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Review article

Long-term clinical performance and complications of zirconia-based tooth- and implant-supported fixed prosthodontic restorations: A summary of systematic reviews

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ABSTRACT

Objectives: To present an overview on systematic reviews on prosthodontic zirconia restorations and to discuss long-term complications as well as information on anatomical and functional changes to the masticatory system.
Data/Sources: MEDLINE, EMBASE, Trip medical, and Cochrane Library databases were searched for systematic reviews up to February 2021. Bias was assessed and clinical survival and complications were analyzed.
Study selection: 38 eligible articles published between 2006 and 2021 were included. The reviews were based on 128 in vivo studies on approximately 10,000 zirconia restorations.
5-year cumulative survival rates varied between 91.2% and 95.9% for tooth-supported (TS) single crowns (SC), 89.4% and 100% for TS multi-unit fixed dental prostheses (FDP), 97.1% and 97.6% for implant-supported (IS) SCs and 93.0% and 100% for IS FDPs. Chipping was the most often technical complication, followed by framework fracture, loss of retention, marginal discrepancies/discoloration, occlusal roughness and abutment/screw loosening. Color mismatch was the only esthetic complication. Biological complications were caries, endodontic complications, tooth fracture, periodontal disease, abrasion/attrition, persisting pain, high sensitivity, peri-implantitis and soft tissue issues. Patients with bruxism were only examined sporadically.
Conclusions: 5-year results for zirconia restorations were satisfactory. The predominant technical problem of veneering fractures could be overcome with adapted design or fabrication and application of monolithic restorations, but reviews of clinical studies on this subject are rare. The impact of zirconia restorations on the masticatory system remains unclear.
Clinical significance: Zirconia restorations are experiencing a rapidly increasing use in dental practice. Being highly wear-resistant, hard and durable, it can be assumed that they do not follow natural abrasion and changes in the masticatory system. Possible long-term effects on the stomatognathic system as a whole should therefore be considered.

1. Introduction

All-ceramic restorations offer advantages over metal-based restorations. For a number of patients, the esthetic advantages of a tooth-colored ceramic restoration particularly are an important basis for decision-making. All-ceramic restorations offer the advantages of being corrosion-free and are comparatively less susceptible to the accumulation of biofilms [1]. Rising precious metal costs and advanced options for chairside manufacturing of ceramic restorations contribute to the increasing spread of ceramics. In recent years, the use of all-ceramic restorations has grown steadily, and zirconia in particular has shown a significant increase. A practical survey on the use of various dental materials among 1.000 German dentists in 2017 shows a share of approximately 60% for all-ceramic posterior crowns and 48% for zirconia based posterior FDPs [2]. Despite this large number of ceramic restorations, long-term documentation is only available for metal-based restorations.

Due to their high strength, early zirconia ceramics were able to expand the range of indications for ceramic restorations to long span restorations. Because of their high opacity they could not meet the esthetic expectations and required veneering with a more esthetic ceramic. Fractures of this veneering are a frequently discussed. Common

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causes are differences in thermal expansion, insufficient support of the veneering ceramic [3] and inadequate adjustment in the patient's mouth [4]. The need for both, mechanically robust and aesthetically pleasing restorations was countered with the development of modern zirconia by reducing the proportion of aluminum oxide, increasing ytterbium doping and coloring of the blanks [5]. With its high hardness and abrasion resistance compared to natural teeth, the question arises, which long-term complications as well as anatomical and functional changes to the masticatory system can occur. This review summary aims to present an overview on available systematic reviews on zirconia-based prosthodontic restorations, to discuss their clinical relevance and to elicit, whether they illuminate these effects sufficiently.

2. Methods

This article followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement guidelines as far as applicable. The protocol of this summary was not registered prospectively.

2.1. Eligibility criteria

Systematic reviews reporting on the clinical performance of tooth- or implant-supported zirconia-based fixed prosthodontic restorations in humans were included. To achieve high sensitivity, no other restrictions were applied. PICOS was therefore defined as depicted in *Table 1*.

For reviews analyzing the same study cohort at different times, only the latest publication was included. For reviews published in multiple languages, only the English version was included.

2.2. Search strategy

A search for systematic reviews on the clinical performance of tooth-supported (TS) or implant-supported (IS) zirconia-based prosthodontic restorations was performed in the databases MEDLINE via OVID, EMBASE via OVID, Trip medical database and the Cochrane Library (via Wiley Online Library). No restrictions on the date of publication or language were placed. The MEDLINE search strategy was adapted from the Cochrane Systematic Review "Metal-free materials for fixed prosthodontic restorations" by Poggio et al. [6]. Although the article focuses on zirconia ceramics, the search terms also included other ceramics to ensure the most comprehensive results possible. The search strategy is listed in *Appendix 1*. The search included articles up to February 10, 2021. Results were transferred to Citavi, Version 6.7 (Swiss Academic Software GmbH) and duplicates removed.

The electronic search was complemented by manual searches of the bibliographies of all included reviews for additional relevant articles and forward snowballing using PubMed functions "Cited by" and "Similar articles" [7].

Titles and abstracts were screened by two authors independently and full texts were collected after agreement. Cohen's kappa was calculated using the online calculator by Hemmerich [8]. Full texts, which did not meet the eligibility criteria were excluded. The process for selecting studies is outlined in a *PRISMA flow diagram (Fig. 1)*.

2.3. Outcomes

Outcomes, which were considered were clinical survival rate and incidence of technical, aesthetical and/or biological complications. Survival was defined as the restoration being clinically acceptable in situ for the follow-up time without refabrication. Complication was defined as one or more adverse events affecting function and/or aesthetics negatively and/or resulting in biological pathologies.

2.4. Methodological quality

To assess the methodological quality and risk of bias of included systematic reviews, a catalog of questions based on AMSTAR 2 [9], which was reduced in scope, was used:

- Was a protocol of the review methods established and published ahead (e.g., via registration at PROSPERO - https://www.crd.york.ac.uk/PROSPERO/) and were deviations from the protocol stated?
- Did the review follow the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [10] or, for publications before 2009, the Quality Of Reporting Of Meta-analyses (QUOROM) statement [11] or did the authors use other appropriate tools to ensure complete and transparent reporting?
- Was a PICO description (population, intervention, control group, outcome) provided to formulate the research question and inclusion criteria?
- Was a comprehensive literature search strategy applied, including multiple databases and additional sources, and comprehensibly documented?
- Did at least two reviewers perform study selection and data extraction?
- Did the authors assess the risk of bias (RoB) and methodological quality of included studies, preferably following the recommendations of the Cochrane Collaboration [12] or by the use of properly developed rating instruments like the Newcastle Ottawa Scale (NOS) [13]?
- Were appropriate methods for statistical analysis, including assessment of heterogeneity if applicable, selected?
- Were the included studies described in adequate detail, including sufficient information on the materials investigated?
- Did the authors account for RoB in individual studies on the results of the meta-analysis and/or in the discussion?
- Did the authors disclose conflicts of interest?

Answers had to be "YES" or "NO" and were documented using Excel spreadsheets (Microsoft). When no quantitative evaluation was carried out, the corresponding field "Statistical analysis" was marked not applicable ("NA"). An overall score was formed and 1 to 3 "YES" rated as an indication of low methodological quality / high risk of bias, 4 to 6 as an indication of medium methodological quality / risk of bias and 7 to 10 as an indication of high methodological quality / low risk of bias.

2.5. Data collection process and data items

Data was collected using Excel spreadsheets (Microsoft). The following information was extracted from systematic reviews: author,

Table 1
PICOS framework.

P (Population)	Subjects who received single or multi-unit fixed prosthodontic restorations
I (Intervention)	Zirconia-based restorations
C (Comparison)	Other types of restorative material or no comparison
O (Outcome)	Clinical survival and technical, biological or esthetic complications
S (Studies)	Systematic reviews

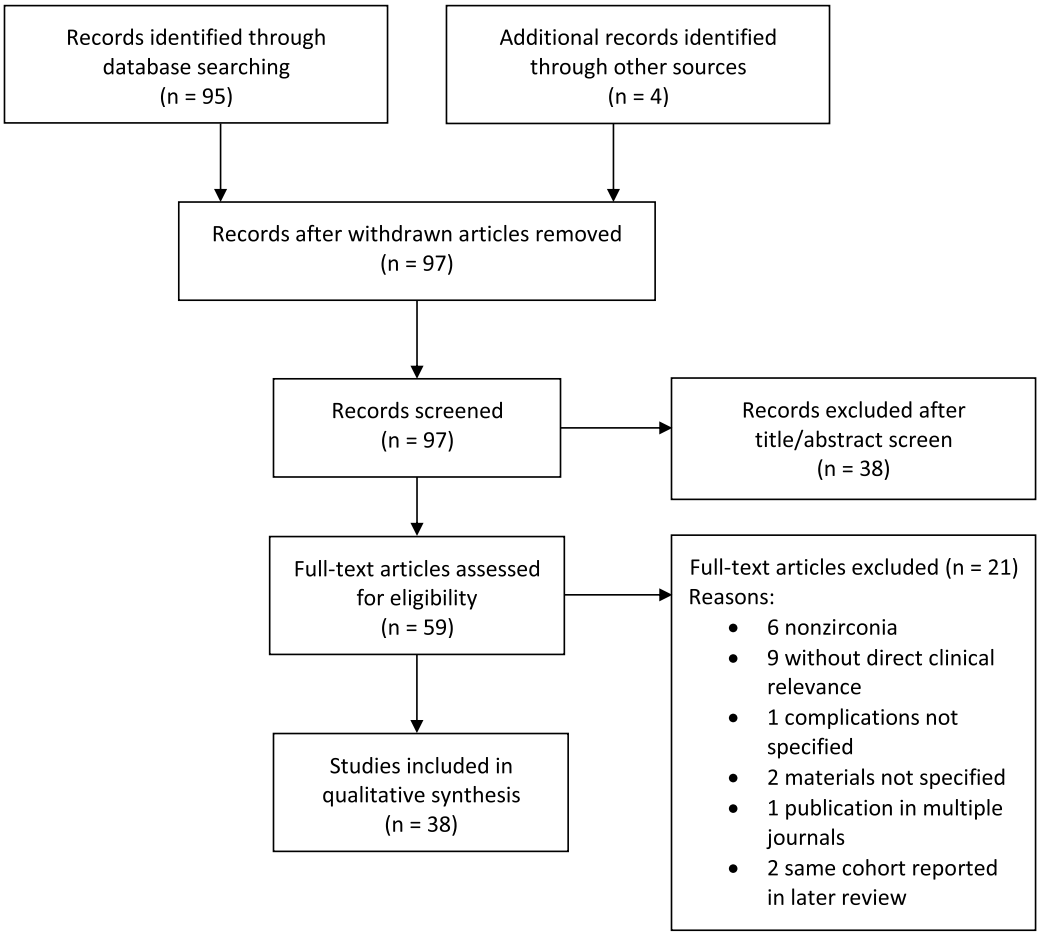

Fig. 1. Flow of information in this review using PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) diagram [10].

title, year, objective, included studies, types of studies, period of studies, type of restoration, region, reporting items, materials, (core) ceramic material details, number of patients, number of restorations, follow up time, survival, technical complications, biological complications, esthetic complications. Complications were noted solely for zirconia restorations if possible. For all primary studies on zirconia included in the systematic reviews the following information was extracted: author, year, study design, type of restoration, veneered or monolithic zirconia, number of patients, number of restorations and follow-up. When different numbers of patients or restorations at baseline and follow-up were provided, numbers at follow-up were selected.

2.6. Statistical analysis

The data was not statistically analyzed because of the heterogeneity of the reviews and the fact, that a significant part of the underlying studies was included in multiple reviews.

3. Results

The MEDLINE search identified 93 systematic reviews. No additional articles were found via EMBASE and Cochrane Library. In Trip Medical Database two additional systematic reviews were found and manual search revealed three additional systematic reviews and a review summary. Two withdrawn articles were removed.

The titles and abstracts of the remaining articles were screened by two authors. For interrater reliability Cohen's kappa was calculated (0.917), indicating almost perfect agreement [14]. A consensus was reached after discussion. For 59 reviews appearing to meet the inclusion criteria or for reviews with insufficient data in the title and abstract, full-text articles were obtained. 21 articles were excluded from the final analysis. 38 reviews remained and were included in the qualitative analysis. 24 of these reviews were related to tooth-supported restorations, seven exclusively to implant-supported restorations and seven to both.

The reviews, published between 2006 and 2021, usually reported survival, success, failure and/or complication rates. A distinction was made between technical, biological, and esthetic causes. All included systematic reviews are listed with details in *Appendix 2*.

The reviews were based on 128 primary in vivo studies reporting on approximately 10,000 zirconia restoration. 29 were randomized controlled trials with 1100 restorations and a follow-up time between 1 and 10 years (mean 3.2). 64 prospective non-RCT studies included 6000 restorations with a follow-up time between 1 and 10.7 years (mean 8.7) and 21 retrospective studies included 2500 restorations with follow-up times between 1 and 10 years (mean 5.2). The remaining studies consisted of 1 consecutive case study and 4 clinical reports as well as 9 studies for which the study designs remained unclear from the reports. Individual studies appeared in 1 to 9 reviews with an arithmetic mean of 2.1 and reviews contained 1 to 26 articles on zirconia with an arithmetic mean of 7.1. Only 20 studies encompassed monolithic zirconia with approximately 500 restorations and follow-up times between 1 and 7 years (mean 2.3). A summary of all zirconia in vivo studies is given in *Appendix 3*.

3.1. Methodological quality of the systematic reviews

Based on the questionnaire, 8 reviews showed low methodological quality / high risk of bias, 12 reviews medium methodological quality / risk of bias and 18 reviews high methodological quality / low risk of bias. Most reviews were carried out by two or more reviewers (79%) and provided a comprehensive search strategy (79%) as well as detailed descriptions of statistical methods (81%) and the included studies (84%). PICO description was first described 2014 and systematical assessment of RoB and methodological quality of included studies as well as adherence to the PRISMA statement started 2016. Subsequently, these techniques were used regularly. The first reviews with a pre-published protocol appeared in 2017 and in 2020, three out of four reviews were registered. Overall, only 63% of the authors disclosed conflicts of interest.

3.2. Methodological quality of systematic reviews (Table 2)

3.2.1. Survival rate

Follow-up times of zirconia studies ranged from six months [15,16] to eleven years [17] with survival rates between 74.8% and 100% for single crowns (SC) [18] and 67% and 100% for multi-unit fixed dental prostheses (FDPs) [19]. Survival rates for tooth-supported zirconia restorations ranged between 91.2% [18] and 95.9% [20] for SCs and 89.4%

Table 2
Methodological quality and risk of bias of systematic reviews on zirconia tooth- and implant-based fixed prosthodontic restorations. (NA = not applicable; Score: 1 to 3: low, 4 to 6: medium and 7 to 10: high methodological quality / low risk of bias).

Author	Year	Published protocoll	PRISMA / QUORUM	PICO	Compr. search	2+ reviewers	Ass. of RoB / method. quality	Statistical analysis	Descr. of studies / materials	Account for RoB	Disclosure of conflicts	Score
Wassermann [16]	2006	NO	NO	NO	NO	NO	NO	NA	YES	NO	NO	1/9
Abduo [65]	2010	NO	NO	NO	NO	NO	NO	NA	NO	NO	NO	0/9
Al-Amleh [58]	2010	NO	NO	NO	NO	NO	NO	NA	NO	NO	NO	0/9
Heintze & Rousson [45]	2010	NO	NO	NO	NO	NO	NO	YES	YES	NO	NO	2/10
Schley [33]	2010	NO	NO	NO	NO	NO	NO	NO	YES	NO	NO	1/10
Petridis [66]	2012	NO	NO	NO	YES	YES	YES	YES	YES	YES	YES	7/10
Raigrodski [68]	2012	NO	NO	NO	NO	NO	NO	NA	YES	NO	NO	1/9
Wang [46]	2012	NO	NO	NO	YES	YES	NO	YES	YES	NO	YES	5/10
Contrepois [64]	2013	NO	NO	NO	YES	YES	NO	NA	YES	NO	NO	3/9
Larsson & Wennerberg [20]	2014	NO	NO	NO	YES	NO	NO	NO	YES	NO	YES	3/10
Schmitter [83]	2014	NO	NO	YES	YES	YES	NO	NA	NO	NO	YES	4/9
Le [17]	2015	NO	NO	NO	YES	YES	NO	NO	YES	NO	YES	4/10
Pjetursson [32]	2015	NO	NO	YES	YES	YES	NO	YES	NO	NO	YES	5/10
Sailer [18]	2015	NO	NO	YES	YES	YES	NO	YES	NO	NO	YES	5/10
Abdulmajeed [62]	2016	NO	YES	YES	YES	YES	YES	NO	YES	YES	NO	7/10
Kassardjian [25]	2016	NO	NO	NO	YES	YES	NO	YES	YES	NO	NO	4/10
Chen [41]	2017	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	9/10
Elshiyab [24]	2017	NO	NO	NO	YES	YES	NO	NO	YES	NO	YES	4/10
Joda [15]	2017	NO	YES	YES	YES	YES	YES	NA	YES	NO	YES	7/9
Poggio [6]	2017	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	10/10
Thoma [21]	2017	NO	YES	NO	NO	YES	NO	YES	NO	NO	YES	4/10
Castillo-Oyague [43]	2018	NO	NO	NO	YES	YES	YES	NA	YES	YES	NO	5/9
Chen [40]	2018	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	9/10
Pjetursson [22]	2018	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	10/10
Rabel [52]	2018	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	10/10
Sailer [23]	2018	YES	YES	YES	NO	YES	NO	YES	YES	NO	YES	7/10
Souza Melo [85]	2018	YES	YES	NO	YES	YES	YES	YES	YES	YES	NO	8/10
Stefanescu [19]	2018	NO	NO	NO	YES	YES	YES	NA	YES	NO	YES	5/9
Alraheam [39]	2019	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	9/10
Bagegni & Abou-Ayas [60]	2019	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	9/10
Gou [72]	2019	NO	YES	NO	YES	YES	NO	NA	YES	NO	NO	4/9
Lemos [51]	2019	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	9/10
Rodrigues [91]	2019	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	9/10
Wong [61]	2019	NO	YES	NO	YES	YES	YES	YES	YES	YES	YES	8/10
Limones [35]	2020	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	10/10
Quigley [63]	2020	NO	YES	YES	YES	NO	YES	NA	YES	NO	NO	5/9
Solá-Ruíz [75]	2020	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	10/10
Vetromilla [27]	2020	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	10/10

Table 3
Overview of complications and failures of zirconia restorations.

Type of complication / failure	Abdulmajeed [62]	Abduo [65]	Al-Amleh [58]	Alraheam [39]	Bagegni & Abou-Ayas [60]	Castillo-Oyague [43]	Chen [40]	Chen [41]	Contrepois [64]	Elshiyab [24]	Gou [72]	Heintze & Rousson [45]	Joda [15]	Kassardjian [25]	Larsson & Wennerberg [20]	Le [17]	Lemos [51]	Limones [35]	Petridis [66]	Pjetursson [22]	Pjetursson [32]	Poggio [6]	Quigley [63]	Rabel [52]	Raigrodski [68]	Rodrigues [91]	Sailer [18]	Sailer [23]	Schley [33]	Schmitter [83]	Solá-Ruiz [75]	Souza Melo [85]	Stefanescu [19]	Thoma [21]	Vetromilla [27]	Wang [46]	Wassermann [16]	Wong [61]	Total
Technical	5	0	3	1	2	3	2	3	0	0	0	3	0	0	4	4	3	3	1	4	4	0	3	5	3	3	3	1	4	0	0	3	4	1	3	1	0	2	81
Fracture of veneering material / chipping	x		x		x	x	x	x				x			x	x	x	x		x	x		x	x	x	x	x	x	x			x	x		x	x		x	25
Framework fracture	x		x			x		x				x			x	x		x		x	x		x	x	x	x	x		x			x	x		x				19
Loss of retention / debonding			x	x		x	x	x				x			x	x				x			x	x	x	x	x		x			x	x	x	x				19
Marginal discrepancies															x		x	x											x				x						5
Marginal discoloration																			x	x																			2
Abutmentfracture	x																				x																	2
Abutment / screw loosening	x				x											x	x				x			x												x		7
Implantfailure	x																																					1
Occlusal roughness																								x														1
Biological	0	0	3	0	0	1	1	2	0	0	0	0	0	0	7	4	3	2	0	4	1	0	4	0	3	3	2	1	3	0	0	0	3	3	1	0	1	0	52
Secondary caries			x			x	x	x							x	x				x			x		x	x	x		x				x	x	x				15
Loss of vitality / endodontic complication															x	x		x		x			x		x	x			x				x	x					10
Abutmenttooth fracture															x	x				x			x		x		x		x								x		8
Extraction of abutmenttooth			x																							x													2
Periodontal disease								x							x	x	x			x			x																6
Abrasion / attrition																		x															x	x					3
Persisting pain			x												x																								2
High sensitivity																	x																						1
Peri-implantitis															x		x																						2
Soft tissue issues															x						x							x											3
Aesthetical	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2
Color mismatch															x											x														2
Total	5	0	6	1	2	4	3	5	0	0	0	3	0	0	12	8	6	5	1	8	5	0	7	5	6	7	5	2	7	0	0	3	7	4	4	1	1	2	135

[19] and 100% [21] for FDPs. For implant-supported restorations values were between 97.1% [20] and 97.6% [22] (SCs) and 93.0% [23] and 100% (FDPs) [17] (Table 3 and 4).

Sailer et al. [18] compared 50 studies on 9434 all-ceramic single crowns with 17 studies on 4663 metal-ceramic single crowns. Zirconia was used in nine studies (1049 crowns). Estimated 5-year survival rate for zirconia was 91.2% versus 95.7% for metal-ceramic. Larsson et al. [20] calculated a 95.9% 5-year cumulative survival on ten studies (830 crowns).

Elshiyab et al. [24] analyzed survival of zirconia crowns under cyclic loading (25 in-vitro studies) and compared the results to the forementioned in-vivo reviews [18,20]. Cumulative 5-year survival rate for TS crowns was 88.8% and comparable to estimated data [18].

All 14 studies by Kassardjian et al. [25] were already included by Sailer et al. [18] and only one analyzed zirconia crowns [26]. The retrospective cohort study contains with 1132 zirconia single crowns the highest sample size in all studies. Vetromilla et al. [27] calculated annual failure rates of 2.87 (metal-ceramics: 0.52) for zirconia inlays, partial crowns and crowns. They found a noticeable difference between the two included randomized controlled trials (5.12) [28,29] and two retrospective studies (0.62) [30,31].

Pjetursson et al. [32] analyzed 40 studies on 1796 metal-ceramic, 208 reinforced glass ceramic, 229 glass-infiltrated alumina and 673 zirconia FDPs. Survival rates for zirconia (90.4%) FDPs were lower than those for metal-ceramic (94.4%). Schley et al. [33] calculated a 5-year survival rate of 94.29% based on nine studies on zirconia FDPs.

Le et al. [17] investigated 23 studies on 776 TS zirconia FDPs and four studies on 70 IS FDPs. Eight studies with 148 FDPs were not included in the forementioned review by Pjetursson et al. [32]. Life table analysis revealed 5-year survival rates of 93.5% for TS FDPs and 100% for IS FDPs.

Stefanescu et al. [19] included ten studies with one not covered by Le et al. [17] and Pjetursson et al. [32]. The additional study [34] had a survival rate of 94% after nine years.

Limones et al. [35] found 5-year survival rates for zirconia (95.4%) and for metal-ceramics FDPs (96.9%), without significant difference between the materials ($p = 0.364$).

In a review by Thoma et al. [21] on resin-bonded bridges (RBBs), three of 29 studies were related to veneered anterior zirconia restorations [36–38]. Estimated 5-year survival rate for zirconia RBBs was 100% compared to 92.8% over all materials. Alraheam et al. [39] included 38 studies on RBBs, two of them on zirconia frameworks for cantilevered anterior FDPs with an average 5-year success rate of 92.07% [36,37]. Chen et al. [40] estimated 5-year survival for those two studies with 100%, because all debondings occurred after traumata and could be rebonded.

In a review on inlay-retained FDPs [41] only one eligible study related to zirconia framework IRFDPs was found with a small sample size of 29 and an estimated 5-year survival rate of 95.8% [42]. Castillo-Oyagüe et al. [43] included a study with a small case number, which could achieve a survival rate of 90% after one year [44].

Heintze et Rousson [45] showed significantly higher 3-year survival rates for metal-ceramic FDPs (97%) compared to for zirconia (90%).

Wang et al. [46] examined clinical fracture rates of all-ceramic crowns in relation to the restored tooth type including 37 studies. Only two were related to veneered zirconia [47,48] and those were also encompassed by Sailer et al. [18].

Wassermann et al. [16] reviewed 21 studies on VITA In-Ceram Classic crowns and FDPs, but only two used In-Ceram Classic Zirconia with just 9 [49] respectively 18 [50] restorations, so no statement on clinical performance could be made.

Extensive reviews were provided on zirconia and metal-ceramic implant supported SCs [22] and FDPs [23], but no study on monolithic zirconia fulfilled the inclusion criteria. 5-year survival rates for SCs were 97.6% (zirconia) versus 98.3% (metal-ceramic) [22] and for FDPs 93.0% (zirconia) and 98.7% (metal-ceramic) [23]. Pjetursson et al. conclude that implant-supported zirconia SCs are a treatment alternative to metal-ceramics with esthetic advantages, Sailer et al. warn of

increased technical complications in relation to framework fractures and chipping. Lemos et al. [51] analyzed 10 additional studies and found no significant differences in survival for IS SCs and FDPs. Rabel et al. [52] reviewed 41 studies with 5-year survival rates for veneered zirconia IS SCs of 91.6% and an overall estimated 10-year survival of 94.4%. One study investigated 74 monolithic zirconia SCs and 35 FDPs 12 and 36 months [53] and found a survival rate of 99.6%.

3.3. Technical complications

Chipping was the most stated technical complication followed by framework fracture, loss of retention, marginal discrepancies, marginal discoloration and color mismatch. Abutment or screw loosening was reported for implant-supported single crowns and FDPs with an advantage for zirconia restorations [22,23]. Rabel et al. [52] moreover found occlusal roughness as a complication in four studies [54–57].

3.4. Chipping and framework fracture

According to Le at al. [17] fracture of the veneering material was the most common technical failure (20), followed by framework fracture (13) and loss of retention (5). Veneer fracture (175) ranked before loss of retention (18). While the incidence of framework fractures was significantly higher for reinforced glass ceramic FDPs and infiltrated glass ceramic FDPs, the incidence of ceramic fractures (chipping and fractures) and loss of retention was significantly higher for densely sintered zirconia FDPs [32]. Limones et al. [35] found chipping to be the only statistically significant complication in zirconia-ceramics compared to metal-ceramics posterior FDPs and it could usually be remedied by polishing.

Al-Amleh et al. [58] reported on an RCT in which one Cercon zirconia crown on a nonvital maxillary second molar without a post fractured in half one month after cementation. The patient had, although lack of excessive parafunctional activity was an inclusion criterion, nocturnal bruxism and therefore had undergone muscle-relaxation splint therapy. After immediate replacement of the crown, no other mechanical failures were reported [59].

Rabel et al. [52] found an estimated chipping rate of 11.8% (95% CI: 6.3 - 21.5) for implant-supported veneered zirconia single crowns after five years. Framework fractures were located more likely in screw-retained crowns compared to cemented single crowns.

Chipping of the veneering material is the predominant complication also for complete-arch fixed implant prostheses [60–62].

3.5. Loss of retention

Loss of retention was the second often type of complication in the systematic review by Le et al. [17], responsible for 9% of the failures and 8% of the complications and was mainly associated with conventional cementation. Quigley et al. [63] examined the clinical efficacy of adhesive bonding methods to zirconia. Due to the number of variables influencing the outcome, they were unable to establish a clear correlation between a bonding protocol and clinical survival.

Table 4
Abbreviations.

AC	all-ceramic	NA	not applicable
CA	complete-arch	NR	not reported
CR	complication rate	PCC	partial ceramic crown
DS	densely sintered	PFM	porcelain fused to metal
FDP	fixed dental prostheses (multi unit)	RB	resin bonded
FR	failure rate	RNC	resin nano ceramic
Frc	fiber-reinforced composite	RR	relative risk
IR	inlay retained	SC	single crown
IS	implant supported	SR	survival rate
LS2	lithium disilicate	TCML	thermal cycling mechanical loading
MA	metal-acrylic	TS	tooth supported
MC	metal-ceramic	ZC	zircon-ceramic

3.6. Marginal discrepancies

Contrepois et al. [64] created a comprehensive systematic review on marginal adaptation of ceramic crowns including 54 studies - 48 in vitro and 6 in vivo - comparing 17 ceramic systems. 30 articles on zirconia were included. No ranking of different systems was provided due to the significant heterogeneity of the selected studies. Overall, marginal gaps between 174 μm and 3.7 μm were measured, with 94.9% less than or equal to 120 μm. The authors identified finishing, value of cementing space, veneering process and cementation as factors affecting marginal fit. They concluded that various systems provide acceptable clinical results for marginal adaptation and hence recommended to select ceramic materials according to their ability to meet clinical and esthetic requirements. Due to the high variability of measurement procedures, Abduo et al. [65] were unable to rank different CAD/CAM manufacturing systems in terms of marginal and/or internal fit. They concluded that veneering zirconia frameworks deteriorated fit, while aging has no effect.

3.7. Marginal discoloration

According to Pjetursson et al. [32], the lowest incidence rate of marginal discoloration occurred in reinforced glass ceramic FDPs with an annual rate of 0.72% and the highest incidence rate in densely sintered zirconia FDPs (6.72%). In comparison, for metal ceramic FDPs the annual incidence rate was 4.82%. In a systematic review on marginal discoloration of all-ceramic restorations, only one study on zirconia was included [66]. This study had four discoloration events in 38 prostheses after a medium follow-up time of five years [67].

3.8. Esthetic complications

Color mismatch was noted in one review and assigned as technical complication [20], but occurred only in one [59] out of the sixteen studies analyzed. No other aesthetical problems were reported.

3.9. Biological complications

Biological complications reported for tooth supported crowns or FDPs were secondary caries, loss of vitality and endodontic treatment, abutment tooth fracture, periodontal disease, abrasion/attrition, persisting pain and high sensitivity.

Pjetursson et al. [32] listed 18 studies reporting on the incidence of secondary caries and found a significantly higher incidence of caries in abutment teeth for densely sintered zirconia. The annual complication rate was 0.65% compared to metal-ceramic FDPs with an annual complication rate of 0.24% ($p = 0.001$). Three studies described loss of vitality for densely sintered zirconia FDPs with a 5-year complication rate of 2.2%. Abutment tooth fractures were reported in 36 studies on 2107 FDPs, out of which 22 were lost. The 5-year complication rate was 0.9% with no statistical significance difference between materials. 29 out of 2096 FDPs in 36 studies were lost due to recurrent periodontal disease resulting in a 5-year failure rate of 1.2%. Higher rates were found for reinforced glass ceramic FDPs (2.9%) and glass-infiltrated alumina FDPs (7.6%) and lower rates for densely sintered zirconia FDPs (0.5%) and metal-ceramic FDPs (0.3%).

Raigrodski et al. [68] found no difference in periodontal parameters for zirconia-based restorations. Roediger et al. [69] reported one abutment loss because of periodontal lesion.

In the review by Le et al. [17] biological failures in tooth supported restorations occurred for caries in eight cases, followed by abutment tooth fracture (7), endodontic treatment (3) and periodontal lesion (1).

Biological complications were endodontic treatment (20), caries (12), abutment tooth fracture (1) and not specified (2). No biological failures or complications were noted for implant supported restorations.

Sailer et al. [23] point to an increased incidence of peri-implantitis or soft tissue issues for zirconia implant-supported FDPs with a 5-year rate of 10.1% versus 3.1% for metal-ceramics. They noted that this comparison is based for zirconia FDPs on only one study on 73 units [70]. Pjetursson et al. [22] saw no statistically significant difference between zirconia and metal-ceramic implant-supported single crowns regarding soft tissue complications and bone loss.

In a study by Koenig and Wulfman et al. [71], two antagonistic teeth opposing monolithic zirconia restorations were lost due to root fracture and one due to severe periodontal disease.

3.10. Antagonist enamel wear

A systematic review on antagonist tooth wear of tooth-supported Y-TZP monolithic zirconia posterior crowns in vivo Gou et al. [72] included five articles on 74 patients between 18 and 73 years with a follow-up time between 12 and 24 months. None of the patients showed symptoms of temporo-mandibular disorder or parafunctional habits. Mundhe et al. [73] revealed more antagonist enamel wear for polished zirconia compared to natural teeth, but less than metal-ceramics. Polished monolithic zirconia crowns showed no accelerated wear compared with metal-ceramic crowns [74]. Solá-Ruíz et al. [75] additionally included three newer studies [76–78]. With follow-up times varying between 6 and 24 months, a high degree of heterogeneity was found in the meta-analysis. Monolithic zirconia crowns showed a mean maximum wear of 58.47 μm. Mean maximum wear of antagonist teeth was 95.45 μm and thus significantly greater compared to opposing natural teeth. Some studies did not show significantly different wear and concluded that polished monolithic zirconia does not accelerate wear in antagonist teeth [74,79]. Koenig and Wulfman et al. [71] observed no zirconia wear after two years in vivo, but glaze wear was highlighted on 100% of occlusal contact points areas after one year.

4. Discussion

The reviews included and the studies on which they were based differed greatly in terms of methodological quality and bias. A Cochrane review on metal-free materials for fixed prosthodontic restorations [6] identified nine randomized controlled trials, five of which dealt with zirconia-based ceramics. Seven out of nine were rated with a high risk of bias and two with an unclear risk of bias. It should be emphasized that in the last five years, in particular through the application of the PRISMA guidelines [80] and tools to assess quality and bias of reviewed studies (like the Cochrane Collaboration's tool [81] or the Newcastle-Ottawa Scale [13]), an increase in the quality of systematic reviews has been discernible. The few RCTs available usually have a small number of patients or short follow-up time. Work focuses on relatively easily measurable technical and, to a lesser extent, on biological complications. But even in these areas there are no uniform evaluation criteria between different articles. The research with high-quality trials generating a high level of scientific evidence has difficulty keeping pace with ongoing industrial progress regarding materials and fabrication processes.

The most extensive reviews for tooth supported single crowns [18] and for FDPs [32] lack of detailed information on the materials used, especially with regard to veneering material.

A very high-quality and transparent review [52] on implant supported all-ceramic single crowns contains very detailed data from the underlying studies, but unfortunately focuses on technical complications and does not include biological complications.

The design of the primary studies often limits the transferability of the results to daily dental practice. With prevalence of sleep bruxism at 12.8% +/- 3.1% and of awake bruxism at between 22.1% and 31.4% [82], patients with bruxism represent a significant proportion of the patient population. However, bruxism was an exclusion criterion in most studies. Especially in 17 studies included in Al-Amleh's et al. [58] systematic review on clinical trials in zirconia. Bruxism has only been discussed as a reason for possible technical complications [59]. Schmitter et al. [83] analyzed the effect of bruxism on the survival of zirconia restorations in 22 prospective studies. Only one study did not apply bruxism as an exclusion criterion, but did not examine it as a complication or confounder [84]. Souza Melo et al. [85] performed a systematic review on the association of sleep bruxism with ceramic restoration failure. Of eight included studies, only one based the diagnosis of sleep bruxism on a questionnaire and clinical inspection [86]. The others only reported clinical evaluation and only one was associated with zirconia single crowns [26]. The meta-analysis showed an increased hazard and an increased probability of failure in patients with sleep bruxism only for anterior ceramic veneers.

A newer prospective study [71], not yet included in former systematic reviews, explicitly included patients with bruxism. They published 2-year results with 45 patients on monolithic zirconia restorations on natural teeth (10 elements) and implants (85 elements), included 29 patients with clinical signs of bruxism. Overall survival after two years was 93.3%, with higher survival for FDPs (100%) compared to crowns (95.8% for implant supported crowns and 76.9% for tooth supported crowns). 80% of catastrophic failures and 76.9% of all complications were found in the bruxism subgroup. Although the data indicate an increased complication rate for this cohort, no statistically significant differences could be shown due to the limited number of cases.

Beside this, other parafunctional habits, temporomandibular disorders, or the impact of zirconia based prosthodontic restorations on the masticatory system on the functional or anatomical level in general were not addressed.

Incidentally, none of the included systematic reviews considered economic outcomes like cost-effectiveness. A review summary by the Canadian Agency for Drugs and Technologies in Health [87] listed only one study comparing all-ceramic and metal-ceramic crowns in this regard, [88].

Le at al. [17] discussed, that more than half of the framework fractures occurred in cases where manufacturer's handling and dimensions instructions were not met. They stated that the exclusion of those cases would lower the risk of framework fracture below 1%. This confirms previous research on failure of all-ceramic FDPs [89] and on the influence of connector design [90].

Chipping fractures were the most common type of technical complications in this review, but mostly did not affect function or aesthetics. The restorations could remain in situ with adjustment or repair [17]. Al-Amleh et al. [58] also noted, that a large number of chippings were only findings in routine review appointments and not detected by the patients. They often had to be polished or slightly repaired with composite resin. Major chipping fractures regularly required replacement. Chipping rates of zirconia varied greatly between individual studies. Heintze and Rousson [45] emphasize in their systematic review, that 85% of all chippings occurred in 4 of 13 investigated studies. Al-Amleh et al. [58] see a possible advantage for hard-milled HIPed zirconia as there were, in contrast to soft-milled non-HIPed zirconia, no reports on framework fractures in their review. According to the systematic review and meta-analysis of 14 studies by Rodrigues et al. [91] - including seven studies with zirconia frameworks, but no monolithic crowns-, CAD/CAM fabricated tooth-supported restorations are associated with higher failure rates compared to those made by conventional techniques. The article leaves it unclear whether the differences are due to the materials or the production methods.

Monolithic or partially veneered zirconia implant supported restorations showed a lower incidence of chipping subjected to limited observation periods [92,93].

Sulaiman et al. [94] did a dental laboratory survey and examined fracture rates of lithium disilicate and zirconia ceramic restorations after

up to 7.5 years with lowest fracture rates for monolithic zirconia single crowns (0.54%). Garling et al. [95] suggest in their study that catastrophic fractures in monolithic disilicate FDPs increased significantly after ten years and suspect, that long-term aging in the oral environment led to fatigue and crack propagation.

The highest incidence of secondary caries was reported in a prospective clinical cohort study on 3- to 5-unit non-HIPed zirconia based posterior FDPs with 21.7% at 5-year follow-up [96] and 27% at 10-year follow-up [97]. Le et al. [17] stated in their review that a prototype soft-milling technology was responsible for 75% of caries incidences. 92% of these caries incidences caused complications and an unusual high occurrence of marginal gaps. Pjetursson et al. [32] also mentioned this outliner in the discussion but didn't as well provide additional calculations. It can be assumed that caries and marginal discoloration are less common events. Endodontic treatment as the most frequent reason for biological complications in Le's review wasn't discussed by the authors [17]. Periodontal diseases have occasionally been reported, but no differences can be seen between the various zirconia restorations [17,19–21,32,40,63]. Koenig and Wulfman et al. [71] point out, that monolithic zirconia restorations "are strong but stiff and unable to absorb stresses" and therefore complications in supporting tooth or implant, bonding or tribological partner can occur.

In vitro as well as in vivo studies have shown a low abrasion for polished zirconia. Satisfactory professional polishing seems to be possible only under laboratory conditions due to the high material hardness. [98]. Adjustment in the patient's mouth often is required in daily practice. Also, long-term water or low temperature degradation supported by the lower Al_2O_3 or Ytterbium content cannot yet be reliably assessed. It must be considered, that increased abrasion of the antagonist is possible in the long term. The question remains as to how the stomatognathic system reacts if the restoration does not follow the natural abrasion of the remaining dentition due to its high hardness. Although this question was asked a decade ago, no study has yet been able to provide any information on this topic.

Second generation monolithic zirconia restorations had excellent or good esthetic FDI (Fédération Dentaire Internationale) scores except for color match and translucency. The judgment by the treating dentists, who rated color as too bright in 65.2%, was more critical than by the patients (2.1%) [71].

The applied questionnaire on bias and methodological quality was a shortened and simplified version of the AMSTAR 2 [9] questionnaire and as such was not validated.

Table 1, 2, 3 and 4.

Due to the fact, that primary studies were included in several reviews and review authors did not consistently report the results of the individual studies, a quantitative analysis was not possible. However, the qualitative approach was suitable to achieve the aim of comprehensively identifying complications recognized so far in available systematic reviews.

5. Conclusion

The analyzed systematic reviews mostly examined veneered all-ceramic restorations. Regarding the technical, biological and aesthetical complications, the reviews show satisfactory results for zirconia-ceramic restorations, usually over 5-year observation periods. The predominant technical problem of veneering fractures could be overcome with adapted design or fabrication and the application of monolithic restorations. The few existing studies appear promising in this regard, but so far only cover short follow-up periods or small patient numbers. Findings on the in vivo behavior have not yet been incorporated into major systematic reviews. Due to the large number and diversity of zirconia-based materials, average values formed in meta-analyses often appear to be of limited practical significance. Likewise, conditions such as temporomandibular disorders, occlusion anomalies or bruxism that are frequently encountered in the general population, often led to exclusion from studies and transferability of the results for patients with these conditions therefore remains unclear. It also must be noted that no investigations on material associated long-term effects on the stomatognathic system as a whole were found. Further studies are required in this regard. For this purpose, uniform evaluation criteria should be established.

CRediT authorship contribution statement

Harald Laumbacher: Writing - original draft, Methodology, Investigation, Data curation, Visualization. **Thomas Strasser:** Writing - review & editing. **Helge Knüttel:** Methodology, Writing - review & editing. **Martin Rosentritt:** Conceptualization, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jdent.2021.103723.

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