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Longevity and risk factors of CAD-CAM manufactured implant-supported all-ceramic crowns - A prospective, multi-center, practice-based cohort study

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ABSTRACT

Objectives: The aim of this prospective, multi-center, practice-based cohort study was to analyze factors associated with the success of implant supported all-ceramic single-unit crowns, made by computer-aided-design/computer-aided-manufacturing (CAD-CAM).

Methods: All-ceramic crowns placed in a private practice-based research network (Ceramic Success Analysis, AG Keramik) were analyzed. Data from 567patients with CAD-CAM implant supported all-ceramic crowns placed between 2008–2023 by 54dentists were evaluated. Firstly, all crowns with at least one follow-up control were included (n = 907). Secondly, all crowns being followed up for ≥ 5years and all failures were included (n = 151). At the latest follow-up visit, crowns were considered as successful (not failed) if they were still in function without the need for additional therapy. Multi-level Cox proportional hazards models were used to evaluate the association between a range of predictors and time of success.

Results: Within a mean follow-up period (SD) of 2.5 (2)years (first scenario) and 6.2 (1.2)years (second scenario) [maximum:12years], 27crowns failed (annual failure rate [AFR]:0.74 %). The main failure types were decementation, (n = 11), fracture of the ceramic (n = 4) or Ti-Base (n = 4). In 5-year-scenario, crowns fabricated in the laboratory had 26times lower failure rate than those fabricated chairside (95 %CI:0.0–0.7;p = 0.038). Furthermore, the use of a silane (HR:0.051;95 %CI:0.0–0.5;p = 0.014) and etching of the ceramic (HR:0.053;95 %CI:0.0–0.8;p = 0.035) resulted in a significantly higher risk for failure than their non-use.

Significance: For CAD-CAM manufactured implant supported all-ceramic crowns, high success rates were found in up to 12-year evaluation. Furthermore, after 5years, no patient-or implant-level factors, but operative-level factor (i.e.fabrication method, use of silane/etching) were significantly associated with failure.

The study was registered in the German Clinical Trials Register (DRKS-ID: DRKS00020271).

1. Introduction

In recent years, the introduction of new digital technologies and ceramic materials with improved mechanical and aesthetic properties has resulted in a shift from metal-ceramic to all-ceramic single implant crowns [1,2]. In particular, the advancements in computer aided design-computer aided manufacturing (CAD-CAM) technology have enabled the use of many new options in recent decades. Materials such

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as zirconia, lithium (di)-silicate ceramics or polymer-infiltrated ceramic-network materials (PICN) have been analyzed in vitro [3,4] and recent systematic reviews and meta-analyses have indicated an increased use of all-ceramic crowns over time [5–7]. However, all reviews highlighted the lack of information on the long-term success of monolithic implant supported all-ceramic crowns and the need to analyze the influence of confounding variables (e.g. framework material, retention type, cement, and location) [6].

Regarding all-ceramic crowns, acceptable failure rates after 5 years have been observed. In a previous systematic review of mostly prospective but also retrospective cohort studies, 5-year survival rates were estimated at 93 % [6] or 95 % [5]. Furthermore, no significant differences between veneered and monolithic crowns in terms of survival were observed. However, the frequency of ceramic chipping was higher in veneered crowns, compared to monolithic single crowns [8]. Furthermore, depending on the implant location, luting material, and ceramic material, differences in terms of success rates were detected [9,10]. The reviews highlighted that the majority of studies conducted on all-ceramic crowns have been carried out in university settings [6], which ensures more standardized data collection in terms of exposures, confounding factors, and outcomes. However, a university setting may not accurately reflect the effectiveness of routine dental care in private practice settings as discussed previously, resulting in limited external validity of the obtained results [11,12]. More specifically, it must be underlined that in daily dental practice, various factors related to the dentist, patient, tooth/implant, and material influence on clinical outcomes. To overcome these issues, studies need to include a large number of restorations within a single dataset [13]. Practice-based studies provide an opportunity to gather substantial amounts of data on a regular basis [14]. Additionally, these studies allow for a better understanding of how daily treatment decisions impact the success of restorations in general dental practice [15].

Hence, the aim of the present prospective, non-interventional, multicenter, practice-based, clinical study was, firstly, to evaluate the longevity of different implant-supported all-ceramic crowns and, secondly, to analyze factors influencing the success of these crowns after up to 12 years of follow-up.

2. Materials and methods

2.1. Study design

A prospective, non-interventional, multi-center, private practice-based, clinical study was conducted according to the European guidelines for good clinical practice (Clinical trials – Directive 2001/20/EC) [16]. This study is reported according to the STROBE guideline for cohort studies [17], and was registered in the German Clinical Trials Register (DRKS-ID: DRKS00020271) [18]. This study was a non-interventional trial, which according to guidelines for good clinical practice (Clinical trials – Directive 2001/20/EC), was not subject to Medical Ethical Committee approval [16,18].

2.2. Crown selection

Since 1994, dentists participating in post-graduate programs in Prosthodontics and/or restoratively-focused postgraduate education or attending training courses on CAD-CAM restorations have been invited to complete a standardized digital entry form for each patient in need of at least one ceramic restoration [16,18] (Appendix Fig. 1). To do so, security and data protection conditions had to follow the protocols of the practice-based research network ‘Ceramic Success Analysis’ (CSA, AG Keramik e.V., Malsch, Germany) had to be accepted before participating in the study. Upon accepting the study protocol, participating dentists were required to consecutively record all restorations that met the inclusion criteria. Once a restoration was recorded, the dentist had a small window to revise the data. After this period, no further edits were permitted. The same protocol was applied for the follow-up data, ensuring consistency in data handling.

For this study, either chairside or laboratory fabricated, implant-supported, CAD-CAM all-ceramic crowns were included. Datasets of

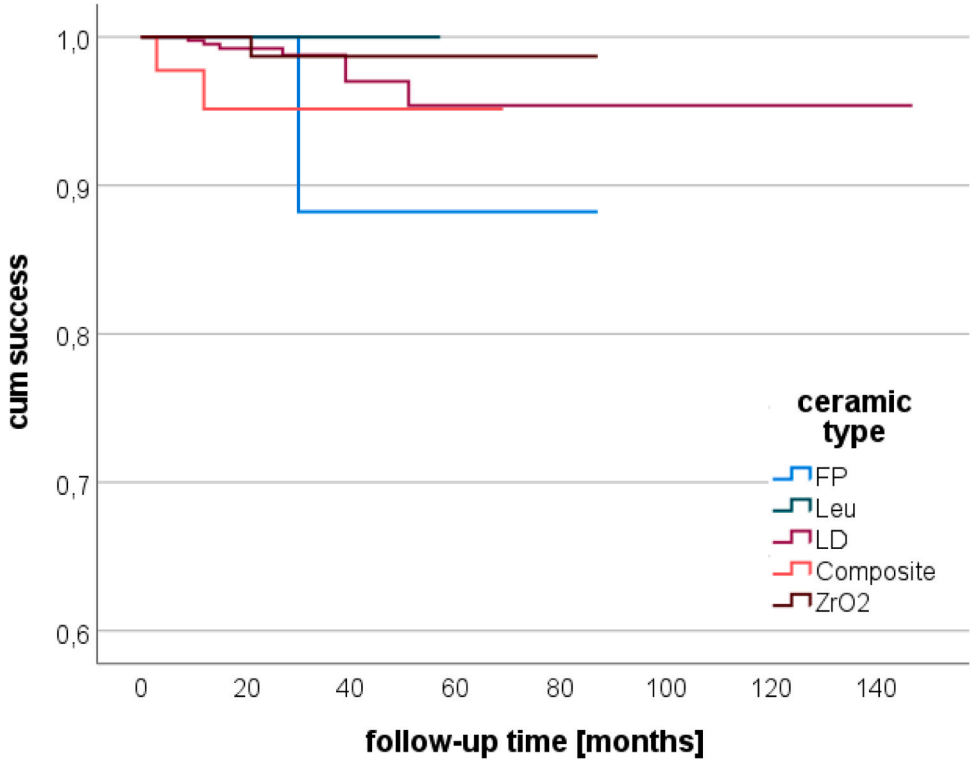

Fig. 1. Kaplan-Meier curve for all-ceramic crowns according to the factor ceramic material.

dentists uploading baseline data but not providing any follow-up information were excluded from analysis. The number of crowns per patient, the number of patients and crowns per dentist, the materials, brands, and techniques being used were not restricted. Furthermore, no combination of material, even not recommended or even contraindicated ones, were intentionally prohibited when entering the datasets. Thus, an additional layer of control and verification of the data's plausibility before analysis was implemented to assess the consistency and reliability of the dentists' data reporting.

2.3. Data extraction

The following data were anonymously collected:
Dentist-level data:

- Country of the dentist, gender of the dentist

Patient-level data:

- Age of the patient, date of the first restorative treatment, date of the second restorative (re-)intervention, date of the last visit, number of implants/crowns included in the study per patient.

Implant-level data:

- Implant site using the Fédération Dentaire Internationale (FDI) notation system, mode of failure.

Technique-level data:

- Type of retention (screw-retained, conventionally or adhesively cement-retained, horizontally screw-retained abutments (conventionally or adhesively cemented), vertically screw-retained abutments (conventionally or adhesively cemented)), abutment material (conventional titanium, conventional zirconia, ceramic crowns bonded to titanium bases), technique-related factors, such as the use of rubber dam, matrix, silane, oxygen-blocking gel, EVA oscillating instrument, ultrasonic cementation

Material-level data:

- Materials used, including ceramic type, adhesive type, luting material, abutment material, etc.

The following data were not inserted in the electronic forms and therefore were not collected:

- Characteristics of study participants (e.g. demographic, clinical, social) and information on exposures and potential confounders
- Characteristics of the study dentists (e.g. demographic, experience, skills, 'dentist profile' [19]) and information on exposures and potential confounders)
- Indications for why an implant and a ceramic crown was chosen
- Peri-implant clinical and radiographic parameters (e.g. bone levels, probing depths, bleeding on probing (PBI))

2.4. Success and failure of treatment

The evaluation of all-ceramic crowns' status was conducted within the same private clinic, typically by the dentist who initially placed the crown. This assessment took place during patients' routine care visits, recall appointments, or when complications with the crown occurred. The observation period commenced when the crown was inserted.

Success: If the crown exhibited no clinical or radiographic signs of failures (e.g.: loss of retention or chipping) at the last follow-up visit, it was judged as successful. Consequently, whenever the crown required replacement, repair, re-cementation or was scheduled for such (technical/ mechanical complications), the intervention was considered a failure. Additionally, if an implant supporting the included crown was lost or if the replacement of the crown was necessitated by a modification in the prosthetic treatment plan, the crown was categorized as failure. Biological complications (e.g. increased peri-implant probing pocket depths associated bleeding on probing and/or peri-implant marginal bone loss) were not considered for the evaluation of success.

2.5. Statistical analysis and power analysis

For descriptive purposes, frequency and percentages of measured baseline characteristics as well as frequency and percentages of different failure types were tabulated. Statistical analysis was performed using SPSS (SPSS 28.0; SPSS, Munich, Germany). Time until any failure was the dependent variable. Kaplan-Meier statistics were used to calculate significant differences between the groups ($p < 0.05$). For Kaplan-Meier statistics, the independent method was used to generate success curves up to 10 years [20]. The annual failure rates (AFR) were calculated from life tables [21].

To reduce reporting bias caused by dentists not reporting their own failures (more information on that can be found in the discussion), a sub-analysis was performed. This sub-analysis focused specifically on all-ceramic crowns that were monitored for more than 5 years and included crowns that failed within the first five years or anytime thereafter. By including these specific cases, the study aimed to minimize the potential impact of dentists selectively not reporting their own failures.

Crude associations between baseline characteristics and time until failure was calculated by fitting separate models for each baseline characteristic as the independent variable. Factors associated with time until failure ($p < 0.25$ [22,23]) in separate models were entered in a non-clustered multivariate Cox regression model (independent model).

For the present study, no prospective power or sample size calculation was performed since this was a comprehensive dataset from an ongoing private practice-based research project. Regarding a retrospective power analysis for categories included in the multivariate Cox regression analysis, the analysis provided a power of ≥ 80 % for the categories of patient's age, number of crowns per patient, arch, implant location, rubber dam, silane, ultrasonic cementation, dental flossing, oxygen-blocking, EVA-instrument, finishing line of the abutment, ceramic type and luting material. Nonetheless, due to its pragmatic design, the study is likely to be underpowered to detect moderate to clinically significant relative risks in some categories.

3. Results

Between February 2008 and September 2023, 907 all-ceramic crowns in 567 patients with at least one follow-up visit were placed by a total of 54 dentists. Of these, a total number of 124 crowns was followed up for 5 years or more or had failed during the first five years. The dentists were located in Germany (n = 50), Austria (n = 1), Ireland (n = 1), Japan (n = 1) and USA (n = 1). The mean number of crowns (standard deviation [SD]) per patient was 1.6 (1.0) and the number of crowns per dentist was 16 (32). Characteristics of implants/crowns are shown in Table 1 and Appendix Table A.1.

3.1. Success

At the end of the overall mean (SD) follow-up period of 2.5 (2) years (maximum: 12 years) 97 % of the crowns (880 out of 907) were considered successful (Table 1) (i.e., no additional of additional treatment). For the 5-year scenario (151 crowns), the mean observation time was 6.2 (1.2) years (5-year success rate: 72 %). The annual failure rates were 0.74 % (all years scenario) and 3.3 % (5-year scenario), respectively. However, AFR between dentists varied widely (mean(95 %CI): 1.4 % (−0.2 %−2.6 %)) The main failure types were de-cementation (n = 11), fracture of the ceramic (n = 4), fracture of the TiBase (n = 4), implant removal (n = 2), and prosthetic reasons (n = 1). For 7 failures the reason for failure was not provided. The success curves of crowns according to ceramic materials are shown in Fig. 1. Success stratified according to the type of retention is presented in Fig. 2.

Table 1
Frequency, number of failures of implant crowns included in study and bivariate Cox proportional hazard regression analyses of time until failure by categories of each baseline characteristic for outcome success.

	Implants						
category	**Frequency [n (%)]**	**Failures [n (%)]**	**p-value**	**HR**	**95 % CI**	**Mean Survival time**	**95 % CI**
overall	907 (100 %)	27 (3 %)				136.9	134 - 139.9
patient-level							
age [years]							
0 −20	3 (0 %)	0 (0 %)		1.0	Reference	In at least one subcategory no failure could be observed. Thus. no median success time could be calculated	
21 −40	108 (12 %)	7 (6 %)	0.941	3772.8	0 – $1.1 * 10^{99}$		
41 −60	450 (50 %)	14 (3 %)	0.948	1509.1	0 – $4.4 * 10^{98}$		
> 60	346 (38 %)	6 (2 %)	0.952	804.9	0 – $2.3 * 10^{98}$		
number of crowns per patient							
1	219 (24 %)	9 (4 %)		1.0	Reference	118.7	112.9 - 124.5
2	141 (16 %)	3 (2 %)	0.265	0.5	0.1 - 1.8	138.5	131.6 - 145.5
3	155 (17 %)	4 (3 %)	0.259	0.5	0.2 - 1.6	101.0	97.2 - 104.7
4	115 (13 %)	3 (3 %)	**0.201**	0.4	0.1 - 1.6	85.6	82.9 - 88.3
≥ 5	277 (31 %)	8 (3 %)	0.313	0.6	0.2 - 1.6	94.1	90.5 - 97.8
arch							
upper	475 (52 %)	19 (4 %)		1.0	Reference	132.7	127.3 - 138.1
lower	432 (48 %)	8 (2 %)	**0.035**	0.4	0.2 - 0.9	126.2	123.9 - 128.5
implat-level							
implant type/ implant location							
incisive	70 (8 %)	3 (4 %)		1.0	Reference	64.9	60.9 - 68.8
canine	21 (2 %)	2 (10 %)	0.527	1.8	0.3 - 10.7	63.0	52.5 - 73.5
premolar	317 (35 %)	6 (2 %)	**0.187**	0.4	0.1 - 1.6	122.6	118.9 - 126.3
molar	499 (55 %)	16 (3 %)	0.500	0.7	0.2 - 2.2	137.0	133.3 - 140.8
PBI							
no bleeding	828 (91 %)	26 (3 %)		1.0	Reference	136.6	133.6 - 139.7
bleeding	79 (9 %)	1 (1 %)	0.535	0.5	0.1 - 3.9	120.0	116.1 - 123.8
technique-level							
type of retention							
screw-retained	334 (37 %)	7 (2 %)		1.0	Reference	102.0	99.8 - 104.1
conventionally or adhesively cement-retained	552 (61 %)	17 (3 %)	**0.187**	1.8	0.7 - 4.4	135.9	131.6 - 140.1
horizontally screw-retained abutments (conventionally or adhesively cemented)	5 (1 %)	1 (20 %)	**< 0.001**	54.7	6 - 500.4	11.2	11.2 - 11.2
vertically screw-retained abutments (conventionally or adhesively cemented)	16 (2 %)	2 (13 %)	**0.033**	5.6	1.2 - 26.8	59.5	49.9 - 69
fabrication method							
chairside	500 (55 %)	16 (3 %)		1.0	Reference	121.9	118 - 125.8
laboratory	407 (45 %)	11 (3 %)	**0.124**	0.5	0.2 - 1.2	138.5	135 - 142
rubber dam							
use	26 (3 %)	3 (12 %)		1.0	Reference	86.4	73.3 - 99.5
no	881 (97 %)	24 (3 %)	**0.060**	0.3	0.1 - 1	137.6	134.7 - 140.4
silane							
yes	561 (62 %)	14 (2 %)		1.0	Reference	100.9	98.7 - 103
no	346 (38 %)	13 (4 %)	**0.150**	1.7	0.8 - 3.7	134.3	128.8 - 139.9
ultrasonic cementation							
yes	60 (7 %)	7 (12 %)		1.0	Reference	69.4	62 - 76.8
no	847 (93 %)	20 (2 %)	**0.001**	0.2	0.1 - 0.5	138.5	135.8 - 141.3
dental flossing							
yes	662 (73 %)	20 (3 %)		1.0	Reference	136.5	132.9 - 140
no	245 (27 %)	7 (3 %)	0.587	0.8	0.3 - 1.9	95.5	92.6 - 98.4
oxygen-blocking							
yes	198 (22 %)	4 (2 %)		1.0	Reference	89.7	87.9 - 91.5
no	709 (78 %)	23 (3 %)	**0.051**	2.9	1 - 8.5	135.5	131.6 - 139.3
EVA instrument							
yes	48 (5 %)	5 (10 %)		1.0	Reference	65.3	54 - 76.7

(*continued on next page*)

Table 1 (*continued*)

category	Implants						
	Frequency [n (%)]	**Failures [n (%)]**	**p-value**	**HR**	**95 % CI**	**Mean Survival time**	**95 % CI**
no	859 (95 %)	22 (3 %)	**0.004**	8.4	1 - 0	138.2	135.5 - 140.9
etching of the ceramic							
0	346 (38 %)	11 (3 %)		1.0	Reference	135.1	129.4 - 140.8
1	561 (62 %)	16 (3 %)	0.405	0.7	0.3 - 1.6	100.5	98.4 - 102.6
material-level							
material of the ceramic							
Feldspathic porcelain (FP)	45 (5 %)	2 (4 %)		1.0	Reference	In at least one subcategory no	
Leucite glass-ceramic (LEU)	18 (2 %)	0 (0 %)	0.978	0.0	0 - 0	failure could be observed. Thus. no	
Lithium dissilicate glass-ceramic (LD)	516 (57 %)	17 (3 %)	0.550	0.6	0.1 - 2.8	median success time could be	
Hybrid Composite	49 (5 %)	3 (6 %)	0.639	1.5	0.3 - 9.2	calculated	
ZrO_2	279 (31 %)	5 (2 %)	0.265	0.4	0.1 – 2.0		
abutment material							
conventional titanium	239 (26 %)	12 (5 %)		1.0	Reference	96.4	91.6 - 101.2
ceramic crowns bonded to titanium bases	475 (52 %)	9 (2 %)	**0.011**	0.3	0.1 - 0.8	96.7	95 - 98.5
conventional zirconia	105 (12 %)	5 (5 %)	0.450	1.5	0.5 - 4.3	71.2	61 - 81.3
n/a	88 (10 %)	1 (1 %)	**0.129**	0.2	0 - 1.6	141.1	134.7 - 147.6
luting material							
photoactivated luting agent	66 (7 %)	6 (9 %)		1.0	Reference	63.0	53.6 - 72.4
dual-cured luting agent	323 (36 %)	9 (3 %)	**0.026**	0.3	0.1 - 0.9	94.9	92.2 - 97.7
chemicalactivated luting agent	144 (16 %)	4 (3 %)	**0.082**	0.3	0.1 - 1.2	136.2	128 - 144.3
n/a	321 (35 %)	7 (2 %)	**0.003**	0.2	0.1 - 0.6	102.0	100 - 104.1

Factors associated with time until failure ($p < 0.25$; bold) in the separate models were entered in the multivariate Cox regression model (Table 2).
* n/a: not available, for some crowns one or two (sub-)categories was/were not provided.

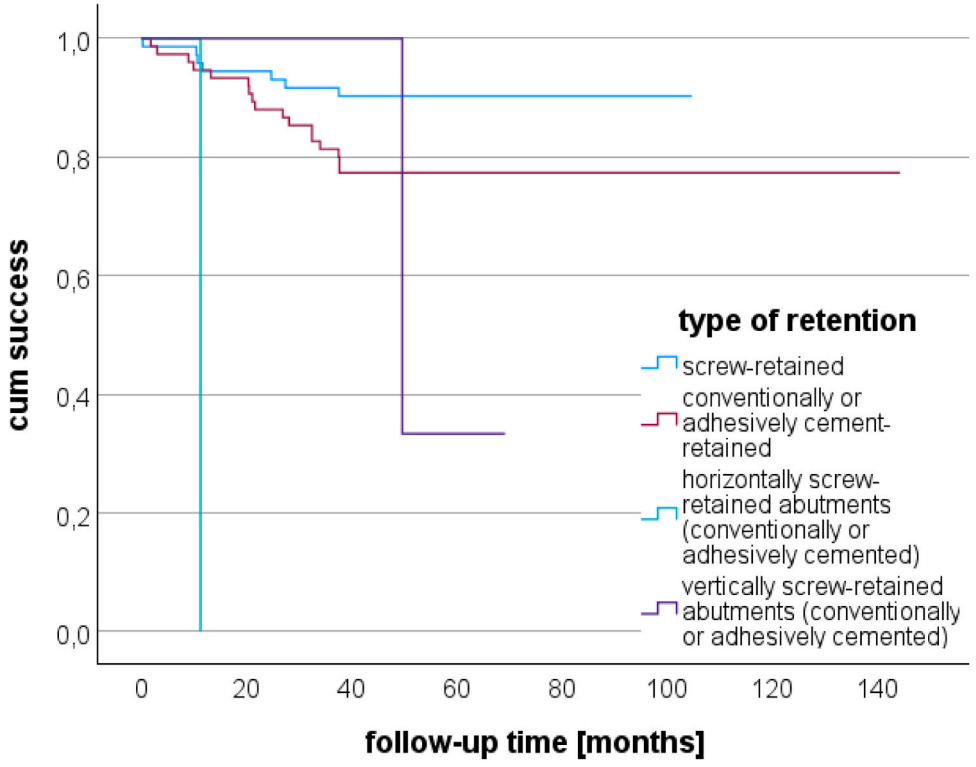

Fig. 2. Kaplan-Meier curve for all-ceramic crowns according to the type of retention.

3.2. Cox regression analysis

Crude bivariate associations between different baseline characteristics and an increased failure rate are given in Table 1 and Appendix Table A.1. The number of crowns per patient, arch, implant location, type of retention, rubber dam, silane, ultrasonic cementation, dental flossing, oxygen blocking, material of the ceramic, material of the abutment and luting material were possibly associated with increased failure rates ($p < 0.25$). In the 5-year scenario, the (non-)significant predictors remained (non-) significant with three exceptions of patient's age and material of the ceramic became significant whereas rubber dam became anon-significant predictors.

The results of the non-clustered multivariate models including factors possibly associated with an increased failure rate in the bivariate

models are shown in Table 2 (first scenario) and Appendix Table A.2 (second scenario). After multivariate regression implant crowns in the lower arch showed a 3 times (95 %CI:0.1–0.9;p = 0.030) lower risk for failure than implant crowns in the upper arch. Furthermore, the use of conventionally or adhesively cemented crowns resulted in 7.6 times (95 %CI:0.0–0.9; p = 0.035) lower risk of failure than the use of screw-retained crowns. The use of screw-retained abutments and conventionally or adhesively cemented implant crowns resulted in a 56 times lower (95 %CI:1.6–1993; p = 0.027) risk for failure than the use of horizontally screw-retained abutments. In material level, the use of crowns bonded to titanium bases resulted in a significantly lower risk for failure than conventional titanium abutments (HR: 0.191; 95 %CI:0.0–0.7; p = 0.016). In the 5-year scenario, however, crowns fabricated in the laboratory showed a 26 times lower (95 %CI:0.0–0.7;p = 0.038) failure rate than those fabricated chairside. Furthermore, the use of a silane (HR: 0.051; 95 %CI:0.0–0.5;p = 0.014) and etching of the ceramic (HR: 0.053; 95 %CI:0.0–0.8;p = 0.035) resulted in a significantly higher risk for failure than their non-use.

Table 2
Multivariate Cox proportional hazard regression analyses of time until failure as function of baseline characteristics identified (for outcome success).

category	p-value	HR	95 % CI
patient-level			
number of crowns per patient	0.087		
1		1.0	Reference
2	0.369	0.521	0.1 - 2.2
3	0.134	0.362	0.1 - 1.4
4	0.061	0.196	0 - 1.1
≥ 5	**0.008**	0.185	0.1 - 0.6
arch	**0.024**		
upper		1.0	Reference
lower	**0.030**	0.335	0.1 - 0.9
implant-level			
implant type/ implant location	0.487		
incisive		1.0	Reference
canine	0.550	1.862	0.2 - 14.3
premolar	0.618	0.680	0.1 - 3.1
molar	0.600	1.473	0.3 - 6.3
technique-level			
type of retention			
screw-retained		1.0	Reference
conventionally or adhesively cement-retained	**0.035**	0.132	0 - 0.9
horizontally screw-retained abutments (conventionally or adhesively cemented)	**0.027**	56.329	1.6 - 1992.9
vertically screw-retained abutments (conventionally or adhesively cemented)	0.872	1.211	0.1 - 12.5
fabrication method			
chairside		1.0	Reference
laboratory	0.384	0.536	0.1 - 2.2
rubber damm			
use		1.0	Reference
non-use	0.529	2.564	0.1 - 48
silane			
use		1.0	Reference
non-use	0.407	1.654	0.5 - 5.4
ultrasonic cementation			
use		1.0	Reference
non-use	0.305	0.461	0.1 - 2
oxygen-blocking			
use		1.0	Reference
non-use	0.700	1.372	0.3 - 6.9
eva instrument			
use		1.0	Reference
non-use	0.100	0.198	0 - 1.4
material-level			
luting material	**0.010**		
photoactivated luting agent		1.0	Reference
dual-cured luting agent	**0.013**	0.136	0 - 0.7
chemicalactivated luting agent	**0.009**	0.071	0 - 0.5
n/a	**0.003**	0.033	0 - 0.3
provisorial	**0.024**	0.046	0 - 0.7
abutment material	**0.030**		
conventional titanium		1.0	Reference
ceramic crowns bonded to titanium bases	**0.016**	0.191	0 - 0.7
conventional zirconia	0.868	0.881	0.2 - 4
n/a	0.255	0.230	0 - 2.9

Bold p-values (p < 0.05) indicate factors strongly associated with a de- or increased failure rate.

4. Discussion

This multi-center, practice-based, clinical cohort study prospectively analyzed the success of all-ceramic crowns. A total of 907 implant supported crowns with at least one follow-up visit were placed by 54 dentists, who followed-up 151 crowns for at least 5 years. The influence of several baseline parameters on the success was analyzed. Overall low annual failure rates at patient-level (arch), technique level (type of retention) and material level (abutment material) factors were significant short-time predictors and technique-level factors (fabrication method, use of silane, etching of the ceramic) were significant longer time predictors for decreased time until failure.

After up to 12 years of observation, the cumulative and annual failure rates were 3 % and 1.2 %, respectively, which are in the same range as previous reviews on implant supported all-ceramic crowns [5–8]. One aspect that should be pointed out as affecting the reported cumulative failure rates is a potential reporting bias [6]. Indeed, data for the present study had to be collected manually via an online platform. Thus, several dentists might not succeed in uploading follow-up data, e. g. due to a loss of motivation, the voluntary characteristic of the CSA network [16] or the factor that the dentists may not choose to report their own failure. Furthermore, a mechanism to identify potentially falsified data sets could be included in the study design. In order to minimize these reporting bias, the sub-analysis focused on two specific scenarios: (1) Only crowns that had been followed up for at least 5 years and (2) All crowns that had failed within the first five years or beyond were included This approach aimed to mitigate reporting bias and enhance the reliability of our findings, since all known negative results were included, whereas all positive censored results in the first five years were omitted. This also results in a much higher cumulative (18 %) failure rate than in the previous meta-analyses. Even the AFR increased to 3.3 %. However, from a clinical perspective, in restorative dentistry, annual failure rates at 5 - 10 years below 6 % are considered satisfactory [13].

One reason for the slightly higher failure rates after 5 years compared to the previous reviews is presumably the definition of success and failure. In the present study, even the need for recementation was considered a failure, whereas it was not considered a failure in previous studies. When the data of recemented crowns were excluded from risk analysis in the present study, annual and cumulative failure rates decreased to 2 % and 0.7 %, respectively. Furthermore, in another systematic review [5], resin-matrix ceramic crowns performed significantly worse than all other ceramic materials, whereas these hybrid materials did not perform worse in the present study. The reason for this could be the nomenclature for these hybrid materials [24]. The terms hybrid-ceramic, resin-matrix ceramic, or polymer-infiltrated ceramic network are often used as synonyms. All terms describe hybrid materials with a similar composition of a ceramic and a composite component. However, the materials differ in terms of the type of ceramic and resin, as well as in the respective material proportions. This variability means that these hybrid materials may not be comparable at all, which could explain the different results of the present work and the systematic reviews.

In the present study implant crowns in the lower arch showed a significantly lower risk for failure than in the upper arch. In the mandible, especially in the anterior region, bone resorption tends to occur at a slower rate compared to the maxilla after tooth loss. In the maxilla, particularly in posterior region, there is a greater tendency for bone resorption, which can compromise the bone quantity and quality and affect crown-implant ratio, and the direction of the loads in relation

to the long axis of the implant, which may increase the mechanical complications. In particular, the direction of occlusal forces in the maxilla tends to be more horizontal/lateral, which increases with bone loss, as the forces tend to be directed eccentric to the long axis of the implant and the crown. These lateral forces can be more damaging to implant crowns because they can cause screw loosening or increased stress at the bone-implant interface. In contrast, the mandibular teeth typically experience more vertical occlusal forces, which are better tolerated by the crown, implant and the surrounding bone. In line with this matter, with the presence of parafunctional habits, such as bruxism, the patient can exert greater lateral forces on maxillary implants, contributing to higher failure rates [25]. Overall, the combination of favorable force direction and distribution in the mandible may contribute to a lower failure rate of implant crowns compared to the maxilla. Another interesting result of the present study is the perceived lower failure risk of cemented implant crowns compared to screw-retained implant crowns. The observation can be attributed to several clinical and biomechanical factors. The comparison between cemented and screw-retained implant crowns shows varying outcomes based on different studies. The review of multiple randomized clinical trials highlighted that screw-retained restorations could experience technical failures such as screw loosening or fractures but were easier to maintain due to their retrievability. Cemented crowns were less prone to mechanical failures like screw loosening [26,27]. The tendency for increased mechanical complications with screw-retained crowns, such as screw loosening or fracture, might be due to the challenge with complete seating of the crown, compared with cement-retained crowns, which have the cement space mostly ranging between 40–120 μm; such a space and the presence of the cement may compensate for non-seated crowns, when the misfit is overlooked/unnoticed. This issue may lead to cement dissolution, which may be seen in the long term as opposed to technical complications that may be seen with screw-retained crowns at earlier stages after the delivery, such as screw loosening or fracture of components due to strains generated at and around the implant-crown interface [25]. Regarding the retrospective power analysis, the analysis of the smallest subcategory to the reference category provided a power of $\geq$ 80 % for the categories patient's age, number of crowns per patient, jaw, implant location, rubber dam, silane, ultrasonic cementation, dental flossing, oxygen-blocking, finishing line of the abutment, ceramic type, luting material. Only for the two categories PBI and fabrication method the power was 8,3 % and 15.5 %. Nonetheless, especially for the second scenario with only 124 all-ceramic crowns the present study may still be underpowered to detect moderate to clinically significant relative risks in some categories. For example, considering an α-error of 25 % (bivariate analysis) and a HR of 1.1 (being the HR between incisors and canines) approximately 1073 implants with a positive PBI scores and 10730 with a negative PBI score (ratio of implants with a positive and negative PBI score) had to be enrolled to provide a power of 80 %. As discussed previously [28], it might be speculated that due to the relatively low number of failures no correlation between 'risk level of caries' and failure rate could be observed and that with a larger sample size or with more failures the influence of some factors as (significant) predictor and the reliability of the present results would increase [28].

The increased risk of clinical failures with chairside milled crowns compared to laboratory-milled crowns can be attributed to several factors. Firstly,

lab-based milling machines are typically larger and more advanced, offering higher precision and better surface detail than smaller chairside units. Chairside milling, while convenient, uses smaller burs, resulting in less detailed and potentially rougher internal surfaces, affecting fit and accuracy. Lab machines, with their range of tools and milling strategies, create more precise restorations [29]. Studies have shown that lab-milled crowns, especially those made with five-axis machines in zirconia, have significantly better marginal trueness than those made chairside using a three-axis milling unit [30]. This difference in precision can affect the marginal fit and internal adaptation of the crown, which are critical for long-term success.Secondly, lab milling provides access to a broader range of materials, such as high-strength ceramics like zirconia, which require sintering—unfeasable in most chairside workflows. Chairside milling often uses materials like lithium disilicate, which, while strong, lacks zirconia's fracture strength. Thirdly, the success of chairside milling depends on the clinician's experience with digital design, whereas lab technicians typically have specialized training and expertise in post-milling processes. Finally, lab-milled crowns undergo quality checks and adjustments by the laboratory technicians, while chairside restorations may require more intraoral adjustments, potentially compromising the fit if not done properly. Moreover, chairside cementation of crowns to titanium bases may lack the precision achieved in a laboratory setting.

In the present study, the influence of potential risk factors slightly changed over time. For instance, the factor type of retention became non-significant predictor over time and the fabrication method or etching of the ceramic became a significant predictor for decreased time until failure. These findings corroborate previous studies in which predictors also changed over time [18,21] and highlights, firstly, that the influences of risk factors on failure of, e.g., dental materials appear only after longer observation times of up to 10 years [31]. In addition, in light of the reported results, an observational period of at least 5 years should be recommended for (in)direct restorations [32]. However, in the present study, it might also be specultated that the much lower number of crowns in the second analysis led to a reduced power and, thus, to a change of risk factors as discussed above. Additionally, even-though the present data provide a representative overview of the success of monolithic implant crowns due to the inclusion of different private practitioners working in different environments, some limitations must be disclosed. First, due to the nature of the study, provided and recorded treatments were not standardized prior to initiation of the investigation. Second, several implants and reconstruction materials from different manufacturers were used. However, this enabled reporting of the outcomes not being limited to only one manufacturer's implants and materials. Therefore, the results can be considered more generalizable.

In conclusion, within the limitations and generalizability of this study, CAD-CAM manufactured all-ceramic implant supported single-unit crowns showed high success rates after up to 12 years in private practice environment. After 5 years, no operative- and no implant-level factors, but a patient-level factor ((fabrication method, use of silane/etching)) was significantly associated with reconstruction failure. Additional clinical studies are needed to increase the level of evidence on patient-related factors not analyzed in the presented data set.

Author contribution

R.J.W. contributed to analysis and interpretation, drafted and critically revised the manuscript.E.J.K. contributed to design, acquisition and interpretation and critically revised the manuscript.B.R. contributed to conception and design, acquisition and interpretation and critically revised the manuscript.A.R. contributed to interpretation and critically revised the manuscript.C.R. contributed to analysis and interpretation and critically revised the manuscript.B.Y. contributed to analysis and interpretation and critically revised the manuscript.S.A.-A. contributed to interpretation, drafted and critically revised the manuscript.All authors gave their final approval and agree to be accountable for all aspects of the work.

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Informed consent

For this type of study, formal consent is not required.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dental.2024.09.008.

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