Received: 19 January 2021 | Revised: 17 June 2021 | Accepted: 28 September 2021

DOI: 10.1111/clr.13871

REVIEW ARTICLE

CLINICAL ORAL IMPLANTS RESEARCH WILEY

Clinical outcomes of all-ceramic single crowns and fixed dental prostheses supported by ceramic implants: A systematic review and meta-analyses

Frank Akito Spitznagel[1] | Marc Balmer[2] | Daniel B. Wiedemeier[3] | Ronald Ernst Jung[2] | Petra Christine Gierthmuehlen[1]

[1]Department of Prosthodontics, School of Dentistry, Heinrich-Heine-University, Düsseldorf, Germany

[2]Clinic of Reconstructive Dentistry, Center of Dental Medicine, University of Zurich, Zurich, Switzerland

[3]Statistical Services, Center of Dental Medicine, University of Zurich, Zurich, Switzerland

Correspondence
Marc Balmer, Clinic of Reconstructive Dentistry, Center of Dental Medicine, University of Zurich, Plattenstraße 11, 8032 Zurich, Switzerland.
Email: marc.balmer@zzm.uzh.ch

Abstract

Objective: To analyze the clinical outcomes of all-ceramic single crowns (SCs) and fixed dental prostheses (FDPs) supported by ceramic implants.

Materials and Methods: Based on a focused question and customized PICO framework, electronic (Medline/EMBASE/Cochrane) and manual searches for studies reporting the clinical outcomes of all-ceramic SCs and FDPs supported by ceramic implants ≥12 months were performed. The primary outcomes were reconstruction survival and the chipping proportion. The secondary outcomes were implant survival, technical complications, and patient-related outcome measurements. Meta-analyses were performed after 1, 2, and 5 years using random-effect meta-analyses.

Results: Eight of the 1,403 initially screened titles and 55 full texts were included. Five reported on monolithic lithium disilicate (LS2) SCs, one on veneered zirconia SCs, and two on veneered zirconia SCs and FDPs, which reported all on cement-retained reconstructions (mean observation: 12.0–61.0 months). Meta-analyses estimated a 5-year survival rate of 94% (95% confidence interval [CI]: 82%–100%) for overall implant survival. Reconstruction survival proportions after 5 years were: monolithic LS2, 100% (95%CI: 95%–100%); veneered zirconia SCs, 89% (95%CI: 62%–100%); and veneered zirconia FDPs 94% (95%CI: 81%–100%). The chipping proportion after 5 years was: monolithic LS2, 2% (95%CI: 0%–11%); veneered zirconia SCs, 38% (95%CI: 24%–54%); and veneered zirconia FDPs, 57% (95%CI: 38%–76%). Further outcomes were summarized descriptively.

Conclusions: Due to the limited data available, only tendencies could be identified. All-ceramic reconstructions supported by ceramic implants demonstrated promising survival rates after mid-term observation. However, high chipping proportions of veneered zirconia SCs and, particularly, FDPs diminished the overall outcome. Monolithic LS2 demonstrated fewer clinical complications. Monolithic reconstructions could be a valid treatment option for ceramic implants.

Spitznagel and Balmer authors should be considered the joint first author.

KEYWORDS
ceramics, dental implants, implant-supported dental prosthesis, meta-analysis, survival analysis, systematic review, treatment outcome, zirconia

1 | INTRODUCTION

Nowadays, ceramic implants made of yttria-stabilized or alumina-toughened zirconia are used as an addendum to titanium implants in oral implantology (Roehling et al., 2018). The reasons for using polycrystalline ceramics as dental implants are diverse, namely patients' requirements for metal-free reconstruction, promising results in preclinical studies, and the favorable response of the peri-implant tissue to biofilm formation (Roehling et al., 2019). Regarding hard tissue integration, several studies reported an osseointegration capacity and bone-to-implant contact values of zirconia implants, which seemingly do not differ from those of titanium implants (Roehling, Gahlert, et al., 2019). Considering soft tissue integration, preclinical data demonstrated that the morphology and dimensions of the peri-implant mucosa are similar between zirconia and titanium implants (Kohal et al., 2004; Thoma et al., 2015). Furthermore, biofilm formation might even be reduced on zirconia compared with that on titanium surfaces (Nascimento et al., 2014; Scarano et al., 2004). Additionally, an experimental study revealed that marginal bone loss is more pronounced around titanium implants after ligature-induced peri-implantitis than around zirconia implants (Roehling, Gahlert, et al., 2019).

Although an increasing number of clinical studies investigating the outcomes of ceramic implants after short- to mid-term observation periods have been published during the last few years (Roehling et al., 2018), the clinical evidence of ceramic implants is still scarce. Promising results with survival rates of ceramic implants of 98.4% and 100% and a marginal bone loss of 0.7 ± 0.6 mm and 1.2 ± 0.76 mm were reported after five and 7.8 years, respectively (Balmer et al., 2020; Lorenz et al., 2019). Hence, zirconia might be a feasible treatment option as an implant material.

Nevertheless, the majority of publications focus mainly on the evaluation results of hard and soft tissue in relation to zirconia implants and provide only limited information about the prosthetic procedures and outcomes (Balmer et al., 2020; Grassi et al., 2015; Kniha et al., 2018; Lorenz et al., 2019). Although studies with an alternative implant material predominantly focus on tissue integration and not on the outcome of the suprastructure, implant, and prosthetic reconstruction should be considered as one complex. The material properties of zirconia differ significantly from titanium, particularly for the much higher elasticity modulus (Guess et al., 2011). This might affect and jeopardize the clinical performance of prosthetic reconstruction. If present, veneering ceramic, in particular, could be the weakest link in this rigid system and therefore be susceptible to chipping. The ceramic fracture and chipping of veneering ceramics of titanium implant-supported all-ceramic SCs (Pjetursson et al., 2018) and multi-unit FDPs (Sailer et al., 2018) are frequent technical complications.

There is currently no systematic review with meta-analysis available that focuses only on the clinical outcomes of ceramic implant-supported SCs or FDPs. Evidence-based treatment guidelines for the restoration of zirconia implants are still lacking. Therefore, the present systematic review aimed to analyze the clinical outcomes in terms of survival and technical complication rates of all-ceramic SCs and FDPs supported by ceramic implants.

2 | MATERIAL AND METHODS

2.1 | Study design

The study protocol was designed and conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Moher et al., 2009). Furthermore, this systematic review was registered at the National Health Institute for Research PROSPERO, International Prospective Register of Systematic Reviews, at the UK's National Institute for Health Research, University of York, Centre for Reviews and Dissemination under the PROSPERO ID: CRD42017081405. Ethics approval was not required for this systematic review.

2.2 | Focused question and PICO

The focus of the present systematic review was "In clinical studies, what are the treatment outcomes of all-ceramic implant-supported SCs and FDPs on ceramic implants after a mean follow-up of at least 12 months?".

A standardized search strategy was employed for all databases. The PICO framework (Akobeng, 2005; Schardt et al., 2007) was customized according to the focused question as follows:

Population: Partially edentulous patients with one or more ceramic implants.

Intervention: All-ceramic implant-supported SCs or three-unit FDPs.

Comparison: Not performed (prognosis as the primary aim).

Outcome: Survival and complication rates on implant and reconstruction level.

2.3 | Search strategy

An electronic systematic search of three online literature databases (Medline via OVID, Cochrane Central Register of Controlled Trials [CENTRAL], and EMBASE via Elsevier databases) was performed for clinical studies in English. All articles published up to June 24, 2020, were included. Additional hand searches were carried out to identify relevant studies by cross-screening the reference list of all obtained full-text articles and recently published reviews relating to the same topic.

2.4 | Search protocol

Specific search terms were organized according to population, intervention, and outcome. Each subclass consisted of different MeSH or Emtree terms as well as free-text words in simple or multiple combinations. The terms were combined with the Boolean operators "OR" and "AND." The detailed search protocol for each database is displayed in File S1.

The search results obtained from all three databases were imported into a reference management software (EndNote X9, Thomson Reuter), and possible duplicates were eliminated.

2.5 | Eligibility criteria

2.5.1 | Inclusion criteria

- Human trials investigating ceramic implants with all-ceramic prosthetic suprastructures
- Clinical studies including randomized controlled clinical trials, controlled studies, prospective cohort trials, prospective case series, and retrospective studies
- Peer-reviewed journals in the English language
- Studies with a minimum of 12 months or more of mean follow-up time of loading
- Case series with 10 or more patients
- Clinical examination at follow-up visits.

2.5.2 | Exclusion criteria

- Case reports, poster abstracts, interviews, or protocols
- *In vitro* and animal studies
- Studies with the same sample (most recent/most complete was considered)
- Studies on removable implant-supported restorations and long-span FDPs (more than three-units)
- Studies not reporting detailed prosthetic suprastructures
- Studies published in a language other than English
- Studies not meeting the inclusion criteria.

2.6 | Screening and selection of the studies

Two authors (FS and MB) independently evaluated the titles and abstracts derived from the initial search for eligibility, referring to the inclusion and exclusion criteria. If any titles or abstracts did not provide sufficient information regarding eligibility, the full-text reports were obtained. Authors FS and MB again independently performed a full-text analysis by assessing the "Material and Methods," "Results," and "Discussion" sections and then double-checked. If the clinical studies selected for full-text analysis were potentially eligible for inclusion but did not provide sufficient information about the outcome of prosthetic reconstruction, the authors were contacted to provide additional data. If no data were available or the author did not respond to the request, the study was excluded. Any disagreement during the screening process was resolved by discussion to achieve consensus.

2.7 | Data extraction

From the included studies, the following parameters were obtained: authors, year of publication, study design, setting, mean observation period, and the number of patients at each evaluated time point. Moreover, the number of implants and reconstructions (SC, FDP) from baseline up to the last follow-up visit, as well as the implant material, implant system, and design (one-piece, two-piece) were recorded.

Additional information such as abutment material, type of retention (cemented, screw-retained), cement used, type of reconstruction (SC, FDP), prosthetic material, and design (monolithic and veneered), and their corresponding brand names were obtained.

The survival rates of the implants and reconstructions as well as any type of complications at the reconstruction level (abutment and framework/bulk-fracture, chipping, occlusal roughness loss of retention, biological complications related to prosthetic outcomes), and patient-related outcome measurements (PROMs) were analyzed. Biological factors on the implant level, such as the occurrence of mucositis and peri-implantitis, were not addressed. Authors were contacted by email in case of doubt or if insufficient data were provided.

2.8 | Risk of bias analysis

A quality assessment of all the included studies was independently evaluated by FS and MB. The Cochrane Collaboration tool for assessing the risk of bias (Higgins et al., 2011) was used for randomized controlled clinical trials (RCTs) and the Newcastle-Ottawa Scale (NOS) (http://www.ohri.ca/programs/clinical_epidemiology/oxford.asp) for prospective observational investigations.

2.9 | Statistical analysis

2.9.1 | Screening process

Inter-rater reliability was evaluated after the title and abstract screening and after full-text analyses and assessed by Cohen's

Kappa using the statistical software R (R Core Team, 2019) and the package irr (Gamer et al., 2012).

2.9.2 | Survival rate of the implants, reconstructions, and chipping rate

Survival of the implant and reconstruction was defined as remaining *in situ* with or without any modifications at the evaluated follow-up time point. If a reconstruction had to be replaced directly after the follow-up examination for any reason, it was counted as a non-survivor. The baseline survival rate of reconstructions and chipping rate were defined as prosthetic insertion. Reconstruction, which could not be evaluated as the patient did not present or due to implant loss, was counted as a drop-out and not as non-survival. Survival rates of implants and reconstructions, respectively, were expressed as proportions by dividing the number of surviving entities by the total number of evaluated entities at the respective time points (survived implants/total implants at risk at specific time points and survived reconstructions/total reconstructions at risk at specific time points, respectively).

Any type of ceramic fracture or chipping was counted without consideration of its extent. The chipping rates were expressed as proportions: chipped reconstructions/total reconstructions at risk at each time point.

The studies were subdivided into three groups: monolithic lithium disilicate SCs (SC.LS2.mono), veneered zirconia SCs (SC. ZrO2. ven), and veneered zirconia FDPs (FDP. ZrO2.ven). Random effects meta-analyses were performed for each endpoint (survival rates of implants, survival rates of prosthetic reconstructions, and chipping rates) after 1, 2, and 5 years of observation time, respectively. Owing to the proportional nature of the data, the Freeman–Tukey double arcsine transformation was used, and Clopper–Pearson confidence intervals were calculated for individual studies. The inverse variance method was used for pooling, and the restricted maximum-likelihood estimator was used to assess between-study variance. Pooled estimates were calculated for each endpoint and each group separately. Moreover, an overall estimate across groups was calculated for the 5-year data, where necessary. All analyses and plots were computed with the statistical software R (R Core Team, 2019), including the packages meta (Balduzzi et al., 2019) and metafor (Viechtbauer, 2010).

3 | RESULTS

The initial electronic search in the three online databases identified a total of 1,403 references (Medline [OVID]: 479, Cochrane [CENTRAL]: 62, and EMBASE: 862) (Figure 1). Of these, 353 duplicates were eliminated, resulting in the titles and abstracts of 1,050 references being screened. After independent evaluation, both raters agreed to exclude 1,004 references at this stage (Cohen's kappa =0.87). The remaining 46 publications were supplemented by an additional nine publications obtained from hand search, resulting in a total of 55 studies for full-text analysis. Subsequently, 47 publications were excluded (Cohen's kappa =1). Eight studies fulfilled the eligibility criteria and were included in the final qualitative and quantitative analyses.

Early studies reporting on the outcome of prototype ceramic implants made of aluminum oxide had to be excluded owing to

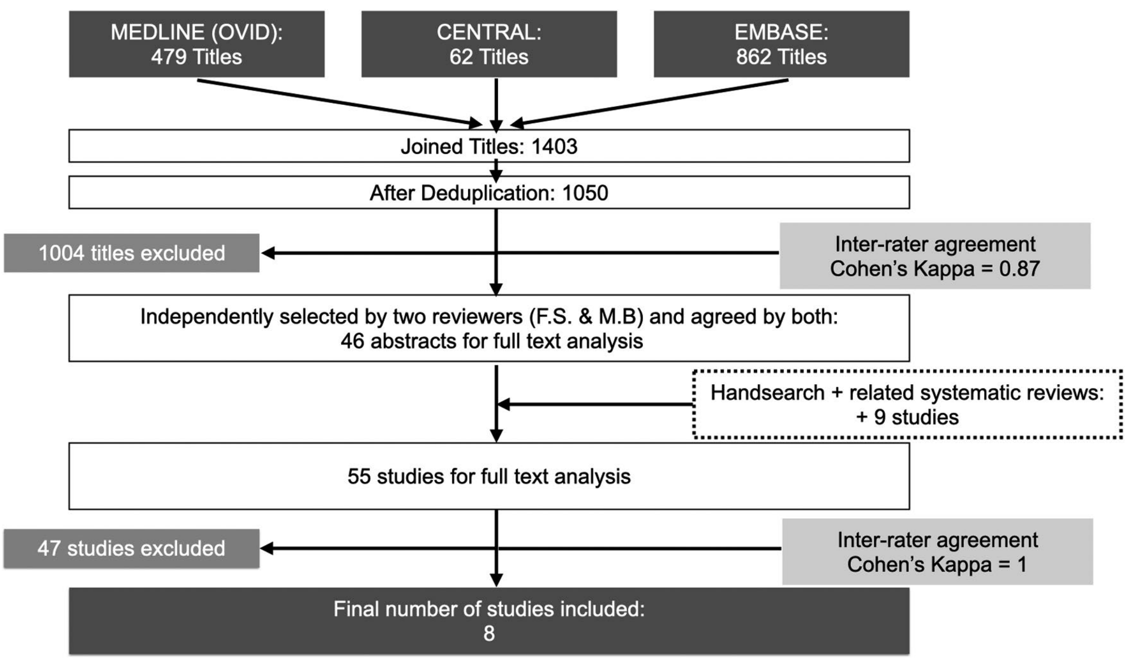

FIGURE 1 Flowchart of the search strategy

TABLE 1 Study characteristics, type of reconstruction, and mean observation time of the included studies

	Authors	Year	Study design	Comparison	Setting	Type of reconstruction	Time from implantation to final reconstruction	Mean observation period of final reconstruction
1	Cannizzaro, Torchio, Felice, Leone, Esposito	2010	RCT	Immediately loaded vs. delayed loaded	Private practices	SC	4–5 months	12 months
2	Cionca, Müller, Mombelli	2015	Prospective cohort	-	University	SC	6.3 ± 2.6 months	18.3 ± 5.7 months
3a)	Spies, Stampf, Kohal	2015	Prospective cohort	-	University	SC	2.8 ± 0.9 months (mandible); 4.4 ± 1.4 months (maxilla)	58.2 months
3b)	Spies, Stampf, Kohal	2015	Prospective cohort	-	University	FDP	2.8 ± 0.9 months (mandible); 4.4 ± 1.4 months (maxilla)	58.2 months
4	Becker, John, Becker, Mainusch, Diedrichs, Schwarz	2017	Prospective cohort	-	University	SC	2.3 months (mandible); 2.8 months (maxilla)	25.5 ± 5.8 months
5	Spies, Pieralli, Vach, Kohal	2017	Prospective cohort	-	University	SC	6.0 ± 2.3 months	55.2 ± 4.2 months
6a)	Spies, Balmer, Jung, Sailer, Vach, Kohal	2019	Prospective cohort	-	University	SC	5.9 ± 4.4 months (mandible); 6.4 ± 2.8 month (maxilla)	61.0 ± 1.4 months
6b)	Spies, Balmer, Jung, Sailer, Vach, Kohal	2019	Prospective cohort	-	University	FDP	5.9 ± 4.4 months (mandible); 6.4 ± 2.8 month (maxilla)	61.0 ± 1.4 months
7	Koller, Steyer, Theisen, Stagnell, Jakse, Payer	2020	RCT	Zirconia vs. titanium implants	University	SC	4 months (mandible); 6 months (maxilla)	80.9 ± 5.5 months
8	Spies, Witkowski, Vach, Kohal	2018	Prospective case series	-	University	FDP	8.2 months	53.6 ± 3.1 months

Abbreviations: FDP, fixed dental prostheses; RCT, randomized controlled trial; SC, single crown.

TABLE 2 Detailed information on the implants, abutments, and reconstructions of the included studies

	Single crowns					
		Implant			Abutment	
	Authors (year)	System	Material	Design	Material	Connection to implant
1	Cannizzaro et al. (2010)	Z-Look3 (Z-Systems)	Zirconia (Y-TZP)	One-piece	-	-
2	Cionca et al. (2015)	ZERAMEX T Implant System (Dentalpoint AG)	Zirconia (ATZ)	Two-piece	Zirconia (ATZ, Metoxit)	Cemented (Panavia F, Kuraray)
3a)	Spies et al. (2015)	ZiUnite (Nobel Biocare)	Zirconia (Y-TZP)	One-piece	-	-
4	Becker et al. (2017)	ZV3 (Zircon Vision GmbH)	Zirconia (Y-TZP)	Two-piece	Fiber glass (ZV3, Zircon Vision GmbH)	Cemented (Panavia F 2.0, Kuraray)
5	Spies et al. (2017)	Ziraldent FR1 (Metoxit AG)	Zirconia (ATZ)	One-piece	-	-
6a)	Spies et al. (2019)	Ceramic implant (vitaclinical, VITA Zahnfabrik)	Zirconia (Y-TZP)	One-piece	-	-
7	Koller et al. (2020)	Ziterion vario Z (Ziterion GmbH)	Zirconia (Y-TZP)	Two-piece	Zirconia (Ziterion)	Cemented (Multilink Automix, Ivoclar Vivadent)
Fixed dental prostheses						
		Implant			**Abutment**	
	Authors	**System**	**Material**	**Design**	**Material**	**Connection to implant**
3b)	Spies et al. (2015)	ZiUnite (Nobel Biocare)	Zirconia (Y-TZP)	One-piece	-	-
8	Spies, Witkowski, et al. (2018)	Ziraldent FR1 (Metoxit AG)	Zirconia (ATZ)	One-piece	-	-
6b)	Spies et al. (2019)	Ceramic implant (vitaclinical, VITA Zahnfabrik)	Zirconia (Y-TZP)	One-piece	-	-

language restriction and/or inappropriate study design. All excluded studies after full-text analysis and individual reasons for exclusion are listed in the reference list as "excluded studies" (File S2).

3.1 | Study characteristics (Tables 1 and 2)

A total of eight studies (Becker et al., 2017; Cannizzaro et al., 2010; Cionca et al., 2015; Koller et al., 2020; Spies et al., 2015, 2017, 2018, 2019) were included in the systematic review and meta-analysis (Tables 1 and 2). Five of them reported on ceramic implant-supported SCs, one on ceramic implant-supported FDPs, and two on both. Five of the included studies were prospective clinical cohort investigations, two were RCTs, and one was a case series. None of the studies had a control group on the level of the suprastructure, consisting of well-documented porcelain fused to metal reconstructions. One RCT used titanium implants as a control group (Koller et al., 2020), whereby only the zirconia implant arm was included for analysis. Another RCT compared immediate loading vs. non-immediate loading of the same zirconia implant (Cannizzaro et al., 2010), where both treatment arms were included. The studies were published between 2010 and 2020 and reported on the mean observation time of reconstructions between 12.0 and 80.9 months.

The eight studies included a total of 334 patients and 408 ceramic implants. Overall, 338 reconstructions (287 SCs and 51 FDPs) were inserted and evaluated.

All applied materials of the included studies at the implant level, abutments, and reconstructions are listed in detail in Table 2. The bulk material of all included implants was either yttria-stabilized tetragonal zirconia or alumina-toughened zirconia.

Five studies reported on a one-piece implant design and three on a two-piece implant design with a separate abutment (Becker et al.,

Reconstruction				
Core	**Design**	**Veneering material**	**Retention**	**Type of cement**
Lithium disilicate (IPS e.max, Ivoclar Vivadent)	Monolithic	-	Cemented	Adhesive (SpeedCem, Ivoclar Vivadent)
Lithium disilicate (IPS e.max Press, Ivoclar Vivadent)	Monolithic	-	Cemented	Adhesive (Panavia F, Kuraray)
Zirconia (Procera Zirconia, Nobel Biocare)	Veneered (hand-layering)	Silicate ceramic (NobelRondoTM Zirconia, Nobel Biocare)	Cemented	Conventional (Ketac Cem, 3M Espe)
Lithium disilicate (IPS e.max, Ivoclar Vivadent)	Monolithic	-	Cemented	Adhesive (Panavia F2.0, Kuraray)
Lithium disilicate (IPS e.max CAD LT, Ivoclar Vivadent)	Monolithic	-	Cemented	Adhesive (Multilink Automix, Ivoclar Vivadent)
Zirconia (Y-TZP) (In-ceram YZ, VITA Zahnfabrik)	Veneered (hand-layering)	Leucite-reinforced feldspathic ceramic (VM9, VITA Zahnfabrik)	Cemented	Adhesive (RelyX Unicem Aplicap, 3M Espe)
Lithium disilicate (IPS e.max CAD, Ivoclar Vivadent)	Monolithic	-	Cemented	Adhesive (Multilink Automix; Ivoclar Vivadent)

Reconstruction				
Core	**Design**	**Veneering material**	**Retention**	**Type of cement**
Zirconia (Procera Zirconia, Nobel Biocare)	Veneered (hand-layering)	Silicate ceramic (NobelRondoTM Zirconia, Nobel Biocare)	Cemented	Conventional (Ketac Cem, 3M Espe)
Zirconia (IPS e.max ZirCAD, Ivoclar Vivadent)	Veneered (overpressed)	Fluor-apatite veneering ceramic (IPS emax ZirPress, Ivoclar Vivadent)	Cemented	Adhesive (Multilink Automix, Ivoclar Vivadent)
Zirconia (Y-TZP) (In-ceram YZ, VITA Zahnfabrik)	Veneered (hand-layering)	Leucite-reinforced feldspathic ceramic (VM9, VITA Zahnfabrik)	Cemented	Adhesive (RelyX Unicem Aplicap, 3M Espe)

2017; Cionca et al., 2015; Koller et al., 2020). The abutments consisted of zirconia or fiberglass and were all adhesively cemented to the implant body. None of the studies reported on screw-retained reconstructions.

All included studies used either monolithic LS2 or veneered zirconia as reconstruction materials. No other ceramic material configurations were used. For SCs, five studies used monolithic LS2 (IPS. e.max Press/IPS. e.max CAD, Ivoclar Vivadent, Schaan, Liechtenstein) (Becker et al., 2017; Cannizzaro et al., 2010; Cionca et al., 2015; Koller et al., 2020; Spies et al., 2017) and two studies, hand-layered, veneered zirconia (Spies et al., 2015, 2019). Implants with a one-piece design were restored with different ceramic configurations, while implants with a two-piece design were exclusively restored with monolithic LS2 SCs. For all studies reporting on FDPs, the core material was zirconia, subsequently veneered by hand-layering (Spies et al., 2015, 2019) or overpressing (Spies Witkowski et al., 2018) with different veneering ceramic materials.

The reconstructions in all studies were adhesively cemented with a single exception, where a conventional glass ionomer cement was used (Spies et al., 2015).

3.2 | Quality assessment (Tables 3a, b)

The methodological quality analyses of the two identified RCTs (Cannizzaro et al., 2010; Koller et al., 2020) were performed using the "Cochrane Collaboration's tool for assessing the risk of bias in randomized trials (Table 3a)." Selection bias, with random sequence generation and allocation concealment, was performed in both studies (computer-generated/web-based); therefore, this was rated as a low risk of bias. A potential performance bias owing to incomplete or impossible blinding of the treating dentists could be observed in both trials. Moreover, both RCTs received industrial support and, therefore, there might be a possible conflict of interest, leading to a high risk of bias rating. The quality assessments for both RCTs are listed in Table 3a.

"Newcastle-Ottawa Scale" was used to evaluate the qualitative assessment for prospective observational studies (Table 3b). All six cohort trials were rated with a moderate methodological quality (NOS star rating: 5–6/9) due to the insufficient selection of controls and comparability.

3.3 | Implant survival (Table 4; Figure 2a–c)

Meta-analyses with groups for surviving implant proportion were performed after 1, 2, and 5 years (Figure 2a–c) (Table 4). Of the initially 408 placed implants, 62 were lost (16.0%), and 21 were counted as dropped-out. Before prosthetic insertion, 18 implants were lost, and one drop-out was reported. Therefore, 389 implants were restored with final restorations. Forty-four implant losses and 20 drop-outs were reported after loading.

After 5 years, a weighted overall survival of 94% (95% confidence interval [CI]: 82%; 100%) was calculated. However, there was considerable residual heterogeneity ($I^2 = 92\%$, $p < .01$). The estimated survival of implants after 5 years ranged between 62% and 100%.

Neither the type of reconstruction (SC. ZrO2.ven vs. FDP. ZrO2. ven) nor the reconstruction material (SC. ZrO2.ven vs. SC.LS2.mono) appeared to influence implant survival at any of the time points evaluated. Studies with two-piece implants were only present in the group with monolithic LS2 SCs. In this group, similar survival rates for one- and two-piece implants were reported. Overall, no implant fracture was observed.

3.4 | Survival of reconstructions (Table 4; Figure 3a–c)

Meta-analyses with groups for surviving reconstructions proportion were performed after 1, 2, and 5 years (Figure 3a–c) (Table 4). At baseline, 338 reconstructions (287 SCs and 51 FDPs) were inserted.

In all of the eight included studies, 20 reconstructions (17 SCs and three FDPs) were counted as non-survivors at different time points. The reasons for the loss of reconstructions were highly specific to each group. In veneered zirconia reconstructions, the severe chip of fractures of the veneering ceramic led to catastrophic failure ($n = 15$). In two-piece implants restored with monolithic LS2 crowns, two abutment fractures and one coherent fracture of the abutment-crown complex caused the failure. One-piece implants restored with monolithic LS2 crowns demonstrated one bulk-fracture and one biological complication (excessive gingival recession).

After 1 and 2 years, the survival rates of all evaluated groups were between 98% and 100%. After 5 years, a weighted overall survival of 95% (95% CI: 87%–100%) was calculated. A moderate residual heterogeneity was observed ($I^2 = 66\%$, $p = .02$). At the study level, the survival of implants after 5 years ranged between 77% and 100%. For veneered zirconia reconstructions, both FDP (94%

TABLE 3A Results of the methodological quality assessment

SCs	Selection bias		Performance bias	Detection bias	Attrition bias	Reporting bias	Other bias	
	Random sequence generation	Allocation concealment	Blinding of participants and personnel	Blinding of outcome assessment	Incomplete outcome data	Selective reporting	Free of other sources of bias	Industrial support
Cannizzaro et al. (2010)[a]	Low	Low	Unclear	Unclear	Low	Low	Unclear	Z-Systems
Koller et al. (2020)[b]	Low	Low	High	High	Low	Low	High	Ziterion

Note: Cochrane Collaboration's tool for assessing the risk of bias in randomized trials was applied.

Abbreviations: RCT, randomized controlled trial; SC, single crown.

[a]RCT of immediate vs. delayed loading.

[b]RCT of zirconia vs. titanium implants.

TABLE 3B "Newcastle-Ottawa Scale" (NOS) methodological quality assessment of cohort studies

	Selection				Comparability		Outcome			Score
	Representativeness of exposed cohort/ cases	Selection of controls	Ascertainment of exposure	Demonstration outcome of interest not present at start of study	Age/Sex	Jaw/Location/ Opposing dentition (2 of 3)	Assessment of outcome	Follow-up long enough	Adequacy of follow-up	Total
SCs										
Cionca et al., (2015)	*	-	*	*	?	-	*	?	*	5
Spies et al., (2015)	*	-	*	*	?	-	*	*	*	6
Becker et al., (2017)	*	-	*	*	?	-	*	*	*	6
Spies et al., (2017)	*	-	*	*	?	?	*	*	*	6
Spies et al., (2019)	*	-	*	*	?	-	*	*	*	6

	Selection				Comparability		Outcome			Score
	Representativeness of exposed cohort/ cases	Selection of controls	Ascertainment of exposure	Demonstration outcome of interest not present at start of study	Age/ Sex	Jaw/Location/ Opposing dentition (2 of 3)	Assessment of outcome	Follow-up long enough	Adequacy of follow-up	Total
FDPs										
Spies et al., (2015)	*	-	*	*	-	-	*	*	*	6
Spies Witkowski, et al. (2018)	*	-	*	*	?	-	*	*	*	6
Spies et al., (2019)	*	-	*	*	-	-	*	*	*	6

Abbreviations: FDP, fixed dental prostheses; SC, single crown.

[95% CI: 81%–100%] and SCs 89% [95% CI: 62%–100%] demonstrated similar survival rates. For SCs, a lower survival rate could be observed for veneered zirconia 89% (95% CI: 62%–100%) than for monolithic LS2 100% (95% CI: 95%–100%).

Only in the group of monolithic LS2 reconstructions, both one- and two-piece implant systems were present, and no difference regarding prosthetic survival rates was detected.

3.5 | Abutment fracture (Tables 2 and 4)

Abutment fractures were solely reported in studies with two-piece implant designs and monolithic LS2 crowns (Tables 2 and 4). Three failures were reported. In two cases, only the zirconia abutments fractured (Cionca et al., 2015), while with one fiberglass abutment, the corresponding crown fractured simultaneously (Becker et al., 2017). However, in all cases, a new crown-abutment complex could be inserted.

3.6 | Framework/bulk-fracture (Tables 2 and 4)

Only one study reported a single bulk-fracture of a monolithic LS2 crown on a one-piece implant 5 months post-loading (Cannizzaro et al., 2010) (Tables 2 and 4). This crown was adhesively inserted with a composite cement.

3.7 | Chipping (Table 5, Figure 4a–c)

Among all possible technical complications, ceramic fracture of the reconstructions (chipping) was the most evaluated and most precisely reported technical factor (Table 5, Figure 4a–c). Of the eight included studies, three (Spies Witkowski, et al., 2018; Spies et al., 2017, 2019) evaluated technical success according to the modified United States Public Health Care (USPHS) criteria (Cvar & Ryge, 2005), four (Cannizzaro et al., 2010; Cionca et al., 2015; Koller et al., 2020; Spies et al., 2015) reported only the occurrence of any chipped reconstructions, and one (Becker et al., 2017) did not provide any information on chipping incidence.

Meta-analyses for chipping rates of reconstructions were performed after 1, 2, and 5 years (Figure 4a–c).

After 1 year, no chipping was reported in studies with monolithic LS2 crowns (0% [95% CI: 0%–3%]). Veneered zirconia SCs (12% [95% CI: 4%–24%]) and FDPs (25% [95% CI: 12%–41%]) demonstrated significantly higher chippings rates. Between zirconia SCs and FDPs, the chipping rate seemingly did not differ.

After 2 years, the chipping proportion increased only in studies with veneered zirconia reconstructions, while no chipping was reported for monolithic LS2 (0% [95% CI: 0%–5%]). Considerable differences were detected between the groups. The chipping proportion was higher for veneered FDPs (46% [95% CI: 30%–63%]) than veneered SCs (20% [95% CI: 13%–29%]).

Up to the 5-year follow-up, the chipping proportion continued to increase substantially for veneered zirconia SCs (38% [95% CI: 24%–54%]) and even more for FDPs (57% [95% CI: 38%–76%]). Only one case of chipping fracture was reported for monolithic LS2, resulting in a significantly lower chipping proportion (2% [95% CI: 0%–11%]) than the other two groups.

For monolithic LS2 crowns, no difference in terms of the chipping proportions could be identified between one- or two-piece implant designs overall at the evaluated time points.

3.8 | Occlusal roughness

Occlusal roughness was reported according to the modified USPHS criteria in three studies with different reconstruction materials after 5 years. Irrespective of the choice of material, all studies observed a significant increase in surface roughness over time for monolithic LS2 SCs (Spies et al., 2017), for hand-layered zirconia SCs (Spies et al., 2019), and overpressed zirconia FDPs (Spies Witkowski, et al., 2018).

3.9 | Loss of retention

Only one decementation of an adhesively seated monolithic LS2 SC on a one-piece implant without specification of time to event was reported (Cannizzaro et al., 2010). Six studies (Becker et al., 2017; Koller et al., 2020; Spies Witkowski, et al., 2018; Spies et al., 2015, 2017, 2019) reported no loss of retention of any reconstruction during the entire observation period.

3.10 | Biological complications related to prosthetic outcomes (Table 4)

A single biological event on a one-piece implant affecting prosthetic outcomes has been reported (Cannizzaro et al., 2010) (Table 4). Four months after loading, inflammation of the peri-implant tissue occurred, leading to a recession after debridement and the subsequent renewal of the SC.

3.11 | PROMs

Patient-related outcome measurements (function, esthetic/appearance, sense, speech, and self-esteem) were evaluated in three studies with a visual analog scale (ranging from 0 and 100%) over 5 years (Spies Witkowski, et al., 2018; Spies et al., 2017, 2019). All three studies reported very similar patterns of PROM changes over the observed period. A significant increase in PROMs could be observed between pre-treatment and prosthetic delivery. After that, satisfaction remained stable at a high level until the end of the study follow-up. However, the occurrence of technical complications did not correlate with patient satisfaction.

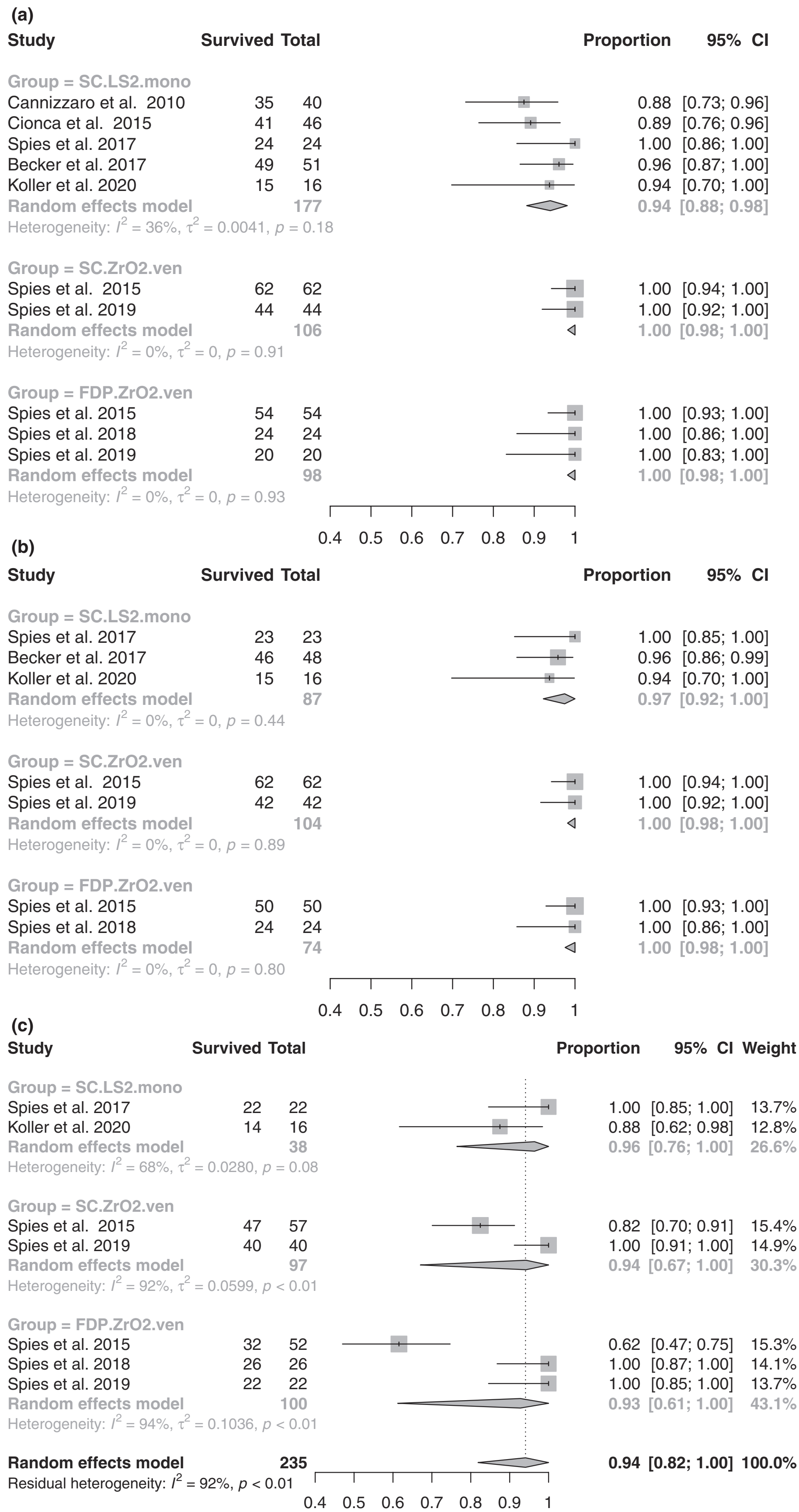

FIGURE 2 (a) Forest plots demonstrating the implant survival rate after 1 year, proportions, and 95% confidence interval [CI] (SC =single crown, FDP =fixed dental prosthesis). (b) Forest plots demonstrating the implant survival rate after 2 years, proportions, and 95% CI. (c) Forest plots demonstrating the implant survival rate after 5 years, proportions, and 95% CI

TABLE 4 The table illustrates the number of evaluated patients and drop-outs as well as numbers of survived, lost, and dropped-out implants and reconstruction at implant placement, baseline, and follow-up visits

Survival of implants and reconstructions	Implantation	Baseline	6 MT	1 year	2 years	3 years
Cionca et al. (2015)						
n patients (evaluated/dropped-out)	32	31	n.r.	(29/2)		
n implants (survived/lost/dropped-out)	49	48	n.r.	(41/5/2)		
n crowns (survived/lost/dropped-out)	x	48	n.r.	(39/2/7)		
Becker et al. (2017)						
n patients (evaluated/dropped-out)	60	52	(52/0)	(51/1)	(48/4)	
n implants (survived/lost/dropped-out)	60	52	(52/0/0)	(49/2/1)	(46/2/4)	
n crowns (survived/lost/dropped-out)	x	52	(52/0/0)	(49/0/3)	(45/1/6)	
Koller et al. (2020)						
n patients (evaluated/dropped-out)	12	12	(12/0)	(12/0)	n.r.	(11/1)
n implants (survived/lost/dropped-out)	16	16	(16/0/0)	(15/1/0)	(15/1/0)	(14/2/0)
n crowns (survived/lost/dropped-out)	x	16	(16/0/0)	(15/0/1)	(15/0/1)	(14/0/2)
Cannizzaro et al. (2010)						
n patients (evaluated/dropped-out)	40	40	n.r.	(40/0)		
n implants (survived/lost/dropped-out)	40	40	n.r.	(35/5/0)		
n crowns (survived/lost/dropped-out)	x	40	n.r.	(33/2/5)		
Spies et al. (2017)						
n patients (evaluated/dropped-out)	27	24	n.r	(24/0)	(23/1)	(23/1)
n implants (survived/lost/dropped-out)	27	24	n.r	(24/0/0)	(23/0/1)	(23/0/1)
n crowns (survived/lost/dropped-out)	x	24	n.r.	(24/0/0)	(23/0/1)	(23/0/1)
Spies et al. (2015)						
n patients (evaluated/dropped-out)	65	62	n.r.	(61/1)	(61/1)	(60/2)
n implants (survived/lost/dropped-out)	66	63	n.r.	(62/0/1)	(62/0/1)	(58/3/2)
n crowns (survived/lost/dropped-out)	x	63	n.r.	(62/0/1)	(62/0/1)	(58/0/5)
Spies et al. (2019)						
n patients (evaluated/dropped-out)	46	44	(44/0)	(44/0)	(42/2)	(40/4)
n implants (survived/lost/dropped-out)	46	44	(44/0/0)	(44/0/0)	(42/0/2)	(40/0/4)
n crowns (survived/lost/dropped-out)	x	44	(44/0/0)	(44/0/0)	(42/0/2)	(40/0/4)
Spies et al. (2015)						
n patients (evaluated/dropped-out)	28	27	n.r.	(27/0)	(25/2)	(25/2)
n implants (survived/lost/dropped-out)	56	54	n.r.	(54/0/0)	(50/0/4)	(50/0/4)
n FDPs (survived/lost/dropped-out)	28	27	n.r.	(27/0/0)	(25/0/2)	(25/0/2)
Spies, Witkowski, et al. (2018)						
n patients (evaluated/dropped-out)	13	13	n.r.	(12/1)	(12/1)	(13/0)
n implants (survived/lost/dropped-out)	26	26	n.r.	(24/0/2)	(24/0/2)	(26/0/0)
n FDPs (survived/lost/dropped-out)	13	13	n.r.	(12/0/1)	(12/0/1)	(13/0/0)
Spies et al. (2019)						
n patients (evaluated/dropped-out)	11	11	(11/0)	(10/1)	n.r.	(11/0)
n implants (survived/lost/dropped-out)	22	22	(22/0/0)	(20/0/2)	n.r.	(22/0/0)
n FDPs (survived/lost/dropped-out)		11	(9/2/0)	(8/2/1)	n.r.	(9/2/0)

Note: The baseline for the survival analyses of the reconstructions is defined as prosthetic insertion. Reconstruction of a lost implant is counted as a drop-out.

Abbreviations: FDP, fixed dental prostheses; SC, single crown.

[a]In case of a loss of one of the two supporting implants, both were counted as lost.

4 years	5 years	Reasons for lost reconstructions (*n*/% of all losses)	SC/FDP	Monolithic/ Veneered	Zirconia/lithium disilicate	One-piece/ two-piece
		Abutment fractures (2/100%)	SC	Monolithic	Lithium disilicate	Two-piece
		Coherent fracture of abutment -crown complex (1/100%)	SC	Monolithic	Lithium disilicate	Two-piece
n.r. n.r. n.r.	(11/1) (14/2/0) (14/0/2)	-	SC	Monolithic	Lithium disilicate	Two-piece
		Bulk-fracture (1/50%); Biological reason (1/50%)	SC	Monolithic	Lithium disilicate	One-piece
(22/2) (22/0/2) (22/0/2)	(22/2) (22/0/2) (22/0/2)	-	SC	Monolithic	Lithium disilicate	One-piece
(59/3) (54/5/4) 54/0/9)	(57/5) (47/10/6) (36/11/16)	Severe chipping of veneering ceramic (1/100%)	SC	Veneered	Zirconia	One-piece
(40/4) (40/0/4) (40/0/4)	(40/4) (40/0/4) (39/1/4)	Severe chipping of veneering ceramic (1/100%)	SC	Veneered	Zirconia	One-piece
(26/1) (44/8[a]/2) (22/0/5)	(26/1) (32/20[a]/2) (15/1/11)	Severe chipping of veneering ceramic (1/100%)	FDP	Veneered	Zirconia	One-piece
(13/0) (26/0/0) (13/0/0)	(13/0) (26/0/0) (13/0/0)	-	FDP	Veneered	Zirconia	One-piece
n.r. n.r. n.r.	(10/11) (22/0/0) (9/2/0)	Severe chipping of veneering ceramic (2/100%)	FDP	Veneered	Zirconia	One-piece

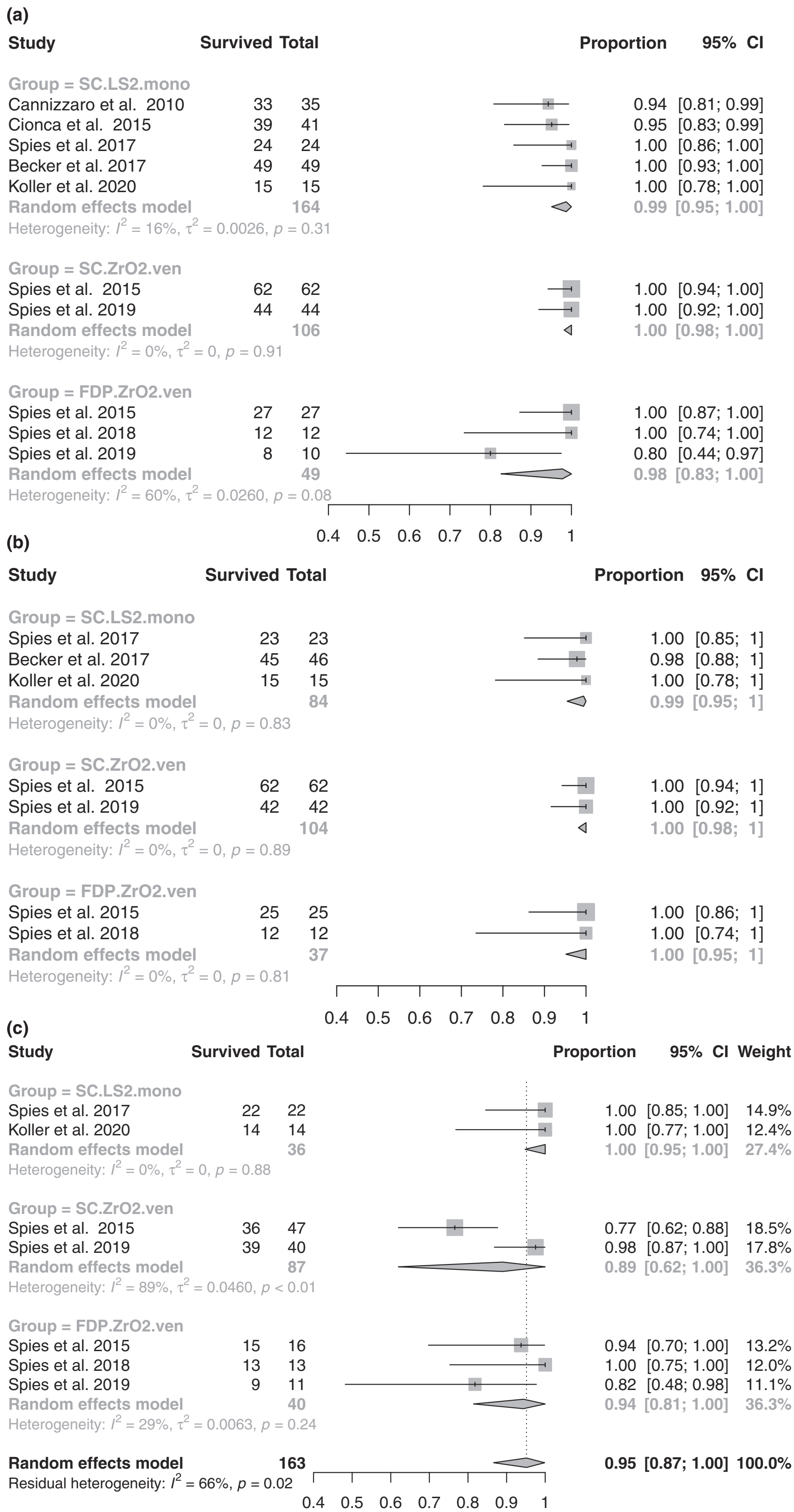

FIGURE 3 (a) Forest plots demonstrating the reconstruction survival rate after 1 year, proportions, 95% confidence interval [CI], and overall weighted survival (SC =single crown, FDP =fixed dental prosthesis). (b) Forest plots demonstrating the reconstruction survival rate after 2 years, proportions, 95% CI, and overall weighted survival. (c) Forest plots demonstrating the reconstruction survival rate after 5 years, proportions, 95% CI, and overall weighted survival

4 | DISCUSSION

The present systematic review aimed to assess the currently available evidence on the clinical performance of all-ceramic SCs and FDPs supported by ceramic implants.

The estimated survival rate for ceramic implants supporting all-ceramic reconstructions yielded a weighted overall survival of 94% (95% CI: 82%–100%), however, with considerable residual heterogeneity ($I^2 = 92\%$, $p < .01$) after 5 years. However, the current systematic review did not primarily aim to calculate the survival rates of ceramic implants. Nevertheless, the calculated survival rates after 1, 2, and 5 years in the current review are in line with other systematic reviews, which reported the survival rates for zirconia oral implants as 92–98.3% after 1 year (Hashim et al., 2016; Pieralli et al., 2017; Roehling et al., 2018) and 97.2% (Roehling et al., 2018) after 2 years and 95% between 1 and 7 years (Haro Adánez et al., 2018).

The survival rate of the implants between the different reconstruction materials (ZrO2 vs. LS2), types of reconstruction (SCs vs. FDPs), and implant design (one-piece vs. two-piece) did not appear to differ between the groups. It may be assumed that the superstructure has no direct influence on the survival of the implant. Instead, individual studies with lower implant survival rates were observed in each group. Studies (Cannizzaro et al., 2010; Cionca et al., 2015; Koller et al., 2020; Spies et al., 2015) with no longer commercially available ceramic implants showed a relatively high implant failure rate (Roehling et al., 2018).

The performed meta-analysis calculated an overall weighted 5-year survival rate of 95% (95% CI: 87%–100%) at the reconstruction level. This result is consistent with the 5-year survival estimates reported in recent systematic reviews of 93%–97.6% for implant-supported all-ceramic SCs (Pjetursson et al., 2018; Rabel et al., 2018) and 93%–98.3% for implant-supported all-ceramic FDPs (Pieralli et al., 2018; Sailer et al., 2018). Although catastrophic failures could be observed rarely, a specific pattern for each group could be identified. In SC. ZrO2.ven and FDP. ZrO2.ven only major chippings, in SC.LS2.mono (two-piece implants) fractures of the abutments and in SC.LS2.mono (one-piece implants), a monolithic bulk-fracture led to the loss of the reconstruction. There is probably a specific weak point in each implant-restoration complex. However, no study with a two-piece design and veneered reconstruction could be included, leaving it unclear whether the abutment or the veneering material represented the weakest link. However, no implant body fracture could be observed. Therefore, it seems that the prosthetic components are more susceptible to technical failures than ceramic implants.

As technical complications provide a deeper insight into prosthetic events, additional meta-analyses were performed for chipping rates over time. By analyzing chipping events after 1, 2, and 5 years (Figure 4a–c), a stronger increase in chipping proportions for veneered zirconia FDPs than veneered zirconia SCs could be observed over time. This resulted in 5-year chipping proportions of 38% for SC. ZrO2.ven and 57% for FDP. ZrO2.ven.

Titanium implant-supported all-ceramic SCs demonstrated comparatively low chipping rates of 2.8%–9% (Pjetursson et al., 2018; Rabel et al., 2018) after 5 years. For all-ceramic titanium implant-supported FDPs, a 5-year chipping rate of 22.8% was noted (Pieralli et al., 2018). A possible explanation for the much higher veneering delamination rate at ceramic implants than titanium implants might be due to missing bending of stiff zirconia implants, leaving no possibility of depressing the chewing load (Spies et al., 2015). Furthermore, the authors stated that the study was conducted in the early stages of computer-aided design and computer-aided manufacturing technology and therefore, not all technical possibilities, such as an individual anatomical design of the framework, were available (Spies et al., 2015). Most of the investigated implants had a one-piece design, combining the implant body and a relatively small height, often conically designed abutment in a single piece. This might have further led to an uneven force distribution and thus impaired prosthetic restoration longevity. In general, chipping rates of veneered FDPs appear higher for both titanium and ceramic implants than those of SCs and question the concept of veneering implant-supported FDPs (Pieralli et al., 2018; Sailer et al., 2018). Moreover, most implant-borne restorations were inserted in the high-loading posterior area, which also favored chipping events. However, not all studies reported chipping events with a consistent score.

In contrast, the chipping proportion confidence interval of monolithic LS2 in the meta-analyses of the present systematic review was narrow and close to 0%, yielding a 5-year chipping proportion of only 2%. Similar short-term results of monolithic ceramic reconstructions on titanium implants were reported with no chipping events (Gierthmuehlen et al., 2020; Joda et al., 2017; Worni et al., 2017). In general, a clear shift toward monolithic prosthetic treatment concepts can be observed for both titanium and ceramic implants to overcome technical complications such as chip-off fractures (Gierthmuehlen et al., 2020; Joda et al., 2017; Koller et al., 2020; Moscovitch, 2015; Spies et al., 2017; Worni et al., 2017).

Increased occlusal roughness and potential surface irregularities might lead to premature failures and subsequent chip-off fractures, especially in veneered configurations (de Kok et al., 2015; Spies Witkowski, et al., 2018). Nevertheless, an increase in occlusal roughness was also observed for both monolithic and veneered SCs and hence does not seem to be the main reason for the increased chipping incidences. A recently published short-term follow-up study on screw-retained titanium implant-supported monolithic LS2 crowns could also observe an increase in surface roughness after 12 months without chipping incidences (Gierthmuehlen et al., 2020).

As only one SC debonded, decementation and debonding do not seem to be major technical complications of ceramic implants. All-ceramic SCs on titanium implants benefit from adhesive luting compared with conventional cementation protocols with increased fracture strengths (Rabel et al., 2018). *In vitro* studies investigating different cement types confirm the positive effect of resin bonding for all-ceramic restorations on one-piece zirconia implants and might

TABLE 5 The table illustrates the number of reconstructions without any fractures, with chippings and lost reconstructions at baseline and every follow-up visit

Chipping events of reconstructions	Baseline	6 MT	1 year	2 years	3 years	4 years	5 years	SC/ FDP	Monolithic/ Veneered	Zirconia/ Lithium disilicate	One-piece/ two-piece	Type of reporting
Cionca et al. (2015)												
n crowns (no fracture/ chipping/lost)	48	n.r.	n.r.					SC	Monolithic	Lithium disilicate	Two-piece	Occurrence
Becker et al. (2017)												
n crowns (no fracture/ chipping/lost)	52	n.r	n.r	n.r				SC	Monolithic	Lithium disilicate	Two-piece	Not reported
Koller et al. (2020)												
n crowns (no fracture/ chipping/lost)	16	(16/0/0)	(15/0/0)	(15/0/0)	(14/0/0)	(14/0/0)	(14/0/0)	SC	Monolithic	Lithium disilicate	Two-piece	Occurrence
Cannizzaro et al. (2010)												
n crowns (no fracture/ chipping/lost)	40	n.r	(33/0/2)					SC	Monolithic	Lithium disilicate	One-piece	Occurrence
Spies et al. (2017)												
n crowns (no fracture/minor chipping/major chipping/lost)	24	(24/0/0/0)	(24/0/0/0)	(23/0/0/0)	(23/0/0/0)	(22/0/0/0)	(21/1/0/0)	SC	Monolithic	Lithium disilicate	One-piece	USPHS
Spies et al. (2015)												
n crowns (no fracture/ chipping/lost)	63	n.r	(57/5/0)	(50/12/0)	(43/15/0)	(36/18/0)	(25/11/11)	SC	Veneered	Zirconia	One-piece	Occurrence
Spies et al. (2019)												
n crowns (no fracture/minor chipping/major chipping/lost)	44	(39/4/1/0)	(36/7/1/0)	(33/8/1/0)	(26/12/2/0)	(23/14/3/0)	(21/13/5/1)	SC	Veneered	Zirconia	One-piece	USPHS
Spies et al. (2015)												
n FDPS (no fracture/ chipping/lost)	27	n.r	(19/8/0)	(13/12/0)	(11/14/0)	(10/12/5)	(6/9/1)	FDP	Veneered	Zirconia	One-piece	Occurrence
Spies, Witkowski, et al. (2018)												
n FDPs (no fracture/minor chipping/major chipping/lost)	13	(12/0/0/0)	(10/2/0/0)	(7/2/3/0)	(6/4/3/0)	(6/4/3/0)	(6/4/3/0)	FDP	Veneered	Zirconia	One-piece	USPHS
Spies et al. (2019)												
n FDPs (no fracture/ chipping/lost)	11	n.r	n.r	n.r	n.r	n.r	n.r	FDP	Veneered	Zirconia	One-piece	Not reported

Note: When the reconstructions are evaluated according to the modified United States Public Health Care (USPHS) criteria, chippings are categorized as (Alpha: no fracture, Bravo: minor chipping [polishable], Charlie: major chipping [exposing the framework], Delta: fraction/loss of reconstruction).

Abbreviations: FDP, fixed dental prostheses; SC, single crowns.

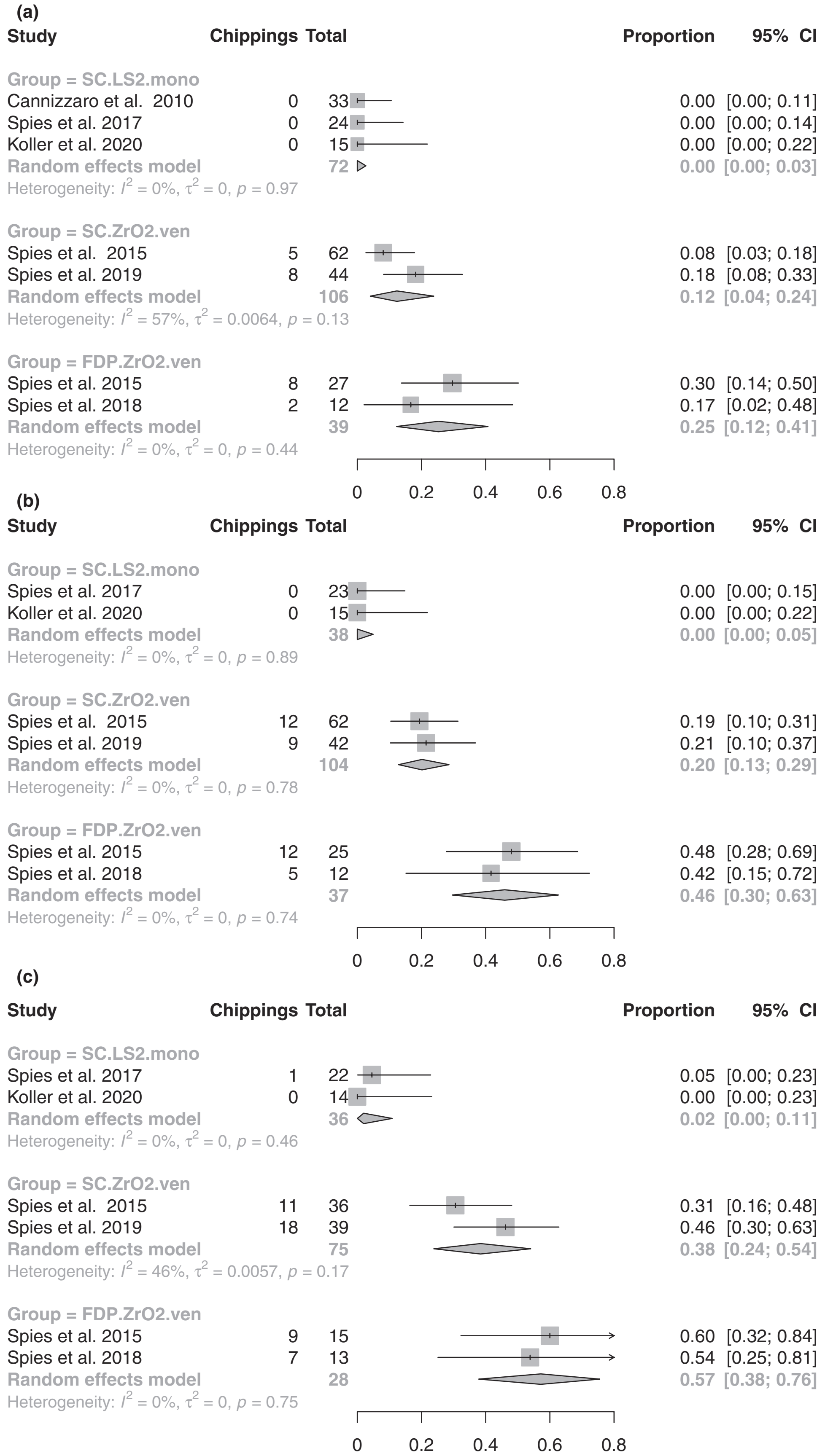

FIGURE 4 (a) Forest plots demonstrating the chipping rate after 1 year, proportions, and a 95% confidence interval [CI] (SC =single crown, FDP =fixed dental prosthesis). (b) Forest plots demonstrating the chipping rate after 2 years, proportions, and 95% CI. (c) Forest plots demonstrating the chipping rate after 5 years, proportions, and 95% CI

further increase survival rates (Nueesch et al., 2019; Rohr et al., 2018). One of the most common risk factors that favor initial inflammation of peri-implant tissue with subsequent bone loss is cement surpluses (Staubli et al., 2017; Wilson, 2009). For reducing and preventing excessive cement remnants, crown venting techniques and pre-cementation devices could show superior *in vitro* results than conventional cementation procedures and are recommended for clinical application (Zaugg et al., 2018).

In the present systematic review, three studies reported PROMs. In these studies, high incidences of technical failures did not impair patient satisfaction. The authors attributed this to a general rehabilitation of posterior support and divergence between dentists' assessments and patient perceptions (Spies Witkowski, et al., 2018).

4.1 | Limitations and future directions

The present findings must be interpreted with caution as the outcomes of this meta-analysis are affected by some shortcomings and might, therefore, only demonstrate tendencies. Eight studies could be identified for final inclusion and meta-analytic modeling. This can lead to a potential distortion and an unusually high impact of a single study on the overall weighted result. Furthermore, the selected studies were mainly published by a single research group with highly skilled and experienced clinicians. Not all of the mentioned studies primarily reported on survival and complications of all-ceramic reconstructions and could not be consistently included across time points. Therefore, a true prosthetic outcome over time is difficult to quantify.

Moreover, none of the clinical trials compared systematically restorations on different implant designs (one-piece vs. two-piece) or different reconstruction materials (e.g., silica-based vs. glass-ceramics vs. resin-matrix-ceramics vs. oxide-ceramics) and designs (monolithic vs. veneered vs. facially veneered).

A potential risk of bias owing to industry support could be found in all of the included studies. Additionally, not all of the investigated zirconia implant systems are currently available in the market, which might compromise some of the present findings (Roehling et al., 2018).

Future long-term comparative studies are required to better understand the prosthodontic-implant complex as a whole.

Until now, favorable screw-retained restorations and associated prevention of cement surpluses were only possible for two-piece titanium implants. The recent introduction of two-piece ceramic oral implants (Janner et al., 2018; Joos et al., 2020; Spies, Fross, et al., 2018; Spies et al., 2016), with a restorative interface allowing screw-retained restorations, might enhance the popularity of ceramic implants as an attractive addendum.

Lately, innovative prosthodontic materials, such as highly translucent zirconia materials with higher yttria contents (4Y-PSZ and 5Y-PSZ) (Zhang & Lawn, 2018), are gaining market share. Moreover, polymer-infiltrated ceramics could be an interesting restorative alternative owing to their dentin-like E-modulus (Swain et al., 2016) and softer nature than the rigid zirconia implant-bone complex (Rohr et al., 2019).

As potential first-line therapies, monolithic all-ceramic reconstructions manufactured from different materials should be further investigated in long-term studies.

5 | CONCLUSION

Within the limitations of this systematic review, all-ceramic SCs and FDPs supported by ceramic implants showed promising survival rates after mid-term observation. However, the high chipping proportions of veneered zirconia SCs and, particularly, FDPs diminish the overall outcome. Monolithic LS2 showed fewer clinical complications. Monolithic reconstructions could be a valid treatment option for ceramic implants, but their mid-to-long-term performance must be further evaluated.

ACKNOWLEDGEMENTS

We are grateful to all responding authors for providing additional information for this review. Open Access funding provided by Universitat Zurich.

CONFLICT OF INTEREST

The authors declare no potential conflicts of interest regarding the authorship and/or publication of this manuscript.

AUTHOR CONTRIBUTION

Frank Akito Spitznagel: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Methodology (equal); Project administration (equal); Validation (equal); Visualization (equal); Writing-original draft (equal); Writing-review & editing (equal). **Marc Balmer:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Methodology (equal); Project administration (equal); Validation (equal); Visualization (equal); Writing-original draft (equal); Writing-review & editing (equal). **Daniel Wiedemeier:** Data curation (equal); Formal analysis (equal); Validation (equal); Visualization (equal); Writing-original draft (equal); Writing-review & editing (equal). **Ronald Ernst Jung:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Methodology (equal); Project administration (equal); Validation (equal); Visualization (equal); Writing-original draft (equal); Writing-review & editing (equal). **Petra Christine Gierthmuehlen:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Methodology (equal); Project administration (equal); Validation (equal); Visualization (equal); Writing-original draft (equal); Writing-review & editing (equal).

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

ORCID

Frank Akito Spitznagel https://orcid.org/0000-0001-5535-2108
Marc Balmer https://orcid.org/0000-0003-0637-8314

Daniel B. Wiedemeier https://orcid.org/0000-0001-8997-700X
Ronald Ernst Jung https://orcid.org/0000-0003-2055-1320
Petra Christine Gierthmuehlen https://orcid.org/0000-0002-4837-2546

REFERENCES

Akobeng, A. K. (2005). Principles of evidence based medicine. *Archives of Disease in Childhood*, *90*(8), 837–840. https://doi.org/10.1136/adc.2005.071761

Balduzzi, S., Rücker, G., & Schwarzer, G. (2019). How to perform a meta-analysis with R: A practical tutorial. *Evidence Based Mental Health*, *22*(4), 153–160. https://doi.org/10.1136/ebmental-2019-300117

Balmer, M., Spies, B. C., Kohal, R. J., Hämmerle, C. H., Vach, K., & Jung, R. E. (2020). Zirconia implants restored with single crowns or fixed dental prostheses: 5-year results of a prospective cohort investigation. *Clinical Oral Implants Research*, *31*(5), 452–462. https://doi.org/10.1111/clr.13581

Becker, J., John, G., Becker, K., Mainusch, S., Diedrichs, G., & Schwarz, F. (2017). Clinical performance of two-piece zirconia implants in the posterior mandible and maxilla: A prospective cohort study over 2 years. *Clinical Oral Implants Research*, *28*(1), 29–35. https://doi.org/10.1111/clr.12610

Cannizzaro, G., Torchio, C., Felice, P., Leone, M., & Esposito, M. (2010). Immediate occlusal versus non-occlusal loading of single zirconia implants. A multicentre pragmatic randomised clinical trial. *European Journal of Oral Implantology*, *3*(2), 111–120.

Cionca, N., Müller, N., & Mombelli, A. (2015). Two-piece zirconia implants supporting all-ceramic crowns: A prospective clinical study. *Clinical Oral Implants Research*, *26*(4), 413–418. https://doi.org/10.1111/clr.12370

Cvar, J. F., & Ryge, G. (2005). Reprint of criteria for the clinical evaluation of dental restorative materials. 1971. *Clinical Oral Investigations*, *9*(4), 215–232.

de Kok, P., Kleverlaan, C. J., de Jager, N., Kuijs, R., & Feilzer, A. J. (2015). Mechanical performance of implant-supported posterior crowns. *Journal of Prosthetic Dentistry*, *114*(1), 59–66. https://doi.org/10.1016/j.prosdent.2014.10.015

Gamer, M., Lemon, J., Fellows, I., & Singh, P. (2012). *irr: Various coefficients of interrater reliability and agreement. R package version 0.84*. Retrieved from https://CRAN.R-project.org/package=irr

Gierthmuehlen, P. C., Berger, L., & Spitznagel, F. A. (2020). Monolithic screw-retained lithium disilicate implant crowns: Preliminary data of a prospective cohort study. *The International Journal of Prosthodontics*, *33*(3), 272–276. https://doi.org/10.11607/ijp.6684

Grassi, F. R., Capogreco, M., Consonni, D., Bilardi, G., Buti, J., & Kalemaj, Z. (2015). Immediate occlusal loading of one-piece zirconia implants: Five-year radiographic and clinical evaluation. *International Journal of Oral and Maxillofacial Implants*, *30*(3), 671–680. https://doi.org/10.11607/jomi.3831

Guess, P. C., Schultheis, S., Bonfante, E. A., Coelho, P. G., Ferencz, J. L., & Silva, N. R. (2011). All-ceramic systems: Laboratory and clinical performance. *Dental Clinics of North America*, *55*(2), 333–352, ix. https://doi.org/10.1016/j.cden.2011.01.005

Haro Adánez, M., Nishihara, H., & Att, W. (2018). A systematic review and meta-analysis on the clinical outcome of zirconia implant-restoration complex. *Journal of Prosthodontic Research*, *62*(4), 397–406. https://doi.org/10.1016/j.jpor.2018.04.007

Hashim, D., Cionca, N., Courvoisier, D. S., & Mombelli, A. (2016). A systematic review of the clinical survival of zirconia implants. *Clinical Oral Investigations*, *20*(7), 1403–1417. https://doi.org/10.1007/s00784-016-1853-9

Higgins, J. P. T., Altman, D. G., Gotzsche, P. C., Juni, P., Moher, D., Oxman, A. D., Savovic, J., Schulz, K. F., Weeks, L., & Sterne, J. A. C. (2011). The cochrane collaboration's tool for assessing risk of bias in randomised trials. *BMJ*, *343*, d5928. https://doi.org/10.1136/bmj.d5928

Janner, S. F. M., Gahlert, M., Bosshardt, D. D., Roehling, S., Milz, S., Higginbottom, F., Buser, D., & Cochran, D. L. (2018). Bone response to functionally loaded, two-piece zirconia implants: A preclinical histometric study. *Clinical Oral Implants Research*, *29*(3), 277–289. https://doi.org/10.1111/clr.13112

Joda, T., Ferrari, M., & Brägger, U. (2017). Monolithic implant-supported lithium disilicate (LS2) crowns in a complete digital workflow: A prospective clinical trial with a 2-year follow-up. *Clinical Implant Dentistry and Related Research*, *19*(3), 505–511. https://doi.org/10.1111/cid.12472

Joos, M., Sailer, I., Filippi, A., Mukaddam, K., Rosentritt, M., & Kuhl, S. (2020). Stability of screw-retention in two-piece zirconia implants: An in vitro study. *Clinical Oral Implants Research*, *31*(7), 607–614. https://doi.org/10.1111/clr.13597

Kniha, K., Schlegel, K. A., Kniha, H., Modabber, A., Holzle, F., & Kniha, K. (2018). Evaluation of peri-implant bone levels and soft tissue dimensions around zirconia implants-a three-year follow-up study. *International Journal of Oral and Maxillofacial Surgery*, *47*(4), 492–498. https://doi.org/10.1016/j.ijom.2017.10.013

Kohal, R. J., Weng, D., Bächle, M., & Strub, J. R. (2004). Loaded custom-made zirconia and titanium implants show similar osseointegration: An animal experiment. *Journal of Periodontology*, *75*(9), 1262–1268. https://doi.org/10.1902/jop.2004.75.9.1262

Koller, M., Steyer, E., Theisen, K., Stagnell, S., Jakse, N., & Payer, M. (2020). Two-piece zirconia versus titanium implants after 80 months: Clinical outcomes from a prospective randomized pilot trial. *Clinical Oral Implants Research*, *31*(4), 388–396. https://doi.org/10.1111/clr.13576

Lorenz, J., Giulini, N., Holscher, W., Schwiertz, A., Schwarz, F., & Sader, R. (2019). Prospective controlled clinical study investigating long-term clinical parameters, patient satisfaction, and microbial contamination of zirconia implants. *Clinical Implant Dentistry and Related Research*, *21*(2), 263–271. https://doi.org/10.1111/cid.12720

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G., & PRISMA Group (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Journal of Clinical Epidemiology*, *62*(10), 1006–1012. https://doi.org/10.1016/j.jclinepi.2009.06.005

Moscovitch, M. (2015). Consecutive case series of monolithic and minimally veneered zirconia restorations on teeth and implants: Up to 68 months. *The International Journal of Periodontics & Restorative Dentistry*, *35*(3), 315–323. https://doi.org/10.11607/prd.2270

Nascimento, C. D., Pita, M. S., Fernandes, F., Pedrazzi, V., de Albuquerque Junior, R. F., & Ribeiro, R. F. (2014). Bacterial adhesion on the titanium and zirconia abutment surfaces. *Clinical Oral Implants Research*, *25*(3), 337–343. https://doi.org/10.1111/clr.12093

Nueesch, R., Conejo, J., Mante, F., Fischer, J., Martin, S., Rohr, N., & Blatz, M. B. (2019). Loading capacity of CAD/CAM-fabricated anterior feldspathic ceramic crowns bonded to one-piece zirconia implants with different cements. *Clinical Oral Implants Research*, *30*(2), 178–186. https://doi.org/10.1111/clr.13404

Pieralli, S., Kohal, R. J., Jung, R. E., Vach, K., & Spies, B. C. (2017). Clinical outcomes of zirconia dental implants: A systematic review. *Journal of Dental Research*, *96*(1), 38–46. https://doi.org/10.1177/0022034516664043

Pieralli, S., Kohal, R. J., Rabel, K., von Stein-Lausnitz, M., Vach, K., & Spies, B. C. (2018). Clinical outcomes of partial and full-arch all-ceramic implant-supported fixed dental prostheses. A systematic review and meta-analysis. *Clinical Oral Implants Research*, *29*(Suppl 18), 224–236. https://doi.org/10.1111/clr.13345

Pjetursson, B. E., Valente, N. A., Strasding, M., Zwahlen, M., Liu, S., & Sailer, I. (2018). A systematic review of the survival and complication rates of zirconia-ceramic and metal-ceramic single crowns. *Clinical Oral Implants Research*, *29*(Suppl 16), 199–214. https://doi.org/10.1111/clr.13306

R Core Team (2019). *R: A language and environment for statistical computing*. Vienna R Foundation for Statistical Computing. Retrieved from https://www.R-project.org

Rabel, K., Spies, B. C., Pieralli, S., Vach, K., & Kohal, R. J. (2018). The clinical performance of all-ceramic implant-supported single crowns: A systematic review and meta-analysis. *Clinical Oral Implants Research*, *29*(Suppl 18), 196–223. https://doi.org/10.1111/clr.13337

Roehling, S., Gahlert, M., Janner, S., Meng, B., Woelfler, H., & Cochran, D. L. (2019). Ligature-induced peri-implant bone loss around loaded zirconia and titanium implants. *International Journal of Oral and Maxillofacial Implants*, *34*(2), 357–365. https://doi.org/10.11607/jomi.7015

Roehling, S., Schlegel, K. A., Woelfler, H., & Gahlert, M. (2018). Performance and outcome of zirconia dental implants in clinical studies: A meta-analysis. *Clinical Oral Implants Research*, *29*(Suppl 16), 135–153. https://doi.org/10.1111/clr.13352

Roehling, S., Schlegel, K. A., Woelfler, H., & Gahlert, M. (2019). Zirconia compared to titanium dental implants in preclinical studies-A systematic review and meta-analysis. *Clinical Oral Implants Research*, *30*(5), 365–395. https://doi.org/10.1111/clr.13425

Rohr, N., Balmer, M., Müller, J. A., Martin, S., & Fischer, J. (2019). Chewing simulation of zirconia implant supported restorations. *Journal of Prosthodontic Research*, *63*(3), 361–367. https://doi.org/10.1016/j.jpor.2019.02.002

Rohr, N., Brunner, S., Märtin, S., & Fischer, J. (2018). Influence of cement type and ceramic primer on retention of polymer-infiltrated ceramic crowns to a one-piece zirconia implant. *Journal of Prosthetic Dentistry*, *119*(1), 138–145. https://doi.org/10.1016/j.prosdent.2017.02.002

Sailer, I., Strasding, M., Valente, N. A., Zwahlen, M., Liu, S., & Pjetursson, B. E. (2018). A systematic review of the survival and complication rates of zirconia-ceramic and metal-ceramic multiple-unit fixed dental prostheses. *Clinical Oral Implants Research*, *29*(Suppl 16), 184–198. https://doi.org/10.1111/clr.13277

Scarano, A., Piattelli, M., Caputi, S., Favero, G. A., & Piattelli, A. (2004). Bacterial adhesion on commercially pure titanium and zirconium oxide disks: An in vivo human study. *Journal of Periodontology*, *75*(2), 292–296. https://doi.org/10.1902/jop.2004.75.2.292

Schardt, C., Adams, M. B., Owens, T., Keitz, S., & Fontelo, P. (2007). Utilization of the PICO framework to improve searching PubMed for clinical questions. *BMC Medical Informatics and Decision Making*, *7*, 16. https://doi.org/10.1186/1472-6947-7-16

Spies, B. C., Balmer, M., Jung, R. E., Sailer, I., Vach, K., & Kohal, R. J. (2019). All-ceramic single crowns supported by zirconia implants: 5-year results of a prospective multicenter study. *Clinical Oral Implants Research*, *30*(5), 466–475. https://doi.org/10.1111/clr.13433

Spies, B. C., Fross, A., Adolfsson, E., Bagegni, A., Doerken, S., & Kohal, R. J. (2018). Stability and aging resistance of a zirconia oral implant using a carbon fiber-reinforced screw for implant-abutment connection. *Dental Materials*, *34*(10), 1585–1595. https://doi.org/10.1016/j.dental.2018.08.290

Spies, B. C., Nold, J., Vach, K., & Kohal, R. J. (2016). Two-piece zirconia oral implants withstand masticatory loads: An investigation in the artificial mouth. *Journal of the Mechanical Behavior of Biomedical Materials*, *53*, 1–10. https://doi.org/10.1016/j.jmbbm.2015.07.005

Spies, B. C., Pieralli, S., Vach, K., & Kohal, R. J. (2017). CAD/CAM-fabricated ceramic implant-supported single crowns made from lithium disilicate: Final results of a 5-year prospective cohort study. *Clinical Implant Dentistry and Related Research*, *19*(5), 876–883. https://doi.org/10.1111/cid.12508

Spies, B. C., Stampf, S., & Kohal, R. J. (2015). Evaluation of zirconia-based all-ceramic single crowns and fixed dental prosthesis on zirconia implants: 5-year results of a prospective cohort study. *Clinical Implant Dentistry and Related Research*, *17*(5), 1014–1028. https://doi.org/10.1111/cid.12203

Spies, B. C., Witkowski, S., Vach, K., & Kohal, R. J. (2018). Clinical and patient-reported outcomes of zirconia-based implant fixed dental prostheses: Results of a prospective case series 5 years after implant placement. *Clinical Oral Implants Research*, *29*(1), 91–99. https://doi.org/10.1111/clr.13072

Staubli, N., Walter, C., Schmidt, J. C., Weiger, R., & Zitzmann, N. U. (2017). Excess cement and the risk of peri-implant disease - a systematic review. *Clinical Oral Implants Research*, *28*(10), 1278–1290. https://doi.org/10.1111/clr.12954

Swain, M. V., Coldea, A., Bilkhair, A., & Guess, P. C. (2016). Interpenetrating network ceramic-resin composite dental restorative materials. *Dental Materials*, *32*(1), 34–42. https://doi.org/10.1016/j.dental.2015.09.009

Thoma, D. S., Benic, G. I., Muñoz, F., Kohal, R., Sanz Martin, I., Cantalapiedra, A. G., Hämmerle, C. H. F., & Jung, R. E. (2015). Histological analysis of loaded zirconia and titanium dental implants: An experimental study in the dog mandible. *Journal of Clinical Periodontology*, *42*(10), 967–975. https://doi.org/10.1111/jcpe.12453

Viechtbauer, W. (2010). Conducting meta-analyses in R with the metafor package. *Journal of Statistical Software*, *36*(3), 1–48.

Wilson, T. G. Jr (2009). The positive relationship between excess cement and peri-implant disease: A prospective clinical endoscopic study. *Journal of Periodontology*, *80*(9), 1388–1392. https://doi.org/10.1902/jop.2009.090115

Worni, A., Katsoulis, J., Kolgeci, L., Worni, M., & Mericske-Stern, R. (2017). Monolithic zirconia reconstructions supported by teeth and implants: 1- to 3-year results of a case series. *Quintessence International*, *48*(6), 459–467. https://doi.org/10.3290/j.qi.a38138

Zaugg, L. K., Zehnder, I., Rohr, N., Fischer, J., & Zitzmann, N. U. (2018). The effects of crown venting or pre-cementing of CAD/CAM-constructed all-ceramic crowns luted on YTZ implants on marginal cement excess. *Clinical Oral Implants Research*, *29*(1), 82–90. https://doi.org/10.1111/clr.13071

Zhang, Y., & Lawn, B. R. (2018). Novel zirconia materials in dentistry. *Journal of Dental Research*, *97*(2), 140–147. https://doi.org/10.1177/0022034517737483

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Spitznagel, F. A., Balmer, M., Wiedemeier, D. B., Jung, R. E., & Gierthmuehlen, P. C. (2022). Clinical outcomes of all-ceramic single crowns and fixed dental prostheses supported by ceramic implants: A systematic review and meta-analyses. *Clinical Oral Implants Research*, 33, 1–20. https://doi.org/10.1111/clr.13871