system used, the type of restoration, the restoration material, and the luting agent.

The selected CAD/CAM systems used in the included studies were Cerec 1, Cerec 2, and Celay. No statistically significant differences between the failure rates of Cerec 1 ($P = .178$) and Celay ($P = .427$) could be identified when compared to Cerec 2 .

The 5-year survival rates differed between 93.8% for Cerec 1, 82.1% for Celay, and 90.2% for Cerec 2 restorations. Cerec 1 and 2 are chairside CAD/CAM systems and Celay is a laboratory system. At the time of the search, no scientific evidence for longer than 3 years of follow-up was found for other CAD/CAM systems that matched the inclusion criteria of this review.

"Endo" crowns, crowns that extend into the pulp chamber as one piece, had a significantly higher failure rate than all other investigated restorations, while inlay/onlays, core crowns, crowns, and "reduced" crowns did not differ significantly. Regarding the 5-year survival rates, it was found that core crowns (92.9%), full crowns (92.3%), and inlay/onlays (92.9%) had a similar survival. Pjetursson et al, in their systematic review on single crowns, reported a 5-year survival rate of 93.3% (95% CI: 91.1% to 95%) for all-ceramic crowns and 95.6% (95% CI: 92.4% to 97.5%) for metal-ceramic crowns.[30]

Restorations requiring less tooth reduction, such as inlays or onlays, can be clinically as successful as full-coverage crowns. This study also suggests that inlay/onlay restorations allow for preservation of the natural tooth structure with a less invasive approach, and that this yields similar long-term results to full-coverage crowns.

The lowest 5-year survival rate was found for "endo" crowns (82.3%), followed by crowns with a reduced abutment height (88.4%). This underlines the limitations of the adhesive luting techniques. This confirms the concern that "endo" crowns may not represent a sufficiently predictable treatment option, as found in a study by Bindl et al on premolars.[8] Regarding the material choice of the restorations in the studies reviewed, glass-ceramics had the highest failure rates and were significantly higher than all other restoration types used ($P < .001$, failure rate: 18.18%).

Ceramics with aluminum oxide (In-Ceram Alumina) or with aluminum and magnesium oxide (In-Ceram Spinell) and a resin-based composite did not differ significantly when compared to feldspathic ceramics (Table 3). The highest 5-year survival rate according to random-effects Poisson regression was 94.2% for restorations fabricated with feldspathic and the lowest was 40.3% for glass-ceramic restorations. Pallesen et al compared feldspathic and glass-ceramic inlays, resulting in the feldspathic ceramic being superior.[16] However, Malament and Socransky determined a survival rate of 92% at 11.3 years for glass-ceramic inlays.[31]

Variations in luting cement did not influence the failure rate significantly. This type of study did not assess the various polymerization shrinkages of different resin cement materials under various curing conditions or the importance of the clinician following manufacturer's guidelines in respect to the choice and use of luting cements.[32]

Conclusions

A lack of studies using a randomization protocol was identified for this particular treatment topic. Several other commercially available CAD/CAM systems fail to show scientific evidence for longer than 3 years, at least at the time of this study's search. Nonetheless, the relevant and selected literature reveals an overall survival

rate of 91.6% after 5 years (95% CI: 88.2% to 94.1%) and an estimated failure rate of 1.75% per year, calculated per 100 restoration years (95% CI: 1.22% to 2.52%). Additional findings include the following: *(1)* there were no significant differences between the failure rates of the different CAD/CAM systems assessed in this study, *(2)* glass-ceramic restorations had a significantly higher failure rate than all other materials ($P < .001$, 18.18%), *(3)* "endo" crowns showed a significantly higher failure rate than any other type of restoration ($P = .026$, 3.90%), and *(4)* the luting cements did not appear to affect the outcome of this study. Long-term survival rates for CAD/CAM technology–fabricated single-tooth restorations demonstrated clinically similar outcomes to conventionally manufactured restorations.

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