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Review

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The effects of physical decontamination methods on zirconia implant surfaces: a systematic review

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ABSTRACT

Purpose: Peri-implantitis therapy and implant maintenance are fundamental practices to enhance the longevity of zirconia implants. However, the use of physical decontamination methods, including hand instruments, polishing devices, ultrasonic scalers, and laser systems, might damage the implant surfaces. The aim of this systematic review was to evaluate the effects of physical decontamination methods on zirconia implant surfaces.

Methods: A systematic search was conducted using 5 electronic databases: Ovid MEDLINE, PubMed, Scopus, Web of Science, and Cochrane. Hand searching of the OpenGrey database, reference lists, and 6 selected dental journals was also performed to identify relevant studies satisfying the eligibility criteria.

Results: Overall, 1049 unique studies were identified, of which 11 studies were deemed suitable for final review. Air-abrasive devices with glycine powder, prophylaxis cups, and ultrasonic scalers with non-metal tips were found to cause minimal to no damage to implant-grade zirconia surfaces. However, hand instruments and ultrasonic scalers with metal tips have the potential to cause major damage to zirconia surfaces. In terms of laser systems, diode lasers appear to be the most promising, as no surface alterations were reported following their use.

Conclusion: Air-abrasive devices and prophylaxis cups are safe for zirconia implant decontamination due to preservation of the implant surface integrity. In contrast, hand instruments and ultrasonic scalers with metal tips should be used with caution. Recommendations for the use of laser systems could not be fully established due to significant heterogeneity among included studies, but diode lasers may be the best-suited system. Further research—specifically, randomised controlled trials—would further confirm the effects of physical decontamination methods in a clinical setting.

Keywords: Dental implants; Decontamination; Dental instruments; Surface properties; Zirconium

Author Contributions

Conceptualization: Nathan Chiang Ping Tan, Catherine Miller, Dileep Sharma. Formal analysis: Nathan Chiang Ping Tan, Ahsen Khan. Funding acquisition: Nathan Chiang Ping Tan, Catherine Miller, Dileep Sharma. Investigation: Nathan Chiang Ping Tan, Ahsen Khan. Methodology: Nathan Chiang Ping Tan, Catherine Miller, Elsa Antunes, Dileep Sharma. Project administration: Catherine Miller, Elsa Antunes, Dileep Sharma. Writing - original draft: Nathan Chiang Ping Tan. Writing - review & editing: Catherine Miller, Elsa Antunes, Ahsen Khan, Dileep Sharma.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

INTRODUCTION

Dental implants have become an increasingly popular treatment option to replace missing teeth due to their predictable success in restoring aesthetics and function to edentulous areas of the dentition [1]. For decades, titanium implants have been considered the gold standard in dental implantology, owing to their excellent biocompatibility, favourable properties, and clinical success [2]. However, despite the current mainstream use of titanium implants in clinical practice, the grey metallic appearance of titanium can compromise the aesthetic outcomes in the presence of gingival recession or a thin gingival biotype [2,3]. It has also been reported that, although rare, implant failure can occur due to the deposition of titanium particles into surrounding tissues and subsequent hypersensitivity reactions in susceptible patients [4]. To overcome these disadvantages, there have been calls for the development of novel implant materials. Recently, zirconia implants have emerged as a prospective alternative to titanium implants [5]. Zirconia is a chemically inert material with minimal local and systemic side effects. It has been extensively used in other biomedical applications, such as orthopaedic surgery for total hip replacement, due to its high fracture resistance and flexural strength [2,5]. Furthermore, zirconia is a highly biocompatible material with an aesthetically pleasing tooth-coloured appearance that aligns with the increasing demand for metal-free implants [2]. A systematic review by Roehling et al. found that the osseointegration potential of zirconia implants is similar to that of titanium implants, despite a slower initial osseointegration process [6].

It is estimated that more than 12 million implants are installed each year worldwide [7]. Concomitantly with the increasing global number of dental implants, complications associated with their use are also anticipated to increase. The 2017 World Workshop Classification of Periodontal and Peri-Implant Disease and Conditions [8] identified the healthy state of periodontal and peri-implant tissues as the absence of inflammation, bleeding on probing, swelling, and suppuration. However, in an inflammatory peri-implant tissue state, peri-implant disease, which is associated with a high incidence of implant failure, can occur [7]. Peri-implant mucositis is an inflammatory process of a reversible nature that is limited to the soft tissues surrounding an implant [8]. It is accompanied by erythema, swelling, bleeding on probing, and/or suppuration [8,9]. If left untreated, peri-implant mucositis can progress to peri-implantitis, which is characterised by the progressive destruction of peri-implant bone [8]. Peri-implantitis is estimated to affect up to 18.8% of implant patients and 9.6% of implants placed [10].

It is well-established that plaque accumulation is the primary cause of peri-implant disease [11]. As soon as an implant is exposed to the oral environment, the implant surface is immediately colonised by micro-organisms within the first 30 minutes [12,13]. The initial bacterial adhesion onto the implant surface is the first, but most important step involved in biofilm formation and the development of peri-implant disease [11]. Implant surface characteristics, such as surface roughness, surface free energy, and surface chemistry, are also known to influence bacterial colonization and plaque accumulation [11,14-16].

Routine supportive periodontal care aims to prevent peri-implant complications by removing plaque from the implant surface. Various physical decontamination methods have been proposed with no definitive gold standard [17,18]. These include the use of ultrasonic scalers, metal and plastic curettes, air-abrasive devices, prophylaxis cups, and laser systems. It is thought that some of the instruments commonly used in peri-implantitis therapy and routine

maintenance procedures have the potential to roughen the implant surface [18]. While a rougher surface is known to facilitate osseointegration, it can also increase the likelihood of bacterial adhesion [19]. Surface alterations in the form of grooves and scratches created during implant decontamination may provide an environment conducive to bacterial colonization, which in turn can lead to peri-implant mucositis and peri-implantitis [18]. Moreover, implant maintenance is a routine part of clinical practice and clinicians should have a good understanding of appropriate prophylaxis measures that can be carried out safely in the dental clinic.

Although a systematic review by Louropoulou et al. [18] examined surface alterations caused by mechanical instruments on titanium implants, no systematic review on the effects of physical decontamination methods on zirconia implant surfaces has been published. Louropoulou et al. [18] concluded that non-metal instruments and rubber cups are suitable for decontaminating smooth titanium surfaces as they preserve the implant surface. Similarly, non-metal instruments and air-abrasive devices cause minimal to no surface damage and are recommended for rough titanium implant surfaces [18]. As titanium and zirconia are implant materials with different physical and chemical properties, there is a need to analyse and critically appraise the scientific literature on zirconia implant decontamination. Therefore, the aim of this systematic review was to evaluate the evidence regarding the effects of various physical decontamination methods on zirconia implant surfaces from the relevant literature.

Focus question

The focus question, "What is the effect of physical decontamination methods commonly used in peri-implantitis therapy on zirconia implant surfaces?" was developed in accordance with the PICO framework.

- Population: Zirconia implants, discs and/or components with a zirconia surface
- Intervention: Different types of physical decontamination methods
- Comparison: Between decontamination methods and/or control group
- Outcomes: Surface roughness and surface alterations (primary outcomes); further predisposition to bacterial adhesion and/or peri-implant disease following instrumentation (secondary outcomes)

METHODS

Protocol and registration

This systematic review was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [20]. The review protocol was registered in the PROSPERO database with the registration number CRD42020173316 [21].

Eligibility criteria

Studies were only included in this review if the following inclusion criteria were met: 1) study designs including *in vitro* studies, animal studies, randomised controlled trials (RCTs), and human *in vivo* studies (published or unpublished); 2) studies involving the use of zirconia dental implants and/or discs; 3) studies examining the use of curettes, scalers, air-abrasive systems, brushes, rubber cups, or lasers as physical decontamination methods; 4) studies making a comparison between interventions and/or a control group.

The exclusion criteria were: 1) cohort studies, reviews, case reports, case series, systematic reviews, or opinions; 2) studies not in the English language; 3) studies for which the full text was inaccessible; 4) studies that did not examine zirconia surfaces; 5) studies combining different treatment modalities within an intervention; 6) studies using surgical or chemotherapeutic methods of decontamination.

Information sources and search strategy

A systematic search was performed of 5 electronic databases: Ovid MEDLINE, PubMed, Scopus, Web of Science, and the Cochrane registry, with no restrictions on the location or date of publication. The search strategy involved a combination of Medical Subject Headings (MeSH) terms, keywords, and Boolean operators (AND, OR), which were customised to each database accordingly to retrieve articles. The search strategy for PubMed is illustrated in Table 1. The full electronic search strategy for all databases can be viewed in Appendix 1. The keywords chosen were intended to maximise the number of relevant studies to be considered for inclusion in the review. Hand searching of 6 selected dental journals was also completed to identify studies that may not have been indexed in the databases listed above. The following journals were searched: *International Journal of Implant Dentistry, Clinical Oral Implant Research, International Journal of Oral & Maxillofacial Implants, Journal of Periodontology, Journal of Clinical Periodontology,* and *Lasers in Dental Science*. The OpenGrey database was also searched, and requests were sent to relevant experts in the field to retrieve any potentially eligible grey literature. The reference list of all eligible studies was hand-searched to ensure literature saturation and to retrieve any additional studies that could potentially meet the eligibility criteria. The search was finalised on March 12, 2020 and re-confirmed on December 16, 2020. The results were exported to be stored in the Endnote reference management software (Endnote version X9.2 Clarivate Analytics, Philadelphia, PA, USA).

Study selection

After eliminating duplicates, the title and abstract of all studies were screened independently by 2 reviewers (N.C.P.T. and A.K.) to identify those meeting the selection criteria. Studies considered potentially eligible by at least 1 reviewer or studies with insufficient information in the title and abstract to make a conclusive decision were obtained for full-text evaluation. The full text was then evaluated independently by the 2 reviewers. Any disagreements between reviewers were resolved by discussion. In the event where a consensus could not be reached, 3 independent reviewers (D.S., C.M.M., and E.A.) were consulted and a final decision was made.

Data collection

Data from the included studies were independently extracted by 2 reviewers (N.C.P.T. and A.K.) using custom-designed spreadsheets (Tables 2 and 3). The extracted data included:

Table 1. PubMed search strategy

#	Searches	Results
1	Zirconium [MeSH Term] OR Zirconium or Zirconia OR Y-TZP	14,197
2	Dental Implants [MeSH Term] OR Dental Implantation [MeSH Term] OR Materials Testing [MeSH Term] OR Dental Implant	116,002
3	ultrasonic OR curette OR curettage OR scaling OR laser OR debridement OR disinfection OR air abrasion OR instrumentation OR decontamination OR dental instruments	1,166,026
4	Surface Property [MeSH Term] OR Surface Properties [MeSH Term]	126,896
5	Surface Roughness OR surface alteration OR surface changes	134,645
6	4 OR 5	245,542
7	1 AND 2 AND 3 AND 6	645

MeSH: Medical Subject Headings.

author, year of publication, implant component, type of intervention, control group, number of treated surfaces, method of outcome assessment, outcome parameters, and conclusion of the study. The final data were agreed upon by the 2 initial reviewers (N.C.P.T. and A.K.) and any differences were resolved by further discussion among the full team of reviewers (N.C.P.T., A.K., D.S., C.M.M., and E.A.). If additional information was necessary, attempts were made to contact the author of corresponding papers for further clarification.

Table 2. Characteristics of the included *in vitro* studies that investigated surface outcome parameters on implant surfaces

Author (yr)	Implant type/ component	Intervention (n=no. of specimens per group)	Control	Measurement tool	Outcome parameter	Study conclusion
Stubinger et al. [33] (2007)	Zirconia discs	Er:YAG laser (n=24) CO_2 laser (n=90) Diode laser (n=12) Control group (n=6) *Six specimens per laser parameter	Untreated discs	SEM Confocal microscopy	S_a [a)]	The diode laser system was the only one to offer surface preservation and safety of zirconia surfaces in the treatment of peri-implantitis.
Vigolo et al. [35] (2010)	Zirconia discs	Control group (n=20) Steel curette (n=20) Plastic curette (n=20) Titanium curette (n=20) Piezoelectric ultrasonic scaler with metal universal tip (n=20) Ultrasonic scaler with steel tip (n=20) Magnetostrictive ultrasonic scaler with a metal straight tip (n=20)	Untreated discs	SEM Profilometry	R_a	All instrument types caused significant alterations to zirconia. Hand instruments resulted in numerous small scratches, whilst ultrasonic scalers caused deep scratches.
Seol et al. [32] (2012)	Zirconia discs Titanium discs Type II gold discs Cobalt-chromium alloy discs Porcelain discs	Ultrasonic scaler with stainless steel (SS) tip (n=5) Ultrasonic scaler with carbon composite (CC) tip (n=5) Ultrasonic scaler with copper alloy (CA) tip (n=5)	Untreated section of disc	SEM Confocal microscopy	R_a	All 3 ultrasonic tips (SS, CC, CA) can be used for zirconia implant maintenance as they did not cause any alterations following scaling. The SS tip induced significant surface alterations on titanium, type II gold alloy, cobalt chrome alloy, and porcelain.
Checketts et al. [26] (2014)	Zirconia discs Type II gold alloy discs Lithium disilicate discs	Control group (n=12) Ultrasonic scaler with metal tip (n=12) Stainless steel curette (n=12) Prophylaxis cup (n=12)	Untreated discs	SEM Profilometry	R_a	No significant surface alterations were seen on zirconia and lithium disilicate specimens with all instrumentation methods. Stainless steel curettes and prophylaxis cup increased surface roughness values for type III gold alloy.
Miranda et al. [30]	Zirconia discs SLA titanium discs	Control group (n=5) Er,Cr:YSGG laser (n=5)	Untreated discs	Confocal microscopy	R_a S_a	The Er:YAG laser system decreased the surface roughness of zirconia samples after 30 seconds of irradiation at 1.5 W and 20 Hz. Conversely, the irradiated SLA Ti surfaces demonstrated an increase in roughness with superficial cracks
Kushima et al. [28] (2016)	Zirconia discs Titanium discs SLA titanium discs	Control group (n=10) Diode laser (n=10)	Pre-treatment control	Confocal microscopy	R_a S_a	Diode laser irradiation for peri-implantitis treatment increased the temperature of zirconia and titanium without surface alterations
Lang et al. [29] (2018)	Zirconia discs Titanium discs Titanium-zirconium discs	Control group (n=4) Plastic curette (n=8) Titanium curette (n=8) Diode laser (n=8)	Untreated discs	SEM Profilometry	R_a	No significant difference in surface roughness was detected in zirconia samples across all instrument types. Repeated instrumentation did not cause any cumulative surface changes for all implant materials.
Vigolo et al. [34] (2018)	Zirconia discs Alumina discs Lithium disilicate discs	Control group (n=16) Steel curettes (n=16) Titanium curettes (n=16)	Untreated discs	Profilometry SEM	R_a	Steel and titanium curettes should be used with caution as it increased the roughness of all materials.

(continued to the next page)

Table 2. (Continued) Characteristics of the included *in vitro* studies that investigated surface outcome parameters on implant surfaces

Author (yr)	Implant type/ component	Intervention (n=no. of specimens per group)	Control	Measurement tool	Outcome parameter	Study conclusion
Nakazawa et al. [31] (2018)	Non-LTD zirconia discs	Untreated control (n=6) Ultrasonic scaler with a plastic (PEEK) tip (n=6) Ultrasonic scaler with a stainless-steel tip (n=6)	Untreated discs	SEM Optical Interferometry	S_a[a)]	Ultrasonic scaling with a stainless-steel tip significantly increased the surface roughness of non-LTD and LTD zirconia discs.
	LTD-induced zirconia discs	Untreated control (n=6) Ultrasonic scaler with a plastic tip (n=6) Ultrasonic scaler with a stainless-steel tip (n=6)				The ultrasonic scaler with the plastic PEEK tip did not cause any visible surface damage on non-LTD and LTD samples. Remnants of the abraded tip was left behind on LTD zirconia discs.
Alhaidary et al. [25] (2019)	Zirconia implants	2940 nm Er:YAG laser at 1.5 W/10 Hz (n=3) 2940 nm Er:YAG laser at 1.5 W/30 Hz (n=3)	Pre-treatment control	Confocal microscopy	R_p	The Er:YAG laser system (1.5 W/10 Hz & 1.5 W/30 Hz) decreased surface roughness and was safe for implant surface decontamination
Huang et al. [27] (2019)	Zirconia discs	Control group (n=12)	Untreated discs	Profilometry	R_a	There were negligible differences in surface morphology among the treated zirconia samples.
	Titanium discs	Titanium curette (n=12) Carbon-fibre reinforced plastic curette (n=12) Ultrasonic scaler with a carbon fibre tip (n=12) Air-abrasive device with glycine powder (n=12)		Atomic force microscopy		Zirconia appears to be a good implant material for long-term maintenance due to its superior resistance to damage from cleaning procedures compared to titanium.

LTD: low-temperature degradation, PEEK: polyether ether ketone, SEM: scanning electron microscopy, R_a: mean roughness (defined as arithmetical mean of the absolute values of the profile deviations from the mean line of the roughness profile), R_p: maximum profile peak height (defined by the highest point along the sampling length), S_a: mean height (defined as the arithmetical mean of the absolute values of surface departure above and below the mean plane within the sampling area).
[a)]Additional surface outcome parameters were investigated by the study.

Table 3. Characteristics of the included *in vitro* studies that investigated bacterial adhesion on zirconia implant surfaces following instrumentation (secondary outcome)

Author (yr)	Implant type/ component	Instruments used to treat specimens	Surface roughness of treated specimens (R_a/S_a)	Bacterial species used	Incubation period	Conclusion of study
Checketts et al. [26] (2014)	Zirconia discs	Untreated group (UG)	0.220 μm (UG)	*Streptococcus mutans* *Lactobacillus acidophilus* *Actinomyces viscosus*	4 days	A significant increase in bacterial adhesion was only seen on zirconia samples treated with the stainless-steel curette (SC)
		Ultrasonic scaler with metal tip (UM)	0.202±0.009 μm (UM)			
		Stainless steel curette (SC)	0.200±0.007 μm (SC)			
		Prophylaxis cup (PC)	0.226±0.018 μm (PC)			
Nakazawa et al. [31] (2018)	Zirconia discs	Untreated group (UG)	0.0014±0.0001 μm (UG)	*Streptococcus mitis* *Streptococcus oralis*	3 and 6 hrs	LTD and ultrasonic scaling did not significantly affect bacterial adhesion among all treatment groups.
		Ultrasonic scaler with a plastic PEEK tip (UP)	0.0016±0.0002 μm (UP)			
		Ultrasonic scaler with a stainless-steel tip (US)	0.0023±0.0005 μm (US)			
	LTD-induced zirconia discs	Untreated group (LUG)	0.0054±0.0006 μm (LUG)			
		Ultrasonic scaler with a plastic tip (LUP)	0.0084±0.0017 μm (LUP)			
		Ultrasonic scaler with a stainless-steel tip (LUS)	0.1171±0.0614 μm (LUS)			
Huang et al. [27] (2019)	Zirconia discs	Untreated group (UG)	0.07 μm (UG)	*Streptococcus mitis*	1 hrs	No statistically significant difference in bacterial adhesion between all treatment groups
		Titanium curette (TC)	0.13±0.06 μm (TC)			
		Carbon-fibre reinforced plastic curette (RPC)	0.11±0.03 μm (RPC)			
		Ultrasonic scaler with a carbon fibre tip (UC)	0.08±0.01 μm (UC)			
		Air-abrasive device with glycine powder (AA)	0.07±0.01 μm (AA)			

LTD: low-temperature degradation, PEEK: polyether ether ketone

Table 4. Modified CONSORT checklist of items for reporting *in vitro* studies of dental materials [22,23]

Item	Domain
1	Abstract: structured summary of trial design, methods, results, and conclusions
Introduction	
2	Scientific background and explanation of rationale with specific objectives and/or hypotheses
Methods	
3	Intervention: the intervention for each group, including how and when it was administered, with sufficient detail to enable replication
4	Outcomes: completely defined, pre-specified primary and secondary measures of outcome, including how and when they were assessed
5	Sample size: how sample size was determined
6	Randomisation: method used to generate the random allocation sequence
7	Allocation: mechanism used to implement the random allocation sequence, describing any steps taken to conceal the sequence until intervention was assigned
8	Implementation: who generated the random allocation sequence, who enrolled teeth, and who assigned teeth to intervention
9	Blinding: if done, who was blinded after assignment to intervention and how
10	Statistics: statistical methods used to compare groups for primary and secondary outcomes
Results	
11	For each primary and secondary outcome, results for each group, and the estimated size of the effect and its precision
Discussion	
12	Trial limitations, addressing sources of potential bias, imprecision, and, if relevant, multiplicity of analyses
Other information	
13	Sources of funding and other support role of funders
14	Where the full trial protocol can be accessed, if available

Quality and risk of bias in individual studies

The quality and risk of bias assessment was performed independently by the 2 reviewers (N.C.P.T. and A.K.) during the data extraction process. Any disagreements or uncertainties were discussed with 3 independent reviewers (D.S., C.M.M., and E.A.) until an agreement was reached. The modified CONSORT checklist of items for reporting *in vitro* studies of dental materials [22,23] was used to assess the risk of bias in the included studies (Table 4). This tool explored 14 domains to determine the risk of bias for each study which, was then categorised as "low," "unclear," or "high."

The objective of this systematic review was to determine which physical decontamination method caused the least surface alterations to zirconia implant surfaces. As such, the strength of recommendations and certainty of evidence for each studied decontamination method was assessed using the Grades of Recommendation, Assessment, Development and Evaluation (GRADE) system [18,24]. Based on information about the studies' risk of bias, imprecision, inconsistency, indirectness, and publication bias, the quality of evidence was then graded as "very low," "low," "moderate," or "high."

Results

Study selection

Figure 1 illustrates the PRISMA flowchart for the literature selection process. Electronic searches of Ovid MEDLINE, PubMed, Web of Science, Scopus, and Cochrane resulted in the identification of 1,721 studies, along with 6 additional papers found by hand-searching. After the removal of duplicates, 1,048 studies were screened according to title and abstract. After screening, 26 studies were selected for a full-text evaluation to assess their eligibility according to the selection criteria. After the evaluation, 11 studies [25-35] were included for the final review. Fifteen studies did not meet the inclusion criteria and were excluded for the following reasons: the study did not investigate interventions for decontamination purposes (n=9); the study did not use zirconia as an implant material (n=5); or there was no comparator or control group (n=1).

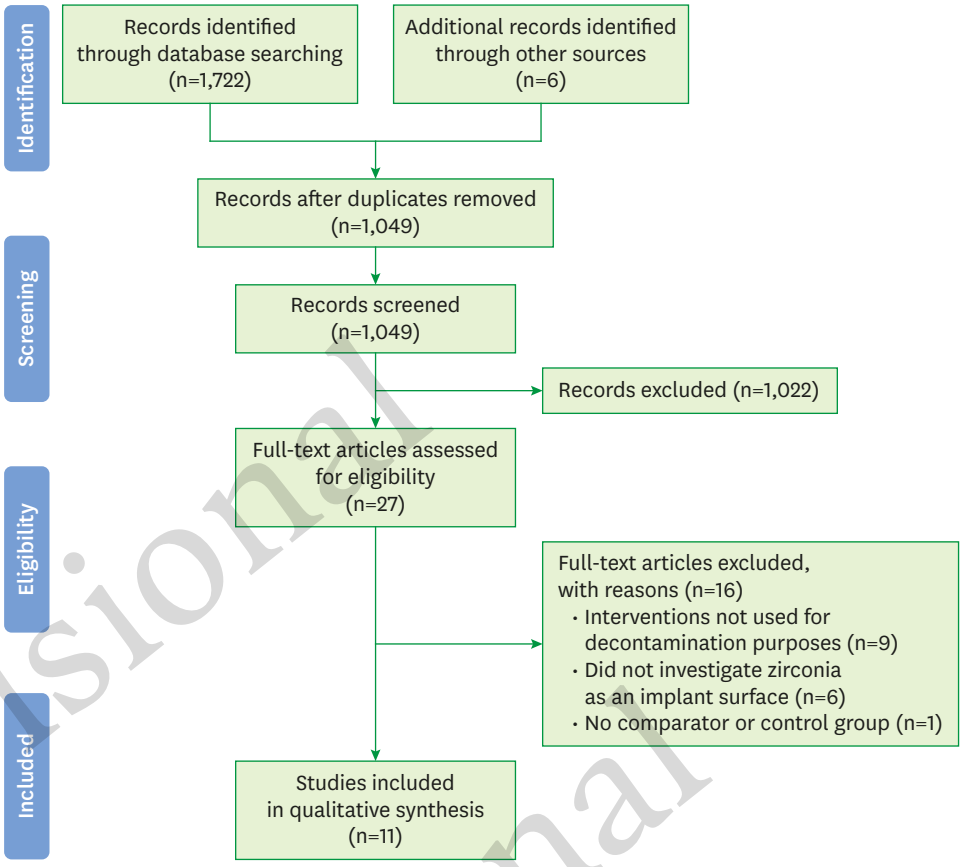

Figure 1. PRISMA flow diagram showing the selection process followed for this review.

Study characteristics

While no restrictions were placed on the date of publications, the studies included in this review were all found to be *in vitro* studies published between 2007 and 2019. No RCTs or *in vivo* studies addressing the review question were found. No unpublished study of relevance was located in the grey literature search.

After an evaluation of the selected studies, only 1 study was found to assess zirconia implants [25] as a test sample, whereas 10 studies [26-35] used zirconia discs to represent an implant surface. In most studies, the implant surface roughness was measured with mean roughness (R_a) or mean height (S_a) as the surface outcome parameter. The R_a is a 2-dimensional parameter defined as the "arithmetical mean of the absolute values of the profile deviation from the mean line" [36]. The S_a is a 3-dimensional area roughness parameter expressed as the "arithmetical mean of the roughness area from the mean plane" [37]. Eight studies [26-30,32,34,35] calculated R_a and 4 studies [28,30,31,33] calculated S_a. One study [25] measured surface roughness according to a different surface parameter, R_p, which involves calculating the maximum profile peak height of the sample [38].

To evaluate implant surface roughness, various instruments were employed to assess surface topography. Qualitative measurements were carried out using scanning electron microscopy (SEM) in 7 studies [26,29,31-35]. Quantitative measurements of R_a or S_a were calculated using

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confocal microscopy in 5 studies [25,28,30,32,33]; profilometry in 5 studies [26,27,29,34,35]; optical interferometry in 1 study [31], and atomic force microscopy in 1 study [27].

Tables 2 and 3 summarise the characteristics of the included studies. Of the 11 included studies, 7 studies investigated scaling and polishing systems and 4 studies examined laser systems for peri-implantitis therapy.

Quality and risk of bias assessment

The quality and risk of bias for all included studies are detailed in Table 5. According to the modified CONSORT checklist for *in vitro* studies, most of the included studies [26,27,29,31,32,34,35] were deemed to be of good quality, with a low risk of bias. Three studies [25,30,33] were found to have a high risk of bias and 1 study [28] had an unclear risk of bias. In terms of the GRADE system, a summary of the quality of evidence and strength of recommendations for each studied intervention is listed in Table 6.

Table 5. Quality of evidence and summary assessment of the included *in vitro* studies according to the modified CONSORT checklist

Study (yr)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Summary assessment
Stubinger et al. [33] (2007)	+	?	+	+	–	n/a	n/a	n/a	–	+	?	?	+	–	High
Vigolo et al. [35] (2010)	+	+	+	+	–	n/a	n/a	n/a	+	+	+	+	–	–	Low
Seol et al. [32] (2012)	+	?	+	+	–	n/a	n/a	n/a	–	+	+	+	+	–	Low
Checketts et al. [26] (2014)	+	+	+	+	–	n/a	n/a	n/a	–	+	+	+	–	–	Low
Miranda et al. [30] (2014)	+	?	–	–	–	n/a	n/a	n/a	–	–	?	+	+	–	High
Kushima et al. [28] (2016)	+	?	+	+	–	n/a	n/a	n/a	–	+	+	?	+	–	Unclear
Lang et al. [29] (2016)	+	+	+	?	+	n/a	n/a	n/a	–	+	+	+	+	–	Low
Vigolo et al. [34] (2017)	+	+	+	+	–	n/a	n/a	n/a	+	+	+	+	–	–	Low
Nakazawa et al. [31] (2018)	+	+	+	+	–	n/a	n/a	n/a	–	+	+	+	+	–	Low
Alhaidary et al. [25] (2019)	+	?	+	?	–	n/a	n/a	n/a	–	+	?	+	+	–	High
Huang et al. [27] (2019)	+	+	+	+	–	n/a	n/a	n/a	–	+	?	+	+	–	Low

+: low risk of bias, ?: unclear risk of bias, –: high risk of bias, n/a: not applicable.

Table 6. GRADE summary of findings

Intervention	No. of specimens treated (studies)	Risk of bias	Inconsistency	Indirectness	Imprecision	Publication bias	Overall certainty of evidence
Non-metal hand instruments	40 (3 studies)	Not serious	Serious[b]	Serious[c]	Indeterminable	Not suspected	⊕⊕◯◯ Low
Metal hand instruments	104 (5 studies)	Not serious	Serious[b]	Serious[c]	Indeterminable	Not suspected	⊕⊕◯◯ Low
Rubber cups	12 (1 study)	Not serious	No	Serious[c]	Indeterminable	Not suspected	⊕⊕⊕◯ Moderate
Air-abrasive devices	12 (1 study)	Not serious	No	Serious[c]	Indeterminable	Not suspected	⊕⊕⊕◯ Moderate
Ultrasonic scalers with non-metal tips	29 (3 studies)	Not serious	Serious[b]	Serious[c]	Indeterminable	Not suspected	⊕⊕◯◯ Low
Ultrasonic scalers with metal tips	94 (4 studies)	Not serious	Serious[b]	Serious[c]	Indeterminable	Not suspected	⊕⊕◯◯ Low
Laser system	155 (5 studies)	Very serious[a]	Serious[b]	Serious[c]	Indeterminable	Not suspected	⊕◯◯◯ Very low

Outcome of interest: surface roughness (for which a single pooled effect estimate was not available and only a narrative synthesis of the evidence was provided).
GRADE Working Group grades of evidence: i) High quality: Further research is very unlikely to change our confidence in the estimate of the effect; ii) Moderate quality: Further research is likely to have an important impact on our confidence in the estimate of the effect and may change the estimate; iii) Low quality: Further research is very likely to have an important impact on our confidence in the estimate of the effect and is likely to change the estimate; iv) Very low quality: Any estimate of the effect is very uncertain
[a]The evidence was downgraded by 2 levels due to very serious concern regarding the risk of bias; 1 or more included studies have high risk of bias. [b]The evidence was downgraded by 1 level due to a high degree of heterogenity in study methodologies. [c]The evidence was downgraded by 1 level due to the use of discs as a representative study material of dental implants.

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Hand scaling and polishing systems

Three studies [27,29,35] evaluated the effects of non-metal hand instruments on zirconia surfaces. In 2 of these studies [27,29], the use of non-metal curettes did not cause any significant alterations to zirconia samples. Huang et al. [27] compared the use of carbon-fibre reinforced plastic curettes on zirconia and titanium discs. While both zirconia and titanium demonstrated a minor increase in surface roughness, there was no statistically significant difference between the treated and untreated groups. Lang et al. [29], who investigated the effects of repeated instrumentation (20 strokes vs. 100 strokes), also found a negligible difference in surface roughness for zirconia samples treated with plastic curettes. Vigolo et al. [35] were the only authors who reported that plastic curettes could cause a significant increase in the surface roughness of zirconia samples.

Five studies [26,27,29,34,35] investigated the use of metal hand instruments; however, the evidence supporting their use for cleaning zirconia surfaces appears to be inconsistent. In 2 studies [34,35] conducted by the same group, steel and titanium curettes resulted in a significant increase in R_a values compared to the non-instrumented control. Titanium curettes displayed a similar abrasive capacity to that of steel curettes, with both instruments causing multiple tiny scratches consistent with irreversible damage to the surface. In contrast, Huang et al. [27] and Lang et al. [29] reported that regardless of the number of strokes applied, titanium curettes did not cause any significant changes to the surface roughness of zirconia samples. Checketts et al. [26] also reported that there was no significant difference between pre- and post-treatment surface roughness for samples treated with stainless steel curettes.

In terms of polishing systems, the use of prophylaxis cups and air-abrasive devices were both examined in 1 study each. Huang et al. [27] reported that air-abrasive devices loaded with glycine powder did not cause any significant changes to the original surface. Similarly, Checketts et al. [26] reported that the use of a prophylaxis cup operating at 5,000 rpm for 20 seconds with fine prophylaxis paste appeared to leave the surface unaltered.

Ultrasonic scaling systems

Three studies [27,31,32] evaluated the effects of ultrasonic scalers with non-metal tips. Huang et al. [27] and Seol et al. [32] found no visible surface alterations to zirconia samples following treatment with carbon-fibre or carbon-composite ultrasonic tips. A study by Nakazawa et al. [31] investigated the effects of an ultrasonic scaler with a polyether ether ketone (PEEK) tip on 2 types of zirconia surfaces. One surface had been autoclaved to artificially induce low temperature degradation (LTD), whilst the other surface had no prior surface treatments (non-LTD). The study found that non-LTD samples did not experience any substantial alterations; however, the surfaces of LTD samples consisted of small peaks rather than pits. Nakazawa et al. [31] commented that the increase in surface roughness was not due to surface damage, but rather debris and remnants of the abraded PEEK tip being left behind after instrumentation.

Four studies [26,31,32,35] evaluated the use of ultrasonic scalers with metal tips. Seol et al. [32] and Checketts et al. [26] did not find any increase in surface roughness following ultrasonic scaling with tips made from conventional metal or copper alloy. Checketts et al. [26], however, reported surface discolouration of zirconia specimens after instrumentation, which was attributed to be residue from the metallic ultrasonic scaler tip. Conversely, Vigolo et al. [35] and Nakazawa et al. [31] reported that ultrasonic scalers with metal tips caused

noticeable damage to zirconia surfaces. This damage was seen in the form of deep scratches in the study of Vigolo et al. [35] and as micro-pits in the study of Nakazawa et al. [31], in which the micro-pits were due to the pull-out of surface grains. Nakazawa et al. [31] also found that LTD-induced samples were increasingly susceptible to surface deterioration due to degradation of the surface physical properties.

Laser systems

Four studies [25,28,29,33] evaluated the effects of laser systems on the surface characteristics of zirconia implant surfaces. The laser systems investigated included Er:YAG lasers, CO_2 lasers, diode lasers, and Er,Cr:YSGG lasers.

Er:YAG laser systems

Two studies [25,33] examined Er:YAG laser systems for implant surface decontamination. In the study by Alhaidary et al. [25], irradiation was performed at 1.5 W/10 Hz and 1.5 W/30 Hz for 120 seconds. The Er:YAG lasers decreased surface roughness by smoothing the original surface at the designated laser parameters. There were also no signs of thermal defects and, as such, the study concluded that Er:YAG lasers are suitable for zirconia implant decontamination at 1.5 W/10 Hz and 1.5 W/30 Hz. Similarly, Stubinger et al. [33], who investigated a number of different laser parameters, found that regardless of power output and irradiation time, Er:YAG lasers did not cause any significant surface alterations.

CO_2 laser systems

One study [33] evaluated a CO_2 laser system and found that the surface damage caused by the CO_2 laser was dependent upon applied energy and irradiation time. Surface alterations were visible after an irradiation time of 10 seconds at a power output of 5 W. As the irradiation time increased, material cracking and melting were apparent after 20 seconds at 4.5 W and 60 seconds at 3.5 W.

Diode laser systems

Three studies [28,29,33] investigated the effects of diode laser irradiation on zirconia implant surfaces with significant inter-study variations in the laser parameters employed. Kushima et al. [28] reported that an 808-nm diode laser at 1 W for 20 seconds did not increase surface roughness parameters. Lang et al. [29] also reported no surface alterations following the use of a diode laser at 1.4 W for 60 seconds. The results from Lang et al. [29] and Kushima et al. [28] are comparable to those of Stubinger et al. [33], who found that irrespective of power output and irradiation time, an 810-nm diode laser did not cause any surface defects such as melting, micro-cracks, or crater-like alterations.

Er,Cr:YSGG laser systems

One study [30] evaluated changes to the surface roughness of zirconia and titanium samples following the use of an Er,Cr:YSGG laser system. Miranda et al. [30] found a significant reduction in surface roughness for zirconia samples subjected to 1.5 W for 30 seconds compared to the untreated control. Titanium samples, in contrast, experienced a significant increase in surface roughness with distinct visual alterations in the form of cracks.

Bacterial adhesion following instrumentation

Three studies [26,27,31] investigated bacterial adhesion following instrumentation (secondary outcome) with different types of bacterial species. Huang et al. [27] inoculated *Streptococcus mitis* for 1 hour, Nakazawa et al. [31] cultured *S. mitis* and *Streptococcus oralis* for 3

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and 6 hours, and Checketts et al. [26] incubated *Streptococcus mutans*, *Lactobacillus acidophilus,* and *Actinomyces viscosus* for 4 days. Both Checketts et al. [26] and Nakazawa et al. [31] counted colony-forming units (CFU), while Huang et al. [27] quantified adhered bacteria using a turbidity test based on optical density. Checketts et al. [26] reported that zirconia samples treated with stainless steel curettes experienced a significant increase in bacterial adhesion despite having minimal surface alterations compared to the untreated control. Huang et al. [27], who reported no significant difference in surface roughness among all treated groups, found no significant difference in bacterial adhesion. Nakazawa et al. [31] also found no difference in bacterial adhesion on non-LTD and LTD samples despite a significant increase in surface roughness for LTD samples treated with plastic and metal ultrasonic scaler tips.

DISCUSSION

Establishing clinical peri-implant health and halting the progression of peri-implant disease are among the primary goals of peri-implantitis therapy [39]. However, despite the growing importance of peri-implantitis therapy and routine maintenance care in everyday clinical practice, no evidence-based protocol for implant decontamination currently exists. This is of significant concern as special guidelines must be taken to select instruments that are safe for implant cleaning and there are no specific guidelines for clinicians to follow. A roughened implant surface is known to promote bacterial adhesion and colonization [14,15]. Surface alterations in the form of scratches or micro-pits may change the surface composition, preventing re-osseointegration especially if bacteria cannot be sufficiently eliminated from the implant surface [40,41]. In this systematic review, we were able to identify and critically appraise 11 studies that reported the effects of various physical decontamination methods on zirconia implant surfaces.

This systematic review found differing results between studies that examined metal and non-metal hand instruments of similar material composition. In some studies [34,35], plastic curettes, steel curettes, and titanium curettes significantly increased the surface roughness of zirconia samples, whilst in other studies [26,27,29], a negligible difference in surface roughness was observed. The discrepancy in the results can be explained by the significant heterogeneity in the treatment parameters employed, angulation of instrumentation, magnitude of force, and number of strokes applied to samples in each study. Furthermore, the chemical composition of zirconia, which has an impact on the hardness as well as the surface texture, may have affected the results. Checketts et al. [26] and Vigolo et al. [34,35] both used a custom device that restricted the instrumentation force to 5 N and 6.9 N, respectively. In contrast, Huang et al. [27] did not consider calibrating the magnitude of force in their study, and Lang et al. [29] performed instrumentation deemed consistent with the amount of force that would be used to remove adherent calculus deposits from a root surface. In addition to force, the number of strokes and angulation of instruments also differed across the studies. Vigolo et al. [34,35] and Checketts et al. [26] carried out 5 strokes with the curette blade at a 70° and 15° angle (relative to the surface), respectively. Huang et al. [27] performed overlapping strokes perpendicular to the surface with no mention of the number of strokes carried out. However, regardless of variations in the methodologies employed between studies, it is important to consider whether these instruments caused any surface alterations. In a clinical setting, there are differences in the way clinicians operate, and variables such as the angulation of instruments and the force and number of strokes will neither be constant nor measured during implant decontamination procedures.

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Polishing systems such as the prophylaxis cup and air-abrasive devices with glycine powder did not cause any damage to zirconia surfaces. However, it should be noted that a prophylaxis cup with fine prophylaxis paste was only examined in 1 study [26] and operated at 1 speed (5,000 rpm) for 20 seconds. Further research needs to be conducted to assess whether the speed of the handpiece and duration of treatment affect implant surface roughness. In terms of air-abrasive devices, Huang et al. [27] operated the device with the water and power output set at the medium level and the nozzle kept 0.5 cm away from the sample and perpendicular to the surface. Again, variables such as air pressure, spraying distance, powder type, and particle size may all have an impact on the abrasive capacity of the device and should be considered during decontamination procedures. The use of air-abrasive devices and prophylaxis cups for implant cleaning appears promising; however, due to the lack of studies on polishing systems, a definitive conclusion regarding their use could not be fully established.

Ultrasonic scalers with metal tips should be used with caution, as some studies [31,35] reported significant alterations in the form of deep scratches or micro-pits following usage. In the study by Nakazawa et al. [31], the effects of LTD and ultrasonic scalers on zirconia surfaces were examined. LTD, also known as aging, is a phenomenon that affects the micro-structural integrity of zirconia implants in prolonged contact with water and bodily fluids [31,42]. It is characterised by a reduction in mechanical strength and an increase in micro-crack generation [42]. Nakazawa et al. [31] found that ultrasonic scaling with a metal tip caused micro-pitting of non-LTD samples due to the pull-out of surface grains. In contrast, LTD samples experienced greater surface wear due to degradation of the surface physical properties. As such, ultrasonic scalers with metal tips may be of significant concern for decontaminating zirconia implants, especially implants that have undergone LTD.

Ultrasonic scalers with non-metal tips such as those made from carbon composite or carbon fibre caused no surface alterations following treatment. In the study by Nakazawa et al. [31], the use of a PEEK tip did not cause any significant surface damage on non-LTD zirconia samples. Conversely, LTD samples experienced a statistically significant increase in surface roughness. The authors suggested that this roughening was caused by debris from instrumentation and remnants of the abraded tip rather than surface damage. The effects of surface debris and instrument residue on tissue healing, bacterial adhesion, and re-osseointegration are relatively unknown and need to be investigated in future studies.

The laser systems investigated include Er:YAG, CO_2, diode, and Er,Cr:YSGG lasers. The results show that the diode laser system is promising for implant decontamination, as despite the various laser parameters employed, there were no signs of surface alterations. In contrast, the CO_2 laser system is not recommended for implant decontamination as its use may cause material cracking and melting. Some laser systems, including Er:YAG and Er,Cr:YSGG lasers, decreased surface roughness by smoothing the implant surface. While a reduction in surface roughness may be beneficial in resisting bacterial adhesion, it may also interfere with tissue healing and the re-osseointegration of implants [43]. It has also been found that if the R_a of the implant surface is below the threshold R_a of 0.2 μm, limited benefits are achieved in terms of reducing the total amount of adhering bacteria [44]. As such, a balance in implant surface roughness must be maintained so that an implant with peri-implantitis has the ability to re-osseointegrate without being at increased risk of bacterial accumulation.

The significant heterogeneity between studies did not allow a quantitative synthesis of the data. Based on the data reviewed, it is not possible to reach a definitive conclusion on which

laser system is suitable for implant decontamination, as each laser parameter defines a new treatment modality. Different brands of lasers classified under the same laser system may differ in terms of their laser tip, wavelength, optical fibre diameter, and frequency, all of which may influence the extent of surface changes [45]. In addition, surface roughness is not the only important factor to consider when evaluating the suitability of laser systems for peri-implantitis therapy. In the oral environment, the effects of laser systems on soft and hard tissues surrounding the implant must also be taken into consideration. For example, while Stubinger et al. [33] found no surface alterations following Er:YAG laser irradiation, the authors did not recommend its use due to the potential of damaging underlying bone and soft tissues. As such, a standardised treatment protocol for laser therapy that is safe and effective for peri-implantitis therapy needs to be clearly established before ideal laser parameters can be evaluated in terms of their effects on implant surface roughness [45].

A direct relationship between decontamination-induced surface roughness and bacterial adhesion could not be determined in studies that investigated bacterial adhesion following instrumentation (secondary outcome). This may have been due to the fact that differences in surface roughness between treated and untreated groups were not significant enough to affect bacterial adhesion on zirconia samples. Furthermore, the surface roughness of zirconia samples in the studies of Huang et al. [27] and Nakazawa et al. [31] was less than the threshold R_a of 0.2 μm (as seen in Table 3), at which the surface topography is known to have a minimal influence over bacterial colonization [44] In the study of Checketts et al. [26], zirconia samples treated with stainless steel curettes experienced a significant increase in bacterial adhesion compared to the untreated group despite minimal differences in surface roughness. This may have been due to the influence of other surface properties, including surface free energy, surface chemistry, and surface hydrophilicity, which are also positively related to bacterial adhesion [14,15]. As such, in these studies, a direct correlation between surface roughness and bacterial adhesion could not be established. It is also recommended that future studies use saliva samples instead of isolated bacterial species, as saliva contains many salivary glycoproteins (i.e., dental pellicles), which affect bacterial adherence.

The results of this review should be interpreted with some caution. First, the conclusions of this review are largely based around *in vitro* studies, which limits the extrapolation of results to the clinical setting. Second, our focus question aimed to evaluate the effect of physical decontamination methods on zirconia implant surfaces; however, our exhaustive search revealed a lack of studies that examined zirconia implants. Ten out of the 11 studies identified used implant-grade zirconia discs to represent the surface of implant bodies. However, the macrostructure of discs is not identical to that of dental implants, affecting the generalizability of the results. In addition, a majority of studies adopted a 1-time decontamination protocol, making it impossible to detect cumulative surface changes that would be associated with a lifetime of peri-implantitis treatment or implant maintenance. Third, significant heterogeneity among studies contributed to the limitation of the review. This heterogeneity was exacerbated by differences in treatment parameters, the use of various roughness parameters (e.g., R_a and S_a), and a range of quantification techniques/equipment. These surface parameters and measuring instruments such as profilometry, confocal microscopy, SEM, and atomic force microscopy provide slightly different roughness values, which hampers a direct quantitative comparison of results [46]. Standardisation of surface roughness outcome measurements and treatment parameters, ideally carried out in a clinical setting, will enable a more comparative evaluation and stronger clinical recommendations. A further limitation of this systematic review is that studies were restricted to those written in

the English language, which may have excluded relevant studies published in languages other than English.

Future research with higher-quality study designs and using zirconia implants rather than implant-grade zirconia needs to be conducted, as a lack of RCTs and *in vivo* studies was apparent. Furthermore, studies aimed to identify appropriate parameters for laser application in peri-implantitis therapy for zirconia implant surfaces. In addition, studies should also investigate the effects of decontamination methods on zirconia implants that have undergone pre-surface modifications such as acid etching and sandblasting, techniques commonly used to improve and achieve osseointegration. Lastly, the cleaning efficacy of decontamination methods on zirconia implant surfaces has not been clearly established and needs to be explored. Surface preservation may not be a desirable outcome if the method of decontamination proves to be ineffective for plaque and calculus removal.

CONCLUSION

Within the limitations of this review, air-abrasive devices and prophylaxis cups appear to be safe for zirconia implant decontamination, whereas hand instruments and ultrasonic scalers with metal tips should be used with caution due to the risk of damaging the implant surface. Further research would help clarify the effects of these decontamination methods in a clinical setting.

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