ORIGINAL RESEARCH

Reasons for Failure of CAD/CAM Restorations in Clinical Studies: A Systematic Review and Meta-analysis

Stephan Lampl[1], Deepa Gurunathan[2], Jogikalmat Krithikadatta[3], Deepak Mehta[4], Desigar Moodley[5]

Abstract

Aim: The systematic review presented herein was performed to descriptively analyze the causes for the failure of computer-aided design/computer-aided manufacture (CAD/CAM) restorations. The meta-analysis reported herein was performed to estimate long-term survival and success rates of CAD–CAM fabrications.

Materials and methods: Using the PICOS paradigm, a systematic search was carried out in the PubMed and Cochrane databases to identify randomized controlled trials (RCTs) and prospective observational studies reporting survival data for CAD/CAM restorations. After selecting studies with a predefined set of selection criteria, data from included prospective clinical studies and RCTs were used for a systematic review aimed at a descriptive analysis of factors associated with failure of CAD–CAM restorations. Data from the included prospective clinical studies were used for meta-analysis, wherein 5-year and 10-year survival and success rates were estimated using Poisson regression models.

Results: The systematic review included data from 9 RCTs and 6 observational studies, which had a median follow-up of 36 months and 60 months, respectively. About 58 failures and 118 technical/ biological complications were noted in the included RCTs and 9 failures along with 58 technical/ biological complications were noted in the prospective clinical studies. Poisson regression indicated an estimated 5-year and 10-year survival rates of 85.55–100 and 71–100, respectively. The estimated 5-year and 10-year success rates were 74.2–92.75 and 33.3–85.5, respectively.

Conclusions: Several technical and biological complications contribute to failure of CAD/CAM restorations. However, CAD/CAM restorations with routine chairside materials might have clinically meaningful success rates in the long term.

Clinical significance: The results presented herein indicate that optimal strategies for mitigation of biological and technical complications may augment the success of CAD/CAM fabrications in restorative dentistry. Studies aimed at identification of such strategies are needed to further enhance the long-term success rates of CAD/CAM restorations.

Keywords: Biological complications, Computer-aided design/computer-aided manufacture materials, Computer-aided design/computer-aided manufacture failure rates, Computer-aided design/computer-aided manufacture success rates, Computer-aided design/computer-aided manufacture survival rates, Technical complications.

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Introduction

The 2022 Global Oral Health Status Report from World Health Organization indicates that an estimated 2 billion people suffer from caries of permanent teeth.[1] Another report by Pandey et al. indicates that the overall prevalence of dental caries in India is about 54.16%.[2] A cross-sectional study by Grewal et al. indicates that about 49.7% patients with dental caries need restorative treatments.[3] The results of a recent survey conducted by the American Academy of Cosmetic Dentistry indicate that the most commonly requested cosmetic treatments in 2019 were direct bonding, crown and bridge work, inlays, onlays, and veneers.[4] This high prevalence of indications for dental restorations and the growing popularity of smile esthetics lends premise to ongoing efforts to continually expand a dentist's armamentarium for durable restorative materials.[5] In these contexts, computer-aided design/computer-aided manufacture (CAD/CAM) technology-facilitated dental restorations offer several advantages to patients and clinicians.[6] Developments of technology in this area have improved durability, marginal adaptation, and esthetic outcomes along with enhancing the speed and ease of fabrications as compared with conventional restorations.[7]

Materials such as zirconia and lithium disilicate ceramics are biocompatible and esthetic-friendly materials in restorative dentistry.[8,9] The success of these chair-side materials to CAD/CAM technologies and their advantages with respect to reduced number of appointments simplified laboratory work and digitalized archiving is an exciting promise and an alternative to conventional "gold-standards".[10] Furthermore, the advent of hybrid ceramics has ushered in the possibility of combining ceramics and composite resins to simulate the optical and mechanical properties of natural

[1–3]Department of Paediatric Dentistry, Saveetha Dental College and Hospitals, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, India

[4]Department of Conservative Dentistry, Saveetha Dental College and Hospitals, Saveetha Institute of Medical and Technical Sciences, Chennai, India; Department of Operative Dentistry, Tohoku University Graduate School of Dentistry, Tohoku University, Sendai, Japan

[5]Smile and Education Centre, Woltfurt, Austria

Corresponding Author: Deepa Gurunathan, Department of Paediatric Dentistry, Saveetha Dental College and Hospitals, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, India, Phone Number: +91 9994619386, e-mail: deepag@saveetha.com

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Table 1: Quality assessment tools used for selecting studies for this analysis

Quality assessment checklist for randomized controlled trials	*Risk of bias domains assessed for quality of prospective clinical studies*[20]
• Hypothesis/Aim/Objectives • Setting of the study or the source of the subjects • Distribution of the study population by age or gender • Inclusion/ Exclusion criteria • Treatment descriptions • Outcomes • Sample size and justification • Control groups (if RCT) • Randomization and blinding • Statement of results and confidence intervals • Dropout rates • Adverse events • Ethics approvals and compliance	• Domain 1: Study design • Domain 2: Study population • Domain 3: Interventions • Domain 4: Outcome measure • Domain 5: Statistical analysis • Domain 6: Results and conclusion • Domain 7: Competing interests
Only studies scoring >90% for the 13 items above were included in the analysis	Only studies with moderate and low risk of bias were included in the analysis

tooth.[5] However, successful outcomes of CAD/CAM-facilitated restorations with these conventional and novel chairside materials crucially depend on several material-related, technical and biological factors.[10–13] Data on the impact of these materials, technical, and biological factors on the long-term survival of CAD/CAM are generally scanty.[14–16]

While available data from published randomized controlled trials (RCTs) and observational studies on CAD/CAM restorations do indicate clinically and statistically meaningful long-term success and survival trends, there is a general paucity of such studies to guide clinical decisions, especially in the long term.[10] Addressing this relative paucity of data, the systematic review part of the report presented herein provides a descriptive analysis of technical and biological complications reported in published RCTs and prospective clinical studies. The meta-analysis part of the report presented herein provides estimates of long-term survival and success rates computed using Poisson regression models.

Several reports have been published, which highlight the need for improving the awareness of dental health and smile esthetics in India.[17–19] Along with promoting preventive and hygiene-related awareness, it is important to also promote treatment-related awareness and shared decision-making for mitigating the burden of dental disease. A key requirement for achieving the latter objective would entail patient-oriented communications on the durability and longevity of CAD/CAM restorations. Furthermore, data on the influence of technical and biological factors that influence the long-term survival of CAD/CAM restorations can help construct evidence-based strategies for enhancing the longevity of CAD/CAM restorations in restorative dentistry. These considerations lend premise to the report presented herein.

Materials and Methods

Search Strategy and Selection Criteria

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines to identify RCTs and observational studies on CAD/CAM restorations published between January 2000 and January 2023. Search string constructed using the Medical Subject Headings (MeSH) terms ((((ceramic*) OR porcelain*) OR Zirconia*)OR resin*)) AND (((((failure) OR survival) OR success) OR clinical evaluation) OR follow up)) AND ((veneer*) OR laminate*) OR inlay*)OR onlay*) OR crown*) AND (CAD/ CAM) AND (Randomized Controlled Trial) was used for searching the Medline (PubMed) database, and the search string using the MeSH terms (laminate or veneer or crown or inlay or onlay) and (ceramic or porcelain or zirconia or resin) and (dental or tooth or teeth) and (clinical and trial or clinical) and (survival or failure or success) and (CAD or CAM) was used for searching Cochrane database. A modified Population, Intervention, Comparator, Outcomes and Study design (PICOS) criteria accounting for any missing comparators (in the prospective studies) were used to define the inclusion criteria. Furthermore, the current analysis was done to identify the causes of failures associated with various materials, and comparators were not considered. In the inclusion criteria, population was defined as human subjects, and interventions were defined as CAD/CAM restorations with restorative materials such as ceramics, composite resins, and zirconia. Furthermore, the outcomes were defined as survival rates and complications, and study designs were defined as randomized controlled trials and prospective clinical studies. Case reports/ case series, systematic reviews, *in vitro* studies, and studies lacking information on survival/ success rates were excluded. A data extraction form was used to collect all the relevant information, which included study information (author and publication date), study design (RCTs, prospective clinical studies, sample size, and subject age), interventions (material type, luting agent), and outcome-related information (number of failures and nature of complications). Secondary caries, endodontic complications, and periodontal pathology were considered as biological complications in the current analysis. The technical complications considered in the analysis included fractures, loss of retention, debonding, and occlusal wear. A custom quality assessment checklist was created and used by the reviewers for assessing the quality of included studies (Table 1). All the randomized controlled studies included had a score of > 90%. Furthermore, a checklist proposed by Moga et al. was used for assessing the risk of bias in the prospective clinical studies included in the current analysis (Table 1).[20] All the included studies had only a moderate or low risk of bias.

Literature Review Process

Two independent reviewers (JK and SL) conducted the literature review and performed assessments of selection criteria, quality assessments of included RCTs, and prospective clinical studies. A third expert (DM) was consulted in case of disagreement. All disagreements were resolved through discussion using DM as a veto.

Flowchart 1: PRISMA flow diagram for selection of studies

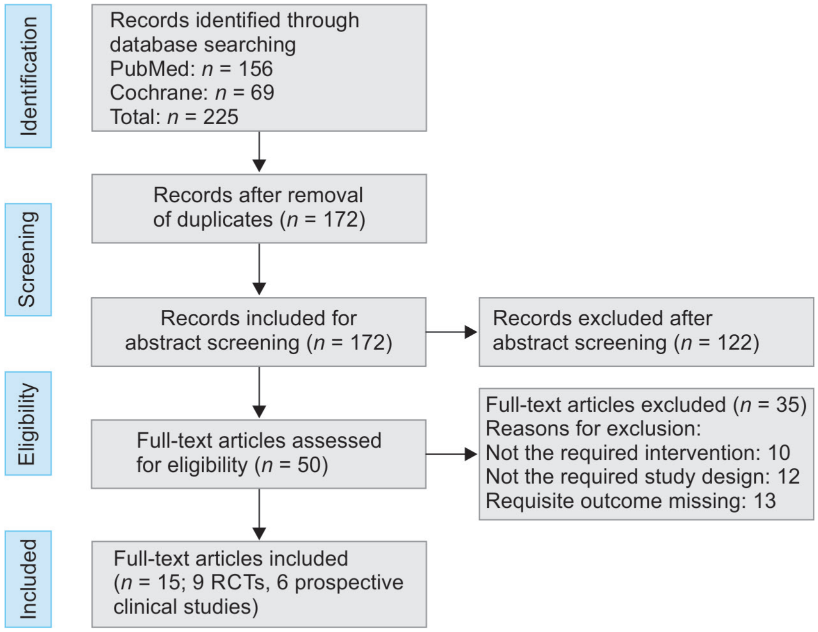


Table 2: Quality assessment checklist (please refer to Table 1)

Author and year of publication	*Q1*	*Q2*	*Q3*	*Q4*	*Q5*	*Q6*	*Q7*	*Q8*	*Q9*	*Q10*	*Q11*	*Q12*	*Q13*	*% Answered*
El-Ma'aita et al. 2022[21]	✓	✓	✓	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	92.3
Schlichting et al. 2022[22]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	100
Gardell et al. 2021[23]	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	92.3
Scholz et al. 2021[24]	✓	✓	✓	✓	✓	✓	–	✓	✓	✓	✓	✓	✓	92.3
Mühlemann et al. 2020[25]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	100
Nassar et al. 2019[26]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	100
Monaco et al. 2017[27]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	100
Naenni et al. 2015[28]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	–	92.3
Sailer et al. 2009[29]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	100

Q1–Q13, Questions 1–13

Statistical Analysis

All the studies in conformity with the predefined inclusion/exclusion and quality assessment criteria were included for qualitative analysis (systematic review). All the prospective clinical studies included in this analysis provided ample information on survival data required for quantitative analysis (meta-analysis). For the purposes of quantitative analysis, survival was defined as a number of fixed dental prostheses that were *in situ*, regardless of complications (technical and/or biological), which included secondary caries, marginal integrity, marginal discoloration, and loss of anatomical form along with surface roughness, endodontic complications, loss of retention, and fractures. Failure rates resulting from biological and technical failures were calculated by dividing the number of failures by the total exposure time. Exposure time for each included study was calculated by taking the sum of exposure time for all fixed dental prostheses. A Poisson regression model was used to analyze the calculated rates. Survival proportions for 3 years, 5 years, and 10 years were estimated with an assumption of constant event rates. The Pearson goodness-of-fit statistics was used to assess the heterogeneity for the model. A p-value < 0.05 was considered significant. All analyses were performed using R Statistical Software (v4.1.2, R Core Team 2021).

Table 3: Assessment of risk of bias

Author and year of publication	*D1*	*D2*	*D3*	*D4*	*D5*	*D6*	*D7*	*Overall*
Chaar et al. 2015[30]	+	++	++	++	++	++	+	+
Reich et al. 2014[31]	++	+	++	++	++	++	++	++
Burke et al. 2013[32]	++	++	++	++	++	++	++	++
Sorrentino et al. 2012[33]	+	++	++	++	++	++	++	++
Schmitt et al. 2009[34]	+	++	++	++	++	++	!	+
Beuer et al. 2009[35]	+	++	++	++	++	++	++	++

Judgement guide: ++ low; + moderate; - serious; ! Critical; D1–D7, Domains 1–7; see Table 2b

Results

Selection of Studies and Assessments of Study Quality

A total of 50 articles were selected after removal of duplicates and abstract screening. Subjecting these 50 articles to the predefined selection criteria and quality assessments (Table 1) resulted in the identification of 15 articles (9 RCTs and 6 prospective clinical studies; Flowchart 1). Tables 2 and 3 present the results of quality assessments of the included studies.

Qualitative Analysis of the Included Studies

Table 4 presents the baseline and survival characteristics as reported in the included randomized controlled studies. The nine randomized controlled studies included in the analysis were conducted between 2009 and 2022 and recruited a total of 405 patients with 569 restorations/ fixed dental prosthesis. The duration of follow-up ranged between 12 and 60 months (median: 36 months, interquartile range (IQR): 15.32). These studies recruited a total of 213 patients with 128 fixed dental prosthesis. The duration of follow-up ranged between 40 and 116.4 months (median: 53 months, IQR: 18.5). In these studies, with a total of 405 patients with 569 restorations/ fixed dental prosthesis, survival rates ranged between 69 and 100% (median: 97.58%, IQR: 7.65). The restoration sites reported in these studies included molars and premolars in mandibular and maxillary regions. A total of 58 failures and 118 technical/biological complications were noted in these studies with a median follow duration of 36 months (range: 12–60 months, IQR: 15.32). Figure 1 depict the distribution of failures and complications noted in these RCTs.

Table 5 presents the baseline and survival characteristics as reported in the included prospective clinical studies. Survival rates in these studies with a total of 213 patients and 243 fixed dental prothesis ranged between 90.5 and 100% (median: 95.3%, IQR: 6.1). The restoration sites reported in these studies included molars and premolars in mandibular and maxillary regions. A total of 9 failures and 58 technical/biological complications were noted in these studies with a median follow-up duration of 53 months (range: 40–116.4 months, IQR: 18.5). Figure 2 present the distribution of failures and complications noted in these prospective observational studies.

Quantitative Analysis of the Included Prospective Clinical Studies

Table 6 presents the estimated failure rates and complication rates. The estimated 5-year and 10-year survival rates and success rates are depicted in Figure 3. These estimates were computed using the Poisson regression model, and the Pearson goodness-of-fit for heterogeneity was not significant ($p > 0.05$). The estimated 5-year and 10-year survival rates were in the range of 85.55–100 and 71–100, respectively. Furthermore, the estimated 5-year and 10-year success rates were in the range of 74.2–92.75 and 33.3–85.5, respectively.

Discussion

Data from randomized clinical studies (9 studies) and prospective clinical studies without randomization (6 studies) were included in this analysis. This mix of included studies provides mutual validity for these two paradigms of clinical investigation. The mean survival rates from the randomized clinical studies included herein were 94.63% over an average follow-up duration of approximately 33 months. While average survival rates were about 95.68 over an average follow-up duration of approximately 63 months among the prospective clinical studies. This observation seems concordant and lends credibility to the predefined selection criteria to include data only from high-quality studies.

In the current study, a custom quality assessment checklist was used for assessing randomized controlled studies and included only those that had a score of >90%. Furthermore, a checklist proposed by Moga et al. was used for assessing the risk of bias in the prospective clinical studies and included only studies with moderate or low risk of bias.[20] Thus, the data included were all from high-quality studies. Biological complications considered for the analysis included caries, endodontic complications, periodontal pathology, and loss of vitality. Whereas fractures of frameworks or veneering and loss of retention were technical complications.

A recent meta-analysis by Rodrigues et al. indicates that the longevity of a tooth-supported ceramic prostheses made by CAD/CAM manufacturing may be lower than that of conventionally made crowns.[36] Another retrospective study by Almukhlis et al. points out that the survival rates of CAD/CAM restorations and conventional restorations may not be significantly different.[37] Another *in vitro* study by Abdullah et al. indicates that provisional crowns made with CAD/CAM technologies may have a better fit and strength as compared with direct provisional crowns.[38] In a reasonable concordance to observations by Abdullah et al., a review by Janeva et al. points out that the introduction and evolution of CAD/CAM technology has augmented the accuracy of fit of milled denture bases, attenuated the denture tooth movement and increased toughness, flexural strength, and elastic modulus.[7] Taken together, these reports point out that despite the technological ease, survival and success-related outcomes with CAD/CAM technologies need empirical evaluation in well-constructed long-term studies with adequate controls.

Saravi et al. in a recent systematic review and meta-analysis highlight the relative scarcity of mid- and long-term clinical performance of CAD/CAM-facilitated restorations and a call for more prospective studies focusing on long-term performance.[10] In their report, Saravi et al. highlight several biological and technical factors that influence the survival and success of CAD/CAM-facilitated restorations.[10] The report presented herein was fundamentally premised on understanding the determinants of failure and long-term survival of CAD/CAM-facilitated restorations. Findings of the current study are in general concordance with the findings of Saravi et al.

The current study analyzed data from both randomized and prospective clinical studies. While chipping fractures seem to be an important technical reason for failure of CAD–CAM-facilitated restorations and have been reported by both randomized clinical studies and prospective long-term clinical studies included in the analysis. However, reports of caries seem to be reported more in long-term clinical studies (22%) as compared with randomized clinical studies (3%) as a failure-determining factor. It might well be that shorter follow-up durations and enhanced physician–patient contact in randomized clinical studies as compared with long-term clinical studies may play a role in modulating the prevalence of caries in randomized clinical studies.

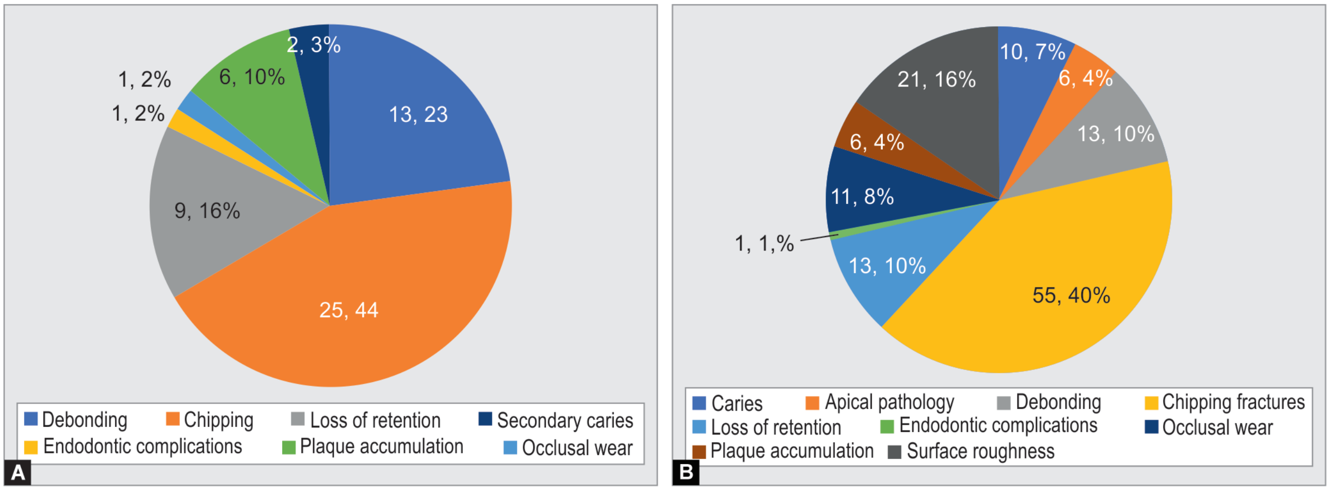
The results presented herein indicate that CAD–CAM-facilitated restorations may have clinically acceptable and meaningful survival and success rates in the long term. However, data for estimating survival and success rates were obtained from only six studies. This limitation of the present analysis warrants more long-term clinical studies designed to better understand the survival and success rates of CAD/CAM restorations.

The objectives of the current analysis were to understand the causes of failures and their distribution in reported literature and arrive at an estimate of the long-term survival of CAD/CAM restorations. However, further studies are needed to specifically quantify the individual impact of technical and biological factors

Table 4: Baseline and survival characteristics as reported in the randomized controlled studies included in the analysis

Author and publication year	*Number of patients*	*Mean age in years*	*CAD/CAM material*	*Number of FDPs*	*Cement*	*Dropout (%)*	*Evaluation criteria**	*Number of failures*	*Nature of complications*
El-Ma'aita et al. 2022[21]	53	34	LDS-reinforced glass ceramic	20	RelyX	9.43	Modified USPHS	0	2 enamel caries in adjacent tooth; 3 apical pathology;
			Monolithic zirconia	20				3 (3 debonding)	3 debonding; 2 enamel caries in adjacent tooth; 1 apical pathology
			Polymer infiltrated hybrid ceramic	20				2 (2 chipping)	2 chipping; 4 enamel caries in adjacent tooth; 2 apical pathology
Schlichting et al. 2022[22]	11	30.4	Ceramic	24	Not reported	0	Modified USPHS	0	None reported
			Composite resin	36				5 (5 chipping fractures)	5 chipping fractures
Gardell et al. 2021[23]	44	NR	LDS-based ceramic	30	Multilink Automix	0	CDA	3 (3 loss of retention)	3 loss of retention recemented
			Zirconium dioxide (ZrO2)-based ceramic	30				6 (6 loss of retention)	2 loss of retention recemented; 4 loss of retention not recemented
Scholz et al. 2021[24]	50	55.9	Partial ceramic crowns with enamel etching	17	RelyX Ultimate	35	FDI	2 (1 endodontic treatment; 1 fracture)	1 endodontic treatment; 1 fracture
			Partial ceramic crowns without enamel etching	28	RelyX Ultimate			6 (2 debonding; 4 fractures)	2 debonding; 4 fractures
			Partial ceramic crown	25	RelyX Unichem			15 (8 debonding; 7 fractures)	8 debonding; 7 fractures
Mühlemann et al. 2020[25]	76	56.4	Porcelain-fused-to-metal	37	Multilink Hybrid Abutment	2.63	Modified USPHS	1 (1 implant fracture)	1 implant fracture; 4 fractures of veneering ceramic; 6 loss of occlusal contact
		57.7	Monolithic zirconia	39				1 (Fracture)	1 fracture; 4 loss of occlusal contact
Nassar et al. 2019[26]	14	NR	Zirconia-reinforced lithium silicate	23	Duolink	0	Modified USPHS	0	None reported
			LDS-based ceramic	23				0	None reported
Monaco et al. 2017[27]	72	44	Ceramic on metal framework	45	Multilink Automix	5.5	Modified USPHS	6 (2 chipping fractures; 4 plaque accumulation)	2 chipping fractures; 4 plaque accumulation
			Zirconia on metal framework	45				8 (3 chipping fractures; 1 occlusal wear; 2 secondary caries; 2 plaque accumulation)	3 chipping fractures; 1 occlusal wear; 2 secondary caries; 2 plaque accumulation
Naenni et al. 2015[28]	40	52.3	Zirconia with pressed veneering ceramic	20	Panavia	10	Modified USPHS	0	8 chipping fractures; 14 surface roughness
			Zirconia with layered veneering ceramic	20				0	4 chipping fractures; 7 surface roughness
Sailer et al. 2009[29]	45	NR	Zirconia-ceramic	36	Variolink	20	Modified USPHS	0	9 minor chipping
			Metal-ceramic	31	Panavia			0	6 minor chipping

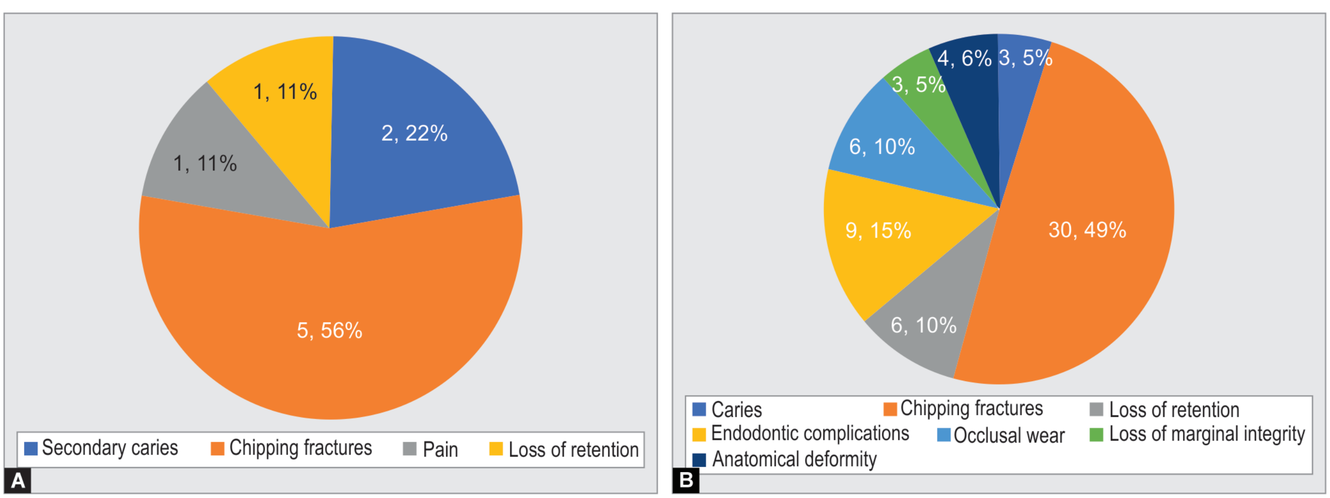
CDA, California Dental Association criteria; FDI, World Dental Federation criteria; USPHS, United States Public Health Service (USPHS) criteria



Figs 1A and B: (A) Distribution of reasons for failures as reported in the included randomized controlled studies. (B) Distribution of technical and biological complications in the included randomized controlled studies

Table 5: Baseline and survival characteristics as reported in the prospective clinical studies included in the analysis

Author and publication year	*Number of patients*	*Mean age in years*	*CAD/CAM material*	*Cement*	*Number of FDPs*	*Dropout (%)*	*Survival rate (%)*	*Number of failures*	*Nature of complications*
Chaar et al. 2015[30]	58	46.8	Zirconia-reinforced alumina ceramic	Glass ionomer	65	9.2	93.6	4 (2 secondary caries; 2 fractures)	15 chipping; 6 loss of retention; 5 endodontic complications; 3 secondary caries
Reich et al. 2014[31]	33	54.8	Lithium disilicate	Multilink Automix	38	3	93	2 (1 fracture; 1 pain)	2 chipping; 3 endodontic complications
Burke et al. 2013[32]	36	NR	Yttria oxide-stabilized zirconium oxide	RelyX	41	20	97	1 (1 chipping)	7 chipping
Sorrentino et al. 2012[33]	37	45.3	Zirconia	RelyX	48	0	100	0	3 chipping; 6 occlusal wear; 3 loss of marginal integrity; 4 anatomical deformity
Schmitt et al. 2009[34]	30	52.2	Zirconia	Glass ionomer	30	10	100	0	3 chipping
Beuer et al. 2009[35]	19	50.9	Zirconia	Glass ionomer	21	0	90.5	2 (1 fracture; 1 loss of retention)	1 endodontic complication

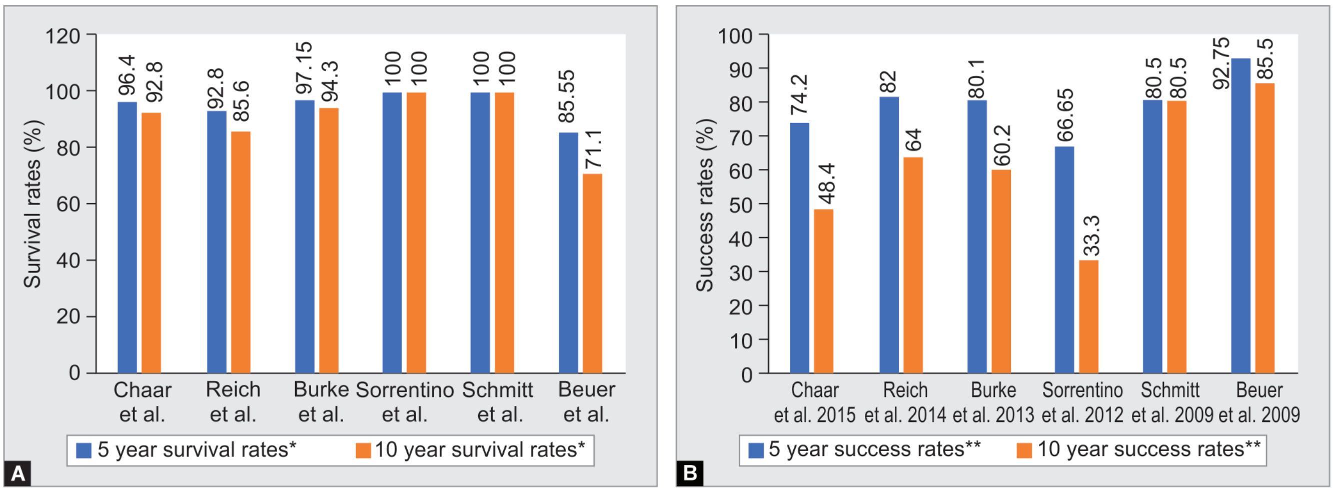


Figs 2A and B: (A) Distribution of reasons for failures in the included prospective clinical studies. (B) Distribution of technical and biological complications in the included prospective clinical studies

Table 6: Estimated failure rates and complications rates in the included prospective clinical studies

Author and publication year	*Total exposure time*	*Number of failures*	*Number of complications*	*Failure rate (per 100 FDP years)**	*Complication rate (per 100 FDP years)***
Chaar et al. 2015[30]	561.88	4	29	0.72 (0.267–1.897)	5.16 (3.587–7.427)
Reich et al. 2014[31]	138.87	2	5	1.44 (0.36–5.759)	3.60 (1.499–8.650)
Burke et al. 2013[32]	176	1	7	0.57 (0.08–4.034)	3.98 (1.896–8.343)
Sorrentino et al. 2012[33]	240	0	16	–	6.67 (4.084–10.882)
Schmitt et al. 2009[34]	77	0	3	–	3.90 (1.257–12.080)
Beuer et al. 2009[35]	68.99	2	1	2.89 (0.725–11.589)	1.45 (0.204–10.289)

*Summary estimate of failure rates: 0.93 (0.0578–1.802) **Summary estimate of complication rates: 4.13 (2.746–5.514)



Figs 3A and B: (A) Estimated 5-year and 10-year survival rates (B) Estimated 5-year and 10-year success rates, *Estimated with the Poisson regression model; Pearson goodness-of-fit for heterogeneity: not significant ($p > 0.05$), **Estimated with the Poisson regression model; Pearson goodness-of-fit for heterogeneity: not significant ($p > 0.05$)

on the long-term survival of CAD/CAM restorations. Furthermore, additional studies are also required to understand the associations of technical and biological factors with material properties of routine chair-side materials. The availability of such data will be helpful in constructing clinical recommendations for steps to prevent the occurrence of technical and biological complications that affect the longevity of CAD/CAM restorations.

Conclusion

Overall, data from available studies indicate that CAD/CAM restorations fabricated with routine chairside materials may exhibit clinically meaningful long-term survival rates. However, several biological and technical factors influence the success of CAD/CAM restorations. Steps to control these technical and biological complications may further augment the benefits offered by CAD/CAM restorations to top clinicians and patients.

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