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REVIEW

Retention of CAD-CAM Implant-Supported Ceramic Restorations Luted to Titanium Bases: A Systematic Review of in-vitro Studies

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Abstract: This review aimed to compare the results of laboratory studies performed on adhesion methods of CAD-CAM implant-supported ceramic restorations to titanium-bases to analyze the factors that could affect this bond strength. The review was directed according to the guidelines delineated in the Preferred Reporting Items for Systematic Review and Meta-Analysis statement. Three databases including PubMed, Google Scholar, and Cochrane were investigated to identify related in vitro studies that mimicked clinical settings and published in international peer-reviewed journals between January 2000 and September 2024. The search yielded 5191 records; of these, 51 full-text articles were evaluated based on eligibility criteria. Ultimately, 31 studies were included. Different factors were assessed as possible influencers on ceramic/Ti-base bonding stability and strength. These include Ti-base height, different mechanical and chemical surface pretreatments of bonding surfaces, ceramic restoration material, luting system, and others. Ti-base abutment height is an important factor and thus it is recommended to use adequate Ti-base abutment height, whereas 3-mm-height should be used cautiously in posterior region. Combination of mechanical and chemical pretreatments of both bonding surfaces seems to enhance the bond strength; however, smooth Ti-bases rather than micro-grooved ones most likely benefit from sandblasting pretreatment. While the type of resin bonding system may affect the bonding performance, the interaction of some cements with definite ceramic materials could enhance the bond strength. The clinician must consider all those factors to have an effective bonding.

Keywords: dental implant, bond strength, Ti-base, ceramic restoration, resin cement, zirconia

Introduction

Osseointegration has transformed dental treatments, making implant-supported prostheses a preferred option for replacing missing teeth. These treatments demonstrate remarkable long-term implant survival rates, often surpassing 95% over ten years.[1–3]

Historically, metal-based handcrafted restorations with feldspathic ceramics were the norm. However, advancements in CAD-CAM technology and the growing demand for esthetic solutions have broadened the scope for all-ceramic reconstructions, making them more cost-effective and efficient to produce.[4]

Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) ceramics are gaining popularity in implant dentistry due to their superior mechanical properties, low water solubility, reduced bacterial adherence, excellent corrosion resistance, and biocompatibility.[5] Currently, zirconia can be classified into different categories depending on the yttria content, homogeneous or hybrid composition, monochromatic or polychromatic, and monolayer or multilayer. Thus, zirconia use has been expanded to include several types of restorations.[6] Lithium disilicate glass-ceramics (LD) is another material known for its outstanding mechanical properties and translucency, making it increasingly used for screw-retained implant crowns with various CAD-CAM systems.[7] Other novel ceramic materials such as the polymer-infiltrated ceramic-network (PICN) are gaining popularity nowadays as implant restorative material.

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The incorporation of CAD-CAM technology into the dental field has led implant manufacturers to develop components compatible with the fully digital process, such as the titanium base abutment (Ti-base).[8] The Ti-base abutment, a prefabricated abutment with a combined digital library, is different from a customizable abutment due to its blending with a digital library.[9] The literature uses several terms for this prefabricated abutment, including Ti-base abutment, titanium-bonding base, titanium insert, hybrid abutment, cementing cap, and titanium cylinder.[8]

Ti-bases offer several advantages. They facilitate the transition to a digital workflow, whether fully or partially, resulting in reduced production costs and significantly improved time efficiency.[4,10] Additionally, zirconia abutments combined with Ti-bases address issues associated with one-piece zirconia abutments, such as higher fracture rates and increased wear at the implant connection.[11] Moreover, combining a Ti-base with a ceramic meso-structure (2-piece hybrid abutment) or a fully contoured restoration (1-piece hybrid-abutment-restoration) customizes a standard component to support peri-implant soft tissue and enhance esthetics.[12] Furthermore, this screwmentable hybrid-abutment-restoration allows the bonding process to be performed in a controlled laboratory environment, reducing the possibility of cement residue.[13]

Although short-term clinical outcomes for Ti-base implant-supported ceramic restorations are promising,[9,14] concerns have been raised regarding the long-term bond stability. In vitro experiments that mimicked five years of clinical use have shown instances of crowns separating from the titanium-base abutments,[12,15] as well as marginal gaps and minor movement between the components.[15] As implant restorations with marginal misfits can lead to greater crestal bone loss compared to these that fit accurately,[16] debonding is the primary cause of most complications and subsequent failures.

Because the weak bond strength between the ceramic restoration and the Ti-base has been a source of worry,[12,15] various laboratory investigations[7,13,15,17–22] have examined this bond and the variables that impacted its strength. For instance, micromechanical[17,19] and chemical pretreatment[17] of ceramic restorations and Ti-bases' bonding surfaces have been shown to impact the bond strength. In addition, various design modifications in Ti-base taper degree, height, texture, and retentive features could influence the bond strength.[7,18,21,22] The type of luting agent could also have an impact.[18,20] While those methods have been supposed to improve retention, the behavior of different bonding protocols of zirconia or glass ceramics to Ti-bases is still unclear. Furthermore, there is a gap in research regarding the long-term retention of ceramic crowns, especially after being subjected to thermomechanical loading. Chewing loading and temperature fluctuations can cause thermomechanical stresses on the restoration-base unit, potentially leading to degradation of the bond interface.[12,15,23]

To the best of author's knowledge, there is a single systematic review[24] that has reviewed laboratory studies regarding the bonding of ceramic restorations to Ti-bases. While that review evaluated studies regardless of being subjected to thermocycling/dynamic loading or not, the present systematic review included only laboratory studies that mimicked clinical settings as well as their tested specimens had to be subjected to thermocycling, thermomechanical loading and/or autoclaving. This was considered as one of the inclusion criteria of this review. Additionally, the current review included not only the studies that evaluated bond strength but also these that assessed the bonding stability against fatigue loading.

The current systematic review aimed to compare the results of laboratory studies performed on adhesion methods of implant-supported fixed CAD-CAM ceramic restorations to titanium-bases to develop clinically relevant recommendations, and to analyze the factors that could affect this bond strength.

The focused question of the present review was: "Which method of using resin cement offers the best retention of CAD-CAM implant-supported ceramic restorations luted to Ti-bases?"

Methods

Protocol

This systematic review was directed according to the guidelines delineated in the Preferred Reporting Items for Systematic Review and Meta-Analysis statement (PRISMA)[25] using the Population, Intervention, Comparison and Outcome (PICO) method.[26] According to the PICO framework (population: CAD-CAM implant-supported ceramic restorations, intervention: adhesion to Ti-bases, comparison: Ti-base height and geometry, surface pre-treatment, ceramic restorative material, luting cement type and thickness, and outcome: bond strength, quality, or stability). As the current study is a systematic review, no need to gain approval from the ethics committee. In addition, this review was not registered.

Eligibility Criteria and Exclusion Criteria

The inclusion and exclusion criteria were set based on PICO (Population, Intervention, Comparison, Outcome) guidelines as presented in Table 1.

Information Sources and Search Strategy

PubMed, Google Scholar, and Cochrane databases were investigated in September, 2024. Additional search was executed in the references of the included manuscripts, some related systematic reviews, and on the web sites of some journals: Clinical Implant Dentistry and Related Research; Clinical Oral Implant research; The International Journal of Oral & Maxillofacial Implants; The International Journal of Prosthodontics; Journal of Prosthetic Dentistry; Journal of Prosthodontics; Journal of Dentistry; Dental Materials; and Journal of Oral Implantology. The specific search keywords can be found in Appendix 1.

Selection Process

The author executed the literature search by firstly screening through titles and abstracts; then, full-text articles were screened if title and abstract did not offer sufficient information. The author then read the full texts of the included articles. Figure 1 displays the flow diagram of manuscripts' identification and inclusion.

Data Collection Process

The author read the full texts of the included articles and extracted all the relevant data of each one, using pre-determined fields in a uniform data extraction sheet. The screening process and data extraction were conducted twice by the author.

Table 1 Inclusion and Exclusion Criteria of in vitro Studies

Criteria	Inclusion Criteria	Exclusion Criteria
Timespan	Between 1 Jan 2000 and 24 Sep.2024	Before 2000
Publishing aspects	Published in international peer reviewed journals in an English language	*Studies not published in international peer reviewed journals *Studies in other languages than English
Study design	In vitro studies	*Animal studies *Case reports *Technique descriptions *Finite element analysis studies *Abstracts
Type of population (P):	* CAD-CAM implant-supported fixed ceramic restorations *Prefabricated Ti-base *Studies that involved ≥5 specimens per group *Specimens stored in water ≥30 days or thermocycled ≥5000 cycles or steam sterilized and/or mechanically loaded (chewing stimulation)	*Not CAD-CAM ceramic restorations *Customized Ti-bases, or Z solid abutments *Study design that does not mimic clinical situations such as ceramic plates, cylinders, disks, <30 days water storage or <5000 cycles TC, or without autoclaving or mechanical loading
Type of interventions (I):	Studies with adequate detail of bonding protocol of ceramic restorations to Ti-bases	Studies without adequate detail of bonding protocol of ceramic restorations to Ti-bases
Type of control (C):	Ti-base height and geometry, surface pre-treatment, ceramic restorative material, luting cement type and thickness.	
Type of outcomes (O):	Studies with quantitative reporting of bond strength and/or durability between ceramic restoration and Ti-bases	Studies without quantitative reporting of bond strength and/or durability

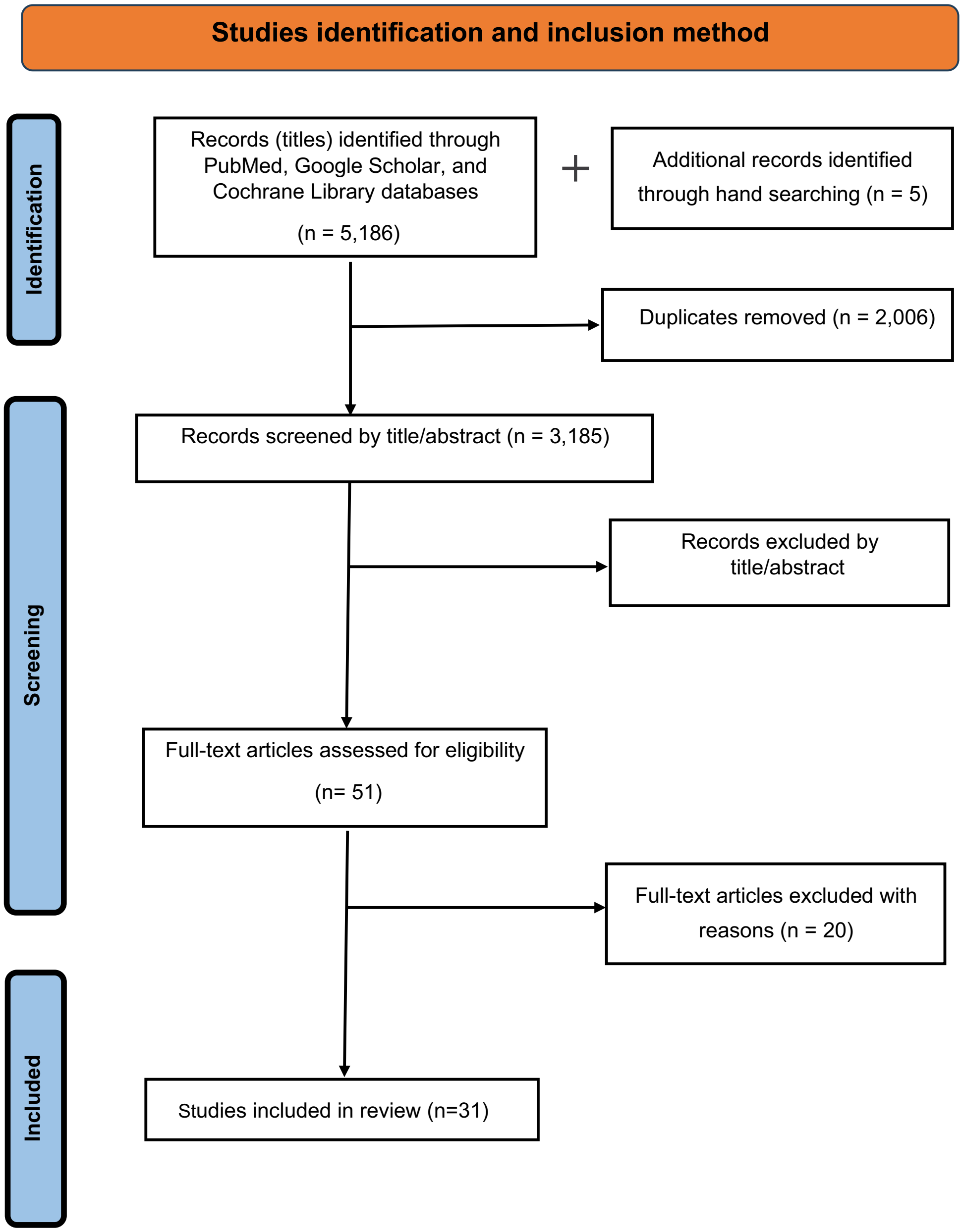

Figure 1 Flow diagram viewing the studies identification and inclusion method.

Data Extraction

The gathered data for laboratory studies comprised the authors' name, year, the evaluated ceramic materials, the used Ti-base system, the number of specimens, the assessed adhesion methods, the pre-treatment protocol, the luting agent, the aging protocol, the bond assessment test, bonding failure mode analysis, and the main outcomes.

Risk of Bias Assessment

The risk of bias was evaluated for each included laboratory study by means of a tool that was evolved especially for dental in vitro studies (QUIN tool).[27] According to this tool, 12 criteria were evaluated for each article, with 2 points scored if the criterion was adequately specified, 1 point if it was inadequately specified, and 0 point if it was not specified. The points were then added to attain a total score for a certain in vitro study. The risk of bias score was calculated by using the following formula: Risk of bias score = (total score × 100)/(2 × number of applicable criteria).

A high risk of bias was considered if the resulting score was <50%, a medium risk if it was 50% to 70%, and low risk if it was >70%.

Synthesis Methods

Since relative heterogeneity was detected among the included studies in relation to methodology, tested and control groups, analyzed variables, and outcome elements, besides to uncontrollable confounding factors, a meta-analysis was not implemented, and instead a descriptive systematic review was presented.

Results

Study Selection

A total of 5186 records were identified from electronic literature search through Sep., 2024, whereas five records were identified after hand searching through references of included studies. After the duplicate removal, 3185 records remained for screening based on titles and abstracts. Of those, fifty-one full-text articles were evaluated based on eligibility criteria. After the exclusion of twenty articles for reasons outlined in Appendix 2, thirty-one studies were included in this systematic review as shown in Figure 1. The studies recognized were published in the past 12 years, between 2013 and 2025. Data from the encompassed studies were tabulated (Table 2).

Table 2 Study Characteristics of Reviewed Studies

Author (Year)	Restoration (Material)	Ti-Base System/ Height (Mm)	Ti-Base and Ceramic Surfaces Pre-Treatment	Luting Agent	Aging Procedure
Gehrke et al (2014)[28]	3Y-TZP copings	XiVe, smooth /4mm	Ti & Z: SB, 50 µm Al_2O_3 at 2-bar	*Panavia 21 *Multilink Implant *Smart-Cem2	60-d WS +15,000 TC (5–55C°)
Von Maltzahn et al (2016)[17]	3Y-TZP copings	S 1020, smooth/3.5mm	*Ti-base: SB, 110 µm Al_2O_3 at 2-bar/None or Alloy Primer or Clearfil or Rocatec according to group *Z: Wiithout pretreatment Vs SB, 110 µm Al_2O_3 at 2-bar/None or Alloy Primer or Clearfil or Rocatec according to group	*Panavia F 2.0 *RelyX Unicem	10,000 TC (5–55C°, 30s)
Fadanelli et al (2017)[29]	3Y-TZP copings	Ti-base, smooth/NS	*Ti-base: SB, 50 µm Al_2O_3 at 2-bar *Z: Metal/Zirconia Primer	*Multilink Automix *RelyX U200	Autoclaving for 15 min at 121 C°
Arce et al (2018)[30]	3Y-TZP crowns	BioHorizons, micro-retentive grooves/4mm facially and 2 mm palatally	Ti-base and Z: Wiithout pretreatment vs MDP primer vs SB, 50µm Al_2O_3 at 2-bar vs SB, 50µm Al_2O_3 at 2-bar/MDP primer	Panavia V5	1-d WS+ 15,000 TC (5–55C°)

(*Continued*)

Table 2 (Continued).

Author (Year)	Restoration (Material)	Ti-Base System/ Height (Mm)	Ti-Base and Ceramic Surfaces Pre-Treatment	Luting Agent	Aging Procedure
Güngör & Nemli (2018)[23]	3Y-TZP copings	Sirona, smooth/4mm	*Ti: SB, 50 µm Al_2O_3 SB at 2-bar/Alloy primer for Panavia F2.0 *Z: Without pretreatment	*Panavia F2.0 *Zirconite *MHA	2000 TC (5–55°C) + 500,000 DL (100 N)
Pils et al (2019)[31]	Z coping	Universal Hybrid, smooth/NS	Ti & Z: SB, 50 µm Al_2O_3 at 2-bar	G-CEM LinkAce	*5000 TC (5–55 °C) + 1.2 million cycles DL (49 N, 1.6 Hz) *Autoclaving (135 °C, 2.17 bar, 28:56 min)
Mehl et al (2018)[32]	5Y-TZP copings	Conelog, macro-retentive elements/ 2.7mm	Ti & Z: SB, 50 µm Al_2O_3 at 2.5-bar	*Panavia SA *RelyX Unicem 2 *MaxCem Elite *SmartCem 2	*3-d WS vs *37,500 TC (5–55C°,30s, 150 d)
Wiedenmann et al (2019)[33]	3Y-TZP copings	Conelog, macro-retentive elements/ 4.7mm	Ti & Z: SB, 50 µm Al_2O_3 at 2-bar/Monobond Plus or Clearfil primer for MHA and Panavia V5, respectively	*MHA *Panavia V5	*20,000 TC (5°-55°C) *Autoclaved groups: 134 C° at 2-bar for 3.5 min
Linkevicius et al (2019)[18]	3Y-TZP copings	BioHorizons, micro-retentive grooves/5mm	*Ti: without pretreatment vs SB, 50 µm Al_2O_3 at 2-bar *Z: without pretreatment	*G-CEM LinkAce *RelyX U200 *Ceka Site	1-d saliva storage + 5000 DL + TC (5–55 C°)
Von Maltzahn et al (2019)[34]	*LD *Z copings	Sirona, smooth/4 mm	*Ti: SB, 50 µm Al_2O_3 at 2-bar/Monobond Plus or Alloy primer according to group *Z & LD: SB, 50 µm Al_2O_3 (Z). HF etch (LD)/ Monobond Plus, Clearfil primer, or RelyX Ceramic primer according to group	*MHA *Panavia F 2.0 *RelyX Unicem	10,000 TC (5–55C°, 30s)
Nouh et al (2019)[12]	*Z *LD copings and crowns	Metal Base, smooth/ 3mm	*Ti: SB, 50 µm Al_2O_3 at 2.5-bar/Monobond Plus primer *Z: SB, 50 µm Al_2O_3 at 1-bar / /Monobond Plus primer *LD: 5% HF etch/ Monobond Plus	MHA	3-d WS+ Thermo-mechanical loading (5 °C–55 °C, 1.2 million cycles,120 N, 3.8 Hz)
Kemarly et al (2020)[35]	LD copings	Sirona, smooth/4mm	*Ti: Without pretreatment vs SB, 50µm Al_2O_3 at 2-bar vs TBS, 30µm at 2-bar/ Without primer vs Monobond Plus vs Alloy primer. *LD: 5% HF etch/ Monobond Plus	MHA	1-d WS+ 2000 TC (5–55C°,30s)

(*Continued*)

Table 2 (Continued).

Author (Year)	Restoration (Material)	Ti-Base System/ Height (Mm)	Ti-Base and Ceramic Surfaces Pre-Treatment	Luting Agent	Aging Procedure
Pacheco et al (2021)[36]	5Y-TZP copings	Neodent, micro-retentive grooves/4mm	*Ti: Alloy primer/ED Primer II *Z: Alloy primer	Panavia F 2.0	2-d WS vs 1.2 million cycles DL (200 N, 3.8 Hz)
Pitta et al (2021a)[19]	LD crowns	Conelog, macro-retentive elements/ 4.7mm	*Ti: Without pretreatment vs TBS, 30 µm at 2.5-bar vs SB, 50µm Al_2O_3 at 2.5-bar vs TBS, 110µm at 2.5-bar *LD: 5% HF etch/ Monobond Plus	MHA	TC (120s, 5–55 C°) + CL (1200 000, 49 N, 1.67 Hz)
Pitta et al (2021b)[15]	*LD *3Y-TZP *PICN *PFM crowns	Conelog, macro-retentive elements/ 5.5mm	*Ti: SB, 50 µm Al_2O_3 at 2.5-bar/primer *Z: TBS, 30 µm at 2-bar/ primer *LD & PICN: 5% HF for 20s and 60s, respectively/ /primer	Panavia 21	TC (5°–55°C, 120s) + 1,200,000 DL (49 N, 1.67 Hz)
Santos-Neto et al (2021)[37]	Z copings	S.I.N., micro-retentive grooves/6 mm	*Ti: Without pretreatment *Z: SB, 50 µm Al_2O_3 at 1-bar/Single Bond Universal for RelyX U200 or Monobond N for Multilink N cement	*RelyX Luting 2 *RelyX U200 *Multilink N	1-d WS vs 1-d WS+5000 TC (5–55C°)
Oddbratt et al (2021)[38]	3Y-TZP copings	Elos Accurate, micro-retentive grooves/ 3mm	*Ti: Primer *Z: SB, 110µm Al_2O_3 at 1-bar/Primer	*MHA *Panavia V5 *RelyX Ultimate	5000 TC (5–55C°)
Bergamo et al (2021)[20]	3Y-TZP crowns	Emfils, macro-retentive elements/4mm	*Ti: Without pretreatment vs SB, 45 µm Al_2O_3 at 2-bar/ Scotchbond Universal with RelyX Ultimate *Z: Scotchbond Universal with RelyX Ultimate	*RelyX U200, *RelyX Ultimate	Autoclaving (10 min,134 C°, at 2 bars)
Burkhardt et al (2021)[39]	LD crowns	Conelog, macro-retentive elements/ 4.7mm	*Ti: SB, 50 µm Al_2O_3 at 2-bar *LD: 5% HF etch/ Monobond Plus	MHA	TC (5–55C°, 120s) + 1,200,000 DL (49 N,1.67 Hz)

(*Continued*)

Table 2 (Continued).

Author (Year)	Restoration (Material)	Ti-Base System/ Height (Mm)	Ti-Base and Ceramic Surfaces Pre-Treatment	Luting Agent	Aging Procedure
Von Maltzahn et al (2021)[40]	3Y-TZP copings	*S 1020, smooth/ 3.5mm *S 1020, titanium nitride-coated/3.5mm	*Ti-bases: Smooth: SB, 110µm Al_2O_3 at 2-bar. Titanium nitride-coated bases: sandblasted before coating (No primer, Alloy Primer or Clearfil Ceramic primer according to group) *Z: SB, 110µm Al_2O_3 at 2-bar/No primer or Clearfil Ceramic primer according to group	Panavia F 2.0	TC 10,000 (5–55C°)
Bjelopavlovic et al (2022)[41]	*Feldspar ceramic *Leucite-reinforced glass ceramic *LD * PICN *Pre-sintered zirconia-reinforced lithium silicate *Fully crystallized zirconia-reinforced lithium silicate crowns	Bego, smooth/NS	*Ti: SB,50-µm Al_2O_3 at 1-bar/Monobond Plus *All crowns: 5% HF/ Monobond Plus	*Multilink Implant *Variolink II *Rely X Unicem *Panavia 2.0 *GC Fujicem	7-d WS+5000 TC (5–55C°, 30s)
Calderon et al (2022)[21]	Z FDPs	*Variobase for crown/ 3.5mm * Variobase, conical for bridge/3.5mm * Variobase, cylindrical for bridge/3.5mm	*Ti: SB, 50 µm Al_2O_3 at 2-bar/Alloy primer *Z: SB, 50 µm Al_2O_3 at 2-bar/Clearfil Ceramic primer	Panavia 21	TC (5–55C°, 120s) + 1,200,000 DL (49N, 1.67 Hz)
Strazzi-Sahyon et al (2023)[42]	3Y-TZP crowns	Emfils, macro-retentive elements/2.5, 4mm	*Ti: SB, 45 µm Al_2O_3 at 2-bar *Z: SB, 30 µm Al_2O_3 at 2-bar Ti & Z: G-Multi primer or Scotchbond Universal adhesive according to cement type	*G-Cem LinkForce *RelyX Ultimate	*Without DL: 1-d storage in moist environment vs *With DL: (1×10^6 cycles; 100 N, 15 Hz)
Chiam et al (2024)[22]	3Y-TZP FDPs	*Variobase, cylindrical/ NS *Variobase, conical/NS	Ti & Z: SB, 50 µm Al_2O_3 at 2.5-bar/primer for Panavia V5, MHA, and RelyX Universal with cylindrical bases.	*Panavia SA *Panavia V5 *MHA *RelyX Universal	1d WS + 5000 TC + 5000 CL (150 N, 1.5 Hz)
Bagegni et al (2023)[43]	3Y-TZP crowns	SIC, smooth/4.7mm	Ti & Zi: SB, 50 µm Al_2O_3 /primer according to cement type	*Speedcem Plus *Panavia SA Universal *Panavia V5 *RelyX Unicem 2 *VITA ADIVA IA-Cem *Ketac CEM *Hoffmann's Phosphate Cement	5 million DL (49 N, 1.2 Hz) +TC (5–55 C°)

(*Continued*)

Table 2 (Continued).

Author (Year)	**Restoration (Material)**	**Ti-Base System/ Height (Mm)**	**Ti-Base and Ceramic Surfaces Pre-Treatment**	**Luting Agent**	**Aging Procedure**
Alseddiek et al (2023)[7]	*4Y-TZP *LD *PICN crowns	TBASE-MPI, macro-retentive elements/4, 7mm	*Ti: SB, 50 µm Al_2O_3 at 2-bar/Monobond Plus *Z: SB, 50 µm Al_2O_3 at 2-bar/Monobond Plus *LD & PICN: 9.5% HF etch for 20s/Monobond Plus	MHA	30 d WS + 5000 TC + 50,000 DL (9 N, 1.7 Hz)
Burkhardt et al (2023)[44]	*3Y-TZP *PICN *LD crowns	Conelog, macro-retentive elements/ 4.7mm	*Ti: SB, 50-µm Al_2O_3 at 2.5-bar/primer *Z: SB, 50-µm Al_2O_3 s at 2.5-bar/primer *LD: 5% HF for 20s/ / primer *PICN: 5% HF for 60s/ / primer	*MHA *Panavia V5 (P5) *RelyX Ultimate (RX)	TC (5 to 55°C, 120s) +1,200,000 DL (49 N, 1.67 Hz)
Ibrahim et al (2023)[45]	4Y-TZP crowns	*GM exact, straight screw access and micro-retentive grooves/6mm *GM AS, angled screw access and micro-retentive grooves/6mm	*Ti: Without pretreatment *Z: SB, 120 µm Al_2O_3 at 2-bar/primer	MHA	TC (5–55 °C) + 250,000 DL (100 N, 1.67 Hz)
Khalifa et al (2023)[46]	LD crowns	*Sirona, smooth/4.7mm *Variobase, macro-retentive elements/5.5mm *SB Variobase, macro-retentive elements/5.5mm *SB NNC Cementable Abutment, smooth/ 5.5mm	*Ti: Without pretreatment of 2 groups vs SB of 2 groups: SB, 50µm Al_2O_3 at 2-bar *LD: 5% HF for 20s/ Monobond Plus primer.	Panavia SA Cement Plus	2000 TC +120000DL (50 N)
Karasan et al (2024)[47]	PICN crowns	*Universal Base, macro-retentive elements/4.3 *Conelog, smooth/4.3 *Prototype conelog, macro-retentive elements/7 * Viteo Base, pre-sandblasted/6 mm *Variobase, macro-retentive elements/5.5 *Varioflex, macro-retentive elements/9	*Ti: SB, 50µm Al_2O_3 at 2.5-bar/Clearfil Ceramic Primer Plus *PICN: 5% HF etch for 60s/Clearfil Ceramic Primer Plus	Panavia V5	TC (5°–55°C, 120s) + DL (1,200,000 cycles, 98 N, 1.67 Hz)
Lafori et al (2024)[48]	*LD *PICN crowns	Conelog, macro-retentive elements/4.3mm	*Ti: SB, 50µm Al_2O_3 at 2.5-bar *LD: 5% HF etch for 20s/ primer *PICN: 5% HF for 60s/ primer	*MHA *Panavia V5	Autoclaving (20.5min, 121°C at 1.1 bar)

(*Continued*)

Table 2 (Continued).

Author (Year)	Compared Adhesion Methods	No. of Specimens/ Group	Bond assessment test	Bonding Failure Mode Analysis After Pullout Test	Outcomes
Gehrke et al (2014)[28]	Comparison of bond strength between 3 resin cements	7/Group	Pull-out retention test (N)	NP	*No significant difference in bond strength between 3 cements *The combination of sandblasting of the bonding surfaces with the use of resin cements offered adequate and stable bonding of Z to Ti-bases.
Von Maltzahn et al (2016)[17]	Comparison of bond strength between 2 cements with each of 6 pretreatment protocols of Ti-bases and Z	10/Group	*Pullout retention test (N) *Microscopic failure mode analysis	*Without SB of Z, with SB of Ti & without primer: adhesive failure at Z-resin interface *With SB of Z and Ti and with primer application: mixed failures	*The type of luting resin had no significant effect on the bond strength *The highest bond strength was recorded when the bonding surfaces of Z and Ti-bases were sandblasted and when a ceramic primer was applied.
Fadanelli et al (2017)[29]	Comparison of bond strength between 2 cements with and without autoclaving	10/Group	* Pullout retention test (N) *Failure mode analysis with 3.5X lens	*Without autoclaving: mainly mixed failure was observed. *After autoclaving: adhesive failure at resin/zirconia interface increased	*Both cements performed equally if no autoclaving was made. *After autoclaving, self-cure resin cement had higher bond strength than dual-cure one.
Arce et al (2018)[30]	Comparison of bond strength between 3 pretreatment protocols of Ti-bases and Z vs control with no pretreatment	15/Group	*Pull-out retention test (N) *Microscopic failure mode analysis	*Without SB of Z & Ti: adhesive failure at Z-resin interface *With SB of Z & Ti: adhesive failure at Z-resin interface and mixed failures	*Sandblasting of Ti-bases having interlocking microgrooves decreased the bond strength to Z crowns. * MDP primer improved bond strength only to SB bonding surfaces but not to non-sandblasted ones.
Güngör & Nemli (2018)[23]	Comparison of bond strength between 3 resin cements with and without thermomechanical loading.	10/Group	*Pull-out retention test (N) *Failure mode analysis using magnifying glass	*Zirconite: adhesive failure at Ti-resin interface *MHA & Panavia F2: adhesive failure at Z-resin interface	Zirconite dual-cure cement offered the highest bond strength.
Pils et al (2019)[31]	Comparison of bond strength between autoclaved and non-autoclaved luted specimens	12/Group	*Pull-out retention test (N) *Failure mode analysis	Completely adhesive failure at Z for both groups	Standard autoclaving procedure did not decrease bond strength.
Mehl et al (2018)[32]	Comparison of bond strength between 4 resin cements with both luting spaces of 63 μm and 102 μm, and with and without thermocycling.	8/Group	*Pull-out retention test (N) *Microscopic failure mode analysis	Mainly adhesive failures at Z-resin interface for all groups	60μm luting space performed better than space of 100 μm.

(*Continued*)

Table 2 (Continued).

Author (Year)	Compared Adhesion Methods	No. of Specimens/ Group	Bond assessment test	Bonding Failure Mode Analysis After Pullout Test	Outcomes
Wiedenmann et al (2019)[33]	Comparison of bond strength between 2 resin cements with each of 4 cleaning methods, and with polishing and without.	10/Group	*Pull-out retention test (MPa) *Microscopic failure mode analysis	*DMA/HEMA-based cement: mainly mixed failures *Bis-GMA /TEGDMA-based cement: mainly adhesive failures at Z-resin interface	* DMA/HEMA-based cement showed higher bond strength than Bis-GMA/TEGDMA-based cement *Polishing and various cleaning methods did not have an influence on bond strength.
Linkevicius et al (2019)[18]	Comparison of bond strength between 3 resin cements with and without sandblasting of Ti-bases	10/Group	*Pull-out retention test (N)	NP	Sandblasting of Ti-bases having micro-retentive grooves significantly decreased the bond strength to Z crowns.
Von Maltzahn et al (2019)[34]	Comparison of bond strength between 2 ceramic materials with 3 resin cements and with different pretreatment protocols.	10/Group	*Pull-out retention test (N) *Microscopic fracture mode analysis	Mixed failures and adhesive failures at Ti-resin interface	*Mechanical surface pretreatment appeared to be more efficient than the chemical treatment alone. *Bond strength between Ti-bases and LD copings was higher than that with Z copings.
Nouh et al (2019)[12]	Comparison of bonding stability between 2 ceramic materials with hybrid-abutment-crown and hybrid-abutment configurations under thermo-mechanical aging	8/Group	Bond failure analysis with DSLR camera and with microscope after aging	NP	During fatigue loading, both ceramic materials showed adhesive failures, while only LD suffered from ceramic fractures besides the adhesive failures
Kemarly et al (2020)[35]	Comparison of bond strength between 3 mechanical pretreatments of Ti-bases with each of 3 chemical pretreatment protocols.	10/Group	*Pull-out retention test (N) *Fracture mode analysis	*Without mechanical pretreatment of Ti-base: adhesive failure at Ti-resin interface *Mechanical pretreatments with no primer of Ti-base: mixed failure *Combined mechanical and primer of Ti-base: fracture of LD with a fragment securely bonded to Ti-Base with some cement on both the dislodged LD and on Ti-base.	Mechanical pretreatment is the prime factor for bonding regardless of chemical pretreatment.
Pacheco et al (2021)[36]	Comparison of bond strength between 3 luting space thicknesses (25, 50, 75 µm)	20/Group	*Pullout retention test (N) *Microscopic failure mode analysis	Mainly adhesive failures at Z-resin interface	The increase of axial luting space thickness to 75 µm reduced the bond strength

(*Continued*)

Table 2 (Continued).

Author (Year)	Compared Adhesion Methods	No. of Specimens/ Group	Bond assessment test	Bonding Failure Mode Analysis After Pullout Test	Outcomes
Pitta et al (2021a)[19]	Comparison of bond strength between 4 pretreatment protocols of Ti-bases	15/Group	*Pullout retention test (N) *Microscopic failure mode analysis	*Non-sandblasted Ti-bases: mainly adhesive failure at Ti-resin interface *SB Ti-bases: mainly mixed failures	Sandblasting of Ti-bases with 50µm Al_2O_3 revealed the highest bond strength among the tested methods.
Pitta et al (2021b)[15]	Comparison of bonding stability between three ceramic materials and PFM under thermo-mechanical aging	12/Group	Bond failure analysis with microscope after aging	NP	Z and PICN revealed inferior bonding capability to Ti-base compared with LD under thermo-mechanical aging
Santos-Neto et al (2021)[37]	Comparison of bond strength between 3 cements with and without thermocycling	7/Group	*Pullout retention test (N) *Microscopic failure mode analysis	*RelyX U200 resin cement: mainly screw fracture and few adhesive failures at Z-resin interface *RelyX Luting 2 glass ionomer cement: mainly adhesive failures at Z-resin interface	Resin cement provided higher bond strength than resin-modified glass ionomer cement.
Oddbratt et al (2021)[38]	Comparison of bond strength between 3 resin cements	10/Group	*Pullout retention test (MPa) *Microscopic failure mode analysis	* MHA: adhesive failure at Ti-resin interface * Panavia and RelyX: adhesive failure at Z-resin interface	Dual-cure resin cements offered higher bond strength than self-cure resin cement.
Bergamo et al (2021)[20]	Comparison of bond strength between 2 resin cements with and without sandblasting of Ti-bases, and with and without autoclaving.	10/Group	Pullout retention test (N)	NP	*Conventional resin cement combined with universal adhesive enhanced bond strength compared with self-adhesive cement without adhesive. *Autoclaving augmented the bond strength of Z crowns luted with self-adhesive resin cement for non-sandblasted Ti-bases
Burkhardt et al (2021)[39]	Comparison of bond strength between 4 cleaning methods of saliva-contaminated Ti-bases prior to cementation with control	12/Group	*Pullout retention test (N) *Bond failure analysis with naked eye and with microscope after aging	NP	All tested cleaning methods allowed the restoration of the bond strength partially except for the alcohol cleaning method.
Von Maltzahn et al (2021)[40]	Comparison of bond strength between smooth Ti-bases and titanium nitride-coated bases with different chemical pretreatments.	10/Group	*Pullout retention test (N) *Microscopic failure mode analysis	Mixed fracture patterns	Titanium nitride-coated bases showed comparable or higher bond strength than smooth Ti-bases.
Bjelopavlovic et al (2022)[41]	Comparison of bond strength between 6 ceramic crown materials with each of 5 cements	75/Group	Pullout retention test (N)	NP	*The ceramic material affected the bond strength. *Use of definite cements led to higher bond strength for some ceramic materials.

(*Continued*)

Table 2 (Continued).

Author (Year)	**Compared Adhesion Methods**	**No. of Specimens/ Group**	**Bond assessment test**	**Bonding Failure Mode Analysis After Pullout Test**	**Outcomes**
Calderon et al (2022)[21]	Comparison of bonding stability between conical, cylindrical, and combination of Ti-bases under thermomechanical aging	15/Group	Bond failure analysis with magnifying glass and with microscope after aging	NP	Cylindrical Ti-bases for bridge showed higher bonding stability under thermomechanical aging.
Strazzi-Sahyon et al (2023)[42]	Comparison of bond strength between 2 resin cements with 2 heights of Ti-bases (2.5,4 mm)	10/Group	*Pullout retention test (N) *Microscopic fracture mode analysis	Mainly mixed failures	*RelyX Ultimate cement accompanying Scotchbond Universal produced higher bond strength than G-Cem LinkForce with G-Multi primer *Increase in abutment height led to an increase in bond strength for RelyX Ultimate cement.
Chiam et al (2024)[22]	Comparison of bond strength between conical and cylindrical Ti-bases with 4 resin cements	10/Group	*Pullout retention test (N) *Microscopic fracture mode analysis	*Conical + Panavia SA: mainly adhesive failure at Z-resin interface *Cylindrical + Panavia SA or V5: adhesive failure at Z-resin interface and mixed failures *Cylindrical + MHA or RelyX: mainly mixed failures	*Both designs of titanium cylinders demonstrated comparable bond strength to FDPs luted with Panavia SA cement. * FDPs luted to cylindrical Ti-bases with MHA and RelyX Universal showed a significant increase in bond strength compared to Panavia cements.
Bagegni et al (2023)[43]	Comparison of bond strength between 7 cements	8/Group	*Pullout retention test (MPa) *Failure mode analysis with magnifying loupes 3.3X	Mainly adhesive failures at Z-resin interface	Self-adhesive cements offered greater bond strength with Panavia SA showing the highest
Alseddiek et al (2023)[7]	Comparison of bond strength between 3 ceramic crown materials with 2 heights of Ti-bases (4,7mm)	7/Group	Pullout retention test (N)	NP	*LD exhibited the highest bond strength whereas Z showed the lowest. *Increasing the height of Ti-base greatly enhanced the bond strength of the three crown materials.
Burkhardt et al (2023)[44]	Comparison of bond strength between 3 ceramic crown materials with each of 3 resin cements.	12/Group	*Pullout retention test (N) *Microscopic marginal integrity analysis after aging *Bond failure analysis with microscope after aging	NP	*Z + RX > PICN + P5 > LD + MHA > PICN + RX (bond strength) *The assessed restorative materials performed favorably with specific bonding systems.
Ibrahim et al (2023)[45]	Comparison of bond strength between straight screw channel Ti-bases and angled screw channel ones	7/Group	*Pullout retention test (N) *Microscopic failure mode analysis	* Straight screw channel base: mixed failure pattern * Angled screw channel base: mainly adhesive failure at Ti-resin interface	Straight screw channel Ti-bases exhibited higher bond strength than angled screw channel.

(*Continued*)

Table 2 (Continued).

Author (Year)	Compared Adhesion Methods	No. of Specimens/ Group	Bond assessment test	Bonding Failure Mode Analysis After Pullout Test	Outcomes
Khalifa et al (2023)[46]	Comparison of bond strength between 4 different Ti-bases /abutments	10/Group	Pullout retention test (N)	NP	Sandblasting significantly enhanced the bond strength of LD crowns to Ti abutments.
Karasan et al (2024)[47]	Comparison of bonding stability between different Ti-base heights and geometries under thermomechanical aging	12/Group	Bond failure analysis with microscope after aging	NP	Ti-base height or its geometrical properties did not lead to significant differences in bonding stability under thermomechanical aging.
Lafori ei al. (2024)[48]	Comparison of bond strength between 2 ceramic crown materials luted with 2 resin cements, and with and without autoclaving	10/Group	*Pullout retention test (N) *Marginal integrity evaluation with magnification *Microscopic fracture mode analysis	*Without autoclaving: mainly adhesive failure at ceramic/resin interface *After autoclaving: adhesive failure at ceramic/resin interface and mixed failure were equally observed	Autoclaving seems to enhance the bond strength of LD and PICN crowns, though it may negatively affect marginal integrity.

Abbreviations: NP, not performed; NS, not specified; Ti-base, titanium base; Z, zirconia; LD, lithium disilicate; FDP, fixed dental prosthesis; Al_2O_3, alumina; SB, sandblasting; MHA, Multilink Hybrid Abutment cement; Y-TZP, Yttria-stabilized tetragonal zirconia polycrystal; PICN, polymer-infiltrated ceramic-network; HF, hydrofluoric acid; DL, dynamic loading; TC, thermocycling; WS, water storage; TBS, tribochemical silica airborne-particle abrasion; PFM, porcelain fused to metal; N, Newton.

Study Characteristics

Broken down by ceramic material bonded to Ti-base, the literature search revealed 19 studies on zirconia framework bonded to Ti-bases,[17,18,20–23,28–33,36–38,40,42,43,45] four studies[19,35,39,46] were on LD copings bonded to Ti-bases, one study[47] was on polymer-infiltrated ceramic-network (PICN) crowns, two studies[12,34] were on both zirconia and LD, four studies were on zirconia, LD, PICN and other ceramics,[7,15,41,44] and one study[48] was on both LD and PICN crowns. Of the 31 included studies, only two studies[21,22] were on FDPs bonded to Ti-bases, while the rest were on single ceramic copings. Study characteristics are presented in Table 2. Overview of the utilized ceramic materials and Ti-bases is presented in Table 3 and the utilized resin cements are presented in Table 4.

Table 3 Overview of the Ceramic Materials and Ti-Bases Utilized

Ceramic Materials			Ti-Base		
Description	**Product Name**	**Manufacturer**	**Description**	**Product Name**	**Manufacturer**
3Y-TZP copings[28]	Cercon Compartis	DeguDent	Ti-base[28]	XiVe TitaniumBase	Dentsply Friadent
3Y-TZP copings[17,40]	Zirkon Biostar	Siladent	Ti base[41]	Bego	Bego Implant Systems
3Y-TZP crowns[30]	Zenostar MO	Ivoclar Vivadent	Ti-base[17,40]	S 1020	Medentika Straumann
3Y-TZP crowns and copings[23,29,43]	InCoris ZI meso	Dentsply Sirona	Ti-base[29]	Abutment-Amplified cemented	P-I Branemark

(*Continued*)

Table 3 (Continued).

Ceramic Materials			**Ti-Base**		
Description	**Product Name**	**Manufacturer**	**Description**	**Product Name**	**Manufacturer**
Z coping[31]	ICE Zirkon Translucent	Zirkozahn	Ti-base[18,30]	Titanium Base Abutment	BioHorizons
Z copings[32,37]	NS	NS	Ti-base[23,34,35,46]	TiBase	Dentsply Sirona
Leucite-reinforced glass ceramic crowns[41]	Empress CAD	Ivoclar Vivadent	Ti-base[31]	Universal Hybrid Abutment	GC Tech.
Z crowns and copings[12,34]	Zenostar	Wieland Dental	Ti-base[43]	SICv Bonding Base	SIC Invent AG
Monolithic Y-TZP FDP[21]	ZOLID H	Amann Girrbach	Ti-base[12]	Metal Base Abutment	FairImplant
5Y-TZP copings[36]	Ceramill Zolid FX	Amann Girrbach	Ti-base[7]	TBASE-MPI	Vitronex
Fully crystallized zirconia-reinforced lithium silicate crowns[41]	Celtra Duo	Dentsply Detrey	Ti-base[37]	Titanium Base	S.I.N. Sistema de implantes
3Y-TZP crowns/copings[15,18]	Lava	3M ESPE	Ti-base[38]	Elos Accurate, Hybrid Base	Elos
4Y-TZP crowns[7]	Ceramill Zolid HT+	Amann Girrbach	Ti-base[47]	Sandblasted, Viteo Base Ti	Ivoclar
3Y-TZP copings and FDP[22,33,38]	IPS e.max ZirCAD	Ivoclar Vivadent	Ti-base[21,46,47]	Variobase for crown	Straumann
4Y-TZP crowns[45]	Zirconia	Chengdu Besmile Biotechnology	Ti-base[21,22]	Variobase Conical for bridge/bar	Straumann
3Y-TZP crowns[44]	CEREC Zirconia Meso	Dentsply Sirona	Ti-base[21,22]	Variobase Cylindrical for bridge/bar	Straumann
3Y-TZP crowns[20,42]	Ceramill Mind	Amann Girrbach	Ti-base[20,42]	Ti-Base	Emfils
Feldspar ceramic crowns[41]	Vita Mark II	VITA Zahnfabrik	Ti-base[47]	Prototype Conelog	BioHorizons
Pre-sintered zirconia-reinforced lithium silicate crowns[41]	Vita Suprinity	VITA Zahnfabrik	Ti-base[15,19,32,33,39,44]	Conelog Titanium Base	Camlog Biotechnologies
LD copings/ crowns[7,12,15,19,34,35,39,44,46,48]	IPS e.max CAD	Ivoclar Vivadent	Ti-base[36]	Titanium base	Neodent
PICN crowns[7,15,41,44,47,48]	VITA Enamic	VITA Zahnfabrik	Ti-base (straight and angled screw channel)[45]	GM exact titanium base GM titanium base AS	Neodent

(*Continued*)

Table 3 (Continued).

Ceramic Materials	Ti-Base		
	Description	**Product Name**	**Manufacturer**
	Ti-base[47]	Varioflex	Thommen Medical
	Ti-base[47]	Universal Base	Nobel Biocare
	Ti-base[48]	Conelog Titanium Base	BioHorizons Camlog
	Ti-base[47]	Conelog Titanium Base	BioHorizons
	Ti-abutment[46]	NNC Cementable Abutment	Straumann

Abbreviations: Y-TZP, Yttria-stabilized tetragonal zirconia polycrystal; PICN, polymer-infiltrated ceramic-network; LD, lithium disilicate.

Table 4 Overview of the Utilized Cements

Cement Name	Type	Curing Mode	Manufacturer
Panavia F2.0	Self-etching	Dual-curing	Kuraray Noritake
Panavia SA Cement Universal	Self-adhesive	Dual-curing	Kuraray Noritake
Panavia 21	Self-etching	Dual-curing	Kuraray Noritake
Panavia V5	Self-etching	Dual-curing	Kuraray Noritake
Panavia 2.0	Self-adhesive	Dual-curing	Kuraray Noritake
Panavia SA Cement Plus	Self-adhesive	Dual-curing	Kuraray Noritake
Smart-Cem2	Self-adhesive	Dual-curing	Dentsply Sirona
MaxCem Elite	Self-adhesive	Dual-curing	Kerr
RelyX Unicem	Self-adhesive	Dual-curing	3M ESPE
RelyX Universal	Self-adhesive	Dual-curing	3M ESPE
RelyX Unicem 2 Automix	Self-adhesive	Dual-curing	3M ESPE
RelyX Ultimate	Self-etch or total etch	Dual-curing	3M ESPE
RelyX U200	Self-adhesive	Dual-curing	3M ESPE
G-CEM LinkAce	Self-adhesive	Dual-curing	GC
Multilink Implant	Self-etching	Dual-curing	Ivoclar Vivadent
Multilink Hybrid Abutment (MHA)	Self-etching	Self-curing	Ivoclar Vivadent
Multilink N	Self-etching	Dual-curing	Ivoclar Vivadent
Multilink Automix	Self-etching	Self-curing	Ivoclar Vivadent
Variolink II	Total-etching	Dual-/light-curing	Ivoclar Vivadent
Ceka Site	Self-adhesive	Self -curing	Ceka Perci-line

(*Continued*)

Table 4 (Continued).

Cement Name	Type	Curing Mode	Manufacturer
Speedcem Plus	Self-adhesive	Dual-curing	Ivoclar Vivadent
Zirconite	Self-adhesive	Dual-curing	BJM Labs
VITA ADIVA IA-Cem	Adhesive	Dual-curing	VITA Zahnfabrik
Ketac CEM	Conventional (Glass ionomer cement)	Self-curing	3M ESPE
GC Fujicem	Conventional (Resin-reinforced glass-ionomer cement)	Self-curing	GC
RelyX Luting 2	Conventional (Resin modified glass ionomer cement)	Dual-curing	3M ESPE
Hoffmann's Phosphate Cement	Conventional (Zinc phosphate cement)	Self-curing	Hoffmann's

All samples in the included studies were subjected to thermocycling, thermocycling combined with water storage, thermo-mechanical aging and/or sterilization. Most of the recognized studies utilized the pull-out retention test to quantify the bond strength, while some of them microscopically analyzed the failure modes after debonding. The mode of failure was classified as an adhesive at the ceramic-resin interface (cement mainly remained on Ti-base surface), adhesive at Ti-base-resin interface (cement mainly remained on ceramic coping surface), mixed failures (cement remained on both ceramic coping and Ti-base surfaces), or catastrophic (fracture of the analyzed sample). Six studies evaluated the bonding stability under thermo-mechanical aging and analyzed the bond failure with magnification after aging.[12,15,21,39,44,47] The outcome was classified as micromovement, loss of retention, or catastrophic (fracture of the analyzed sample). Two studies microscopically analysed the external marginal integrity at the interface between the ceramic coping and Ti-base, one after aging[44] and the other after pull-out test[48] (Table 2).

Risk of Bias in Studies

Based on QUIN's tool, 4 studies revealed a high risk of bias, 25 studies revealed a medium risk of bias, while only 2 studies revealed a low risk of bias as presented in Table 5.

Table 5 Quality Assessment by QUIN Tool

Study (Year)	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	Total Score	Risk of Bias Score	Risk of Bias
Gehrke et al (2014)[28]	2	0	1	1	2	0	0	1	0	0	1	2	10	41.66	High
Von Maltzahn et al (2016)[17]	2	0	2	2	1	0	0	2	0	0	2	2	13	54.16	Medium
Fadanelli et al (2017)[29]	2	0	2	2	1	0	1	2	0	0	1	2	13	54.16	Medium
Mehl et al (2018)[32]	2	0	2	2	1	0	0	1	0	0	2	2	12	50	Medium
Arce et al (2018)[30]	2	0	2	2	1	0	0	2	0	0	2	2	13	54.16	Medium
Güngör & Nemli (2018)[23]	2	0	2	2	2	0	1	2	0	0	2	2	15	62.5	Medium
Pils et al (2019)[31]	2	0	1	2	1	0	0	2	0	0	2	1	11	45.83	High

(*Continued*)

Table 5 (Continued).

Study (Year)	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	Total Score	Risk of Bias Score	Risk of Bias
Von Maltzahn et al (2019)[34]	1	0	2	1	1	0	0	2	0	0	2	2	11	45.83	High
Linkevicius et al (2019)[18]	2	0	2	2	1	0	0	1	0	0	2	1	11	45.83	High
Wiedenmann et al (2019)[33]	2	0	2	2	1	0	0	1	0	0	2	2	12	50	Medium
Nouh et al (2019)[12]	2	0	2	2	1	0	0	1	0	0	2	2	12	50	Medium
Kemarly et al (2020)[35]	2	0	2	2	1	0	0	2	0	0	1	2	12	50	Medium
Pacheco et al (2021)[36]	2	2	2	2	2	0	2	2	2	1	2	2	21	87.5	Low
Bergamo et al (2021)[20]	2	0	1	2	2	0	0	2	0	0	2	2	13	54.16	Medium
Santos-Neto et al (2021)[37]	2	0	1	2	2	0	1	2	0	0	2	2	14	58.33	Medium
Pitta et al (2021a)[19]	2	1	2	2	1	0	0	2	0	0	2	2	14	58.33	Medium
Pitta et al (2021b)[15]	2	1	1	2	1	0	0	2	1	0	2	2	14	58.33	Medium
Burkhardt et al (2021)[39]	2	1	2	2	1	0	0	2	1	0	2	2	15	62.5	Medium
Oddbratt et al (2021)[38]	2	0	2	2	2	0	0	2	0	0	2	2	14	58.33	Medium
Von Maltzahn et al (2021)[40]	2	1	2	2	1	0	0	2	0	0	2	2	14	58.33	Medium
Calderon et al (2022)[21]	2	0	2	2	2	0	0	2	1	0	2	2	15	62.5	Medium
Bjelopavlovic et al (2022)[41]	1	0	2	1	2	0	0	2	0	0	2	2	12	50	Medium
Bagegni et al (2023)[43]	2	0	2	2	2	0	0	2	0	0	2	2	14	58.33	Medium
Chiam et al (2024)[22]	2	2	1	2	2	0	1	2	1	0	2	2	17	70.83	Low
Ibrahim et al (2023)[45]	2	1	2	2	2	0	0	2	0	0	2	1	14	58.33	Medium
Alseddiek et al (2023)[7]	2	2	2	2	2	0	0	2	0	0	2	2	16	66.66	Medium
Burkhardt et al (2023)[44]	2	0	2	2	2	0	0	2	1	0	2	2	15	62.5	Medium
Strazzi-Sahyon et al (2023)[42]	2	0	1	2	2	0	0	2	1	0	2	2	14	58.33	Medium

(*Continued*)

Table 5 (Continued).

Study (Year)	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	Total Score	Risk of Bias Score	Risk of Bias
Karasan et al (2024)[47]	2	1	2	2	2	0	0	2	0	0	2	2	15	62.5	Medium
Lafori ei al. (2024)[48]	2	1	2	2	2	0	0	2	0	0	2	2	15	62.5	Medium
Khalifa et al (2023)[46]	2	0	2	2	2	0	2	2	0	0	2	2	16	66.66	Medium

Notes: QUIN tool criteria: C1: clearly stated aims/objectives, C2: detailed explanation of sample size calculation, C3: detailed explanation of sampling technique, C4: details of comparison group, C5: detailed explanation of methodology, C6: operator details, C7: randomization, C8: method of measurement of outcome, C9: outcome assessor details, C10: blinding, C11: statistical analysis, C12: presentation of results. Risk of bias: <50% high risk, 50% to 70% medium risk, >70% low risk.

Data Synthesis

Ti-Base Height

Increasing the height of sandblasted Ti-bases from 4 to 7 mm greatly enhanced the bond strength of zirconia, LD and PICN crowns, as reported by a recent in vitro study.[7] Another study showed that increasing the height of sandblasted Ti-bases from 2.5 to 4 mm led to an increase in retention values of zirconia crowns luted with self-etch resin cement (RelyX Ultimate) but not for those luted with self-adhesive resin cement (G-CEM LinkForce).[42] This finding might be due to the more fluidity and the better micromechanical interlocking of G-CEM LinkForce cement, making the height factor less influential.[42] In addition, zirconia and LD crowns, representing maxillary premolar, luted to 3-mm height sandblasted Ti-bases revealed considerable failure during fatigue loading.[12] On the other hand, a recent study demonstrated that changes in sandblasted Ti-base height did not lead to significant differences in bonding stability of PICN crowns under thermomechanical fatigue aging; however, height affected the fracture resistance of those crowns.[47]

Ti-Base Geometry for Single Crown

Different sandblasted Ti-base geometrical features did not lead to significant differences in bonding stability of PICN crowns under thermomechanical aging.[47] However, it has been shown that zirconia crowns luted to non-treated 6-mm-height Ti-bases with straight-screw-channel exhibited higher bond strength than those luted to angled-screw-channel bases.[45]

Ti-Base Geometry for Multi-Unit FDPs

Regarding the design of Ti-bases that support zirconia multi-unit FDPs, a study compared the bonding stability against thermo-mechanical aging of zirconia 3-unit FDPs luted to different configurations of sandblasted Ti-bases: conical for bridges, cylindrical for crowns, cylindrical for bridges, and combination. It showed that Ti-base design affected the bonding stability against aging, with cylindrical Ti-bases offering higher bonding stability, while combination of conical and cylindrical Ti-bases resulted in the uppermost debonding rate.[21] Nonetheless, another study demonstrated that either design of sandblasted titanium cylinders, cylindrical or conical, demonstrated comparable bond strength to zirconia FDPs when luted with self-adhesive resin cement (Panavia SA); however, the cylindrical titanium cylinders with macro-retentive features retained more residual cement after debonding; entailing higher bond strength.[22]

Mechanical Pretreatment of Ti-Base

Several studies evaluated the effect of mechanical pretreatment of Ti-bases on the bond strength to conforming ceramic crowns, where an increase in bond strength was shown by most of the identified in vitro studies when smooth Ti-bases or those having macro-retentive features were roughened by air abrasion in comparison with the non-treated bases.[19,20,28,35,46] On the contrary, two in vitro studies[18,30] revealed that sandblasting of Ti-bases that have interlocking microgrooves with 50µm Al_2O_3 significantly decreased the bond strength to zirconia copings compared with the non-treated bases, besides a mixed failure mode was more observed compared to adhesive failure at zirconia-resin interface that was predominant before sandblasting.[30]

Furthermore, coating the Ti-bases with titanium nitride has been shown to enhance the bond strength to zirconia copings in comparison with the non-coated sandblasted Ti-bases.[40]

Various roughening procedures with different grain sizes of alumina particles (45, 50 and 110μm) have been proposed, whereas 50μm Al_2O_3 particles were found to provide greater surface roughness on the smooth Ti-bases and consequently higher bond strength to ceramic crowns in comparison to other sizes or procedures.[19]

Mechanical Pretreatment of Ceramic Coping

The identified in vitro study showed that sandblasting of the zirconia bonding surfaces with 110μm Al_2O_3 at 2 bar pressure enhanced the bond strength to sandblasted Ti-bases compared with no mechanical pretreatment of zirconia.[17] However, analyzing the fracture pattern still revealed adhesive failures at zirconia-resin interface even after sandblasting alone without primer application on both sandblasted bonding surfaces, concluding that zirconia-resin bonding is the weakest point.[17] To avoid microcracks of zirconia,[17] one to two bar pressure was utilized by most of the studies, even though other studies utilized 2.5 bar pressure.[22,32,44]

Concerning the mechanical pretreatment of LD copings, all studies etched the bonding surfaces with 5% hydrofluoric acid (HF) for 20s,[12,15,19,34,35,39,41,44,46,48] except one study[7] that etched the surfaces with 9.5% HF etch for 20s. Whereas PICN crowns were etched with 5% HF for 60s[15,41,44,47,48] or with 9.5% HF for 20s.[7]

Chemical Surface Pretreatment

An in vitro study[17] compared between different chemical pretreatments to bonding surfaces of zirconia and Ti-bases with application of two different MDP monomer-based primers (Alloy primer, Clearfil Ceramic) or tribochemical silica coating treatment (Rocatec system). The highest bond strength was recorded when the bonding surfaces of both zirconia and Ti-bases were sandblasted with 110μm Al_2O_3 and when an MDP-based primer (Clearfil Ceramic) was applied, concluding that combination of mechanical and chemical pretreatments of both bonding surfaces led to the most effective bonding and to the less incidence of adhesive failure at zirconia-resin interface.[17] In agreement with that finding, another study showed that the application of an MDP monomer-based primer (Clearfil Ceramic) improved the retention of zirconia crowns to Ti-bases when both bonding surfaces were sandblasted; however, it did not do so with the non-sandblasted bonding surfaces.[30] Additionally, the application of a phosphate monomer-based primer (Monobond plus) on ceramic copings and Ti-bases in combination with mechanical pretreatment of both bonding surfaces resulted in the strongest bonding of LD and zirconia copings to Ti-bases, in comparison to other primers (Alloy primer, RelyX ceramic, or Clearfil Ceramic), as reported from an in vitro study.[34] Furthermore, Kemarly et al[35] demonstrated that although the mechanical pretreatment of Ti-bases is the prime factor for enhancing the bonding of LD copings, the combination of mechanical pretreatment of the bonding surfaces with an application of a phosphate monomer-based primer (Monobond plus) resulted in the highest bond strength, in comparison to another primer (alloy primer) or no primer application. Regarding titanium nitride-coated bases, chemical pretreatment with primer application did not influence the bond strength to zirconia copings.[40]

Type of Luting Cement

Several identified in vitro studies demonstrated that the type of luting agent could affect the bond strength of ceramic restorations luted to Ti-bases.[18,20,22,23,32,33,37,38,42,43,48]

When comparing resin cements with conventional cements to lute zirconia copings to Ti-bases, Santos-Neto et al[37] demonstrated that resin cements provided higher bond strength than conventional cement (resin-modified glass ionomer). Bagegni et al[43] also compared between seven different cements including self-adhesive resin, adhesive resin and conventional cements, and showed that self-adhesive resin cements offered the greatest retentive strength. However, the researchers concluded that most of the tested cements are appropriate to lute zirconia crowns to Ti-bases.[43]

Comparing different types of resin cements, Linkevicius et al[18] who compared between three resin cements found significantly higher bond strength for phosphate monomer-based resin cements (G-CEM LinkAce, RelyX U200) than non-phosphate containing cement (Ceka Site). Güngor and Nemli[23] also showed that the phosphate monomer–based self-adhesive resin cement (Zirconite) had significantly higher bond strength than the other investigated self-etch resin cements (MHA, Panavia F 2.0), as well as the failure pattern analysis showed an adhesive failure at the titanium-resin interface with this cement (Zirconite) in spite of the non-treated zirconia surfaces.[23] The higher bond strength of Zirconite to zirconia may be attributed to the higher degree of monomer conversion.[23] In addition, Wiedenmann et al[33] demonstrated that DMA/HEMA-based cement (MHA) revealed higher bond strength and less adhesive failure at zirconia-resin interfaces than Bis-GMA/TEGDMA-based cement (Panavia V5) did. In agreement with this study, Chiam et al[22] found that self-adhesive resin cement (RelyX Universal) and DMA/HEMA-based cement (MHA) showed a significantly higher bond strength compared to Bis-GMA/TEGDMA-based cements (Panavia V5, Panavia SA), when luting zirconia FDPs to cylindrical Ti-bases. Furthermore, Bergamo et al[20] showed that self-etch resin cement accompanied with an MDP-based universal primer (RelyX Ultimate cement/Scotchbond Universal) offered higher bond strength than self-adhesive resin cement without an adhesive (RelyX U200). Moreover, Strazzi-Sahyon et al[42] showed that self-etch resin cement (RelyX Ultimate) accompanied by an MDP-primer with higher pH (Scotchbond Universal) offered higher bond strength than self-adhesive cement (G-Cem LinkForce) with an MDP-primer with lower pH (G-Multi Prime). Oddbratt et al[38] reported that non–MDP monomer-based self-etch dual-cure resin cements (Panavia V5, RelyX Ultimate) offered higher bond strength than non–MDP monomer-based self-etch self-cure resin cement (MHA). Mehl et al[32] also showed significantly higher bond strength for MDP monomer– or phosphate monomer–based self-adhesive resin cements (Panavia SA, RelyX Unicem) compared to other investigated MDP monomer– or phosphate monomer–based self-etch resin cements (MaxCem Elite, SmartCem 2).

In contrast, two identified in vitro studies showed that the type of resin cement did not affect the bond strength since no significant differences were recorded between MDP monomer– or phosphate monomer–based self-adhesive or self-etch resin cements.[17,28] Analogously, another in vitro study[29] reported that dual-cure self-adhesive (RelyX U200) or self-cure self-etch (Multilink) resin cements had comparable bond strength; however, self-cure resin cement offered higher retention than dual-cure one after autoclaving.[29] Similarly, a recent study showed that the two resin cements, dual-cure (Panavia V5) and self-cure (MHA), performed equally when luting PICN and LD crowns; however, self-cure resin cement showed higher retention values than dual-cure for PICN crowns after autoclaving.[48]

Additionally, two identified in vitro studies showed that the bond strength between ceramic copings and Ti-bases relied on the utilized bonding system in connection with ceramic restorative material, because some definite cements led to higher bond strength for some specific ceramic materials.[41,44]

CAD-CAM Ceramic Restorative Material

If the type of ceramic restorative material significantly influenced the bond strength to Ti-bases was investigated in several studies.[7,12,15,41,44,48] An in vitro study showed that during thermo-mechanical fatigue aging, both zirconia and LD crowns luted to 3-mm height sandblasted Ti-bases showed adhesive failures between Ti-bases and ceramic crowns, while only LD ones suffered from ceramic fractures besides the adhesive failures.[12] The adhesive failure could be explained by the reduced bonding surface area of the short Ti-bases regardless of the restorative material; while the lower fracture strength of LD could justify the ceramic fracture that occurred during fatigue loading.[12]

Another in vitro study[15] showed that ceramic crowns luted to 5.5 mm-height sandblasted Ti-bases showed variable bonding stability under thermo-mechanical aging, with LD revealing superior stability compared to PICN and zirconia crowns, respectively. The result of this study agrees with that of another study that showed higher bond strength for LD copings luted to 4-mm-height sandblasted Ti-bases compared with zirconia ones.[34] Similarly, an in vitro study[7] showed that LD crowns exhibited the highest bond strength to sandblasted Ti-bases, whereas zirconia showed the lowest. On the other hand, a recent in vitro study[48] revealed that there were no significant differences in the bond strength between LD and PICN crowns luted to 4.3-mm-height sandblasted Ti-bases. In addition, other studies demonstrated that though significant differences in bond strength were recorded between different ceramic restorative materials, the use of definite cement led to higher bond strength for some ceramic materials; thus, they recommended to use a definite bonding system for each ceramic material.[41,44]

Luting Space Thickness

An in vitro study showed that an increase of axial luting space thickness from 25 to 50μm or from 50 to 75μm reduced the bond strength of zirconia copings luted to 4-mm-height non-sandblasted Ti-bases; however, it did not reduce the marginal fit.[36] Another investigation also revealed that 60μm luting space thickness offered better retentive strength than 100μm thickness for zirconia copings luted to 2.7-mm-height sandblasted Ti-bases.[32]

Contamination of Ti-Bases Prior to Cementation

An in vitro study[39] showed that saliva contamination of Ti-bases even followed by cleaning can have an undesirable effect on the bonding of LD crowns to Ti-bases. However, cleaning methods like 1-minute water spray active rinsing, application of suspension of zirconium oxide particles, or re-sandblasting of Ti-bases allowed the restoration of the bond strength partially, with suspension of zirconium oxide particles achieving the best results. In contrast, cleaning with alcohol bath had a negative effect.[39]

Polishing of the Adhesive Gap

An in vitro study showed that polishing of the adhesive gap for zirconia abutments luted to 10.5-mm-height sandblasted Ti-bases did not have an influence on the bond strength.[33] Ceramic polishers for 10s duration were utilized to reach an optimal surface roughness.[33]

Cleaning Methods/Sterilization

An in vitro study demonstrated that various decontamination methods including ultrasonic cleaning according to the Finevo Cleaning Protocol, autoclaving, and low-pressure plasma application did not influence the bond strength of zirconia abutments luted to sandblasted Ti-bases.[33] This finding agrees with another study revealing that autoclaving did not decrease the bond strength between zirconia abutments and sandblasted Ti-bases.[31] Notably, an in vitro study showed that steam autoclaving enhanced the bond strength of zirconia abutments luted to sandblasted Ti-bases with self-cure self-etch resin cement; however, it did so with dual-cure self-adhesive resin cement, while failure pattern analysis showed an increase in adhesive failure at zirconia-resin interface after autoclaving.[29] In addition, autoclaving augmented the bond strength of zirconia crowns luted to non-sandblasted Ti-bases with self-adhesive resin cement, while it did not do so when a self-etch conventional resin cement or sandblasted Ti-bases were used.[20] Furthermore, autoclaving enhanced the bond strength of LD and PICN crowns luted to sandblasted Ti-bases with either self-cure or dual-cure self-etching resin cements; however, higher retention values were recorded for self-cure resin cement when luting PICN crowns.[48] In spite of enhancing the bond strength, steam autoclaving was shown to negatively affect the marginal integrity.[48]

Figure 2 summarizes the assessed factors as potential influencers on bond strength between CAD-CAM implant-supported ceramic restorations and Ti-bases.

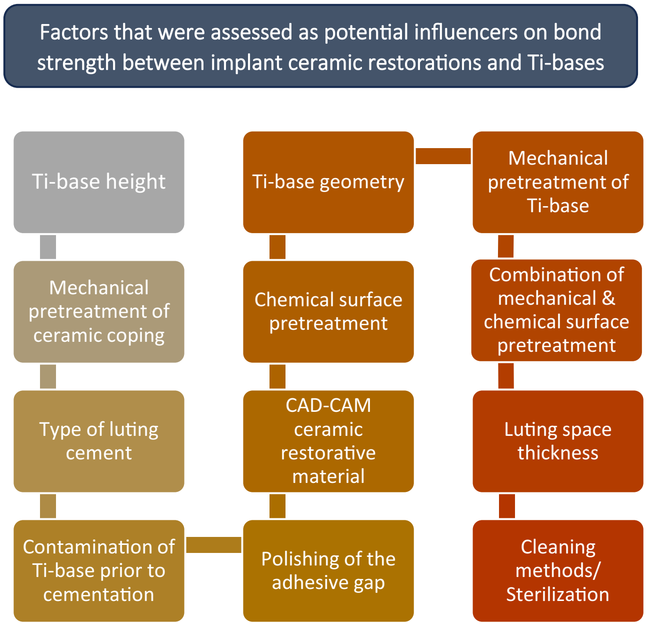

Figure 2 Flow diagram viewing the factors that were assessed as potential influencers on bond strength between CAD-CAM implant-supported ceramic restorations and Ti-bases.

Discussion

The rapid advancement of digital technologies and the introduction of new ceramic materials that offer superior mechanical and esthetic qualities have largely attributed to the notable transition from metal-ceramic to all-ceramic CAD-CAM implant restorations bonded to Ti-bases.[4,9]

The current systematic review aimed to compare the results of laboratory studies performed on adhesion methods of CAD-CAM implant-supported ceramic restorations to titanium-bases to develop clinically relevant recommendations, and to analyze the factors that could affect this bond strength.

About the impact of Ti-base abutment height on the bond strength to ceramic crowns, it has been found that the height affected the bond stability and strength.[7,12,42] This is because the increase in the Ti-base abutment height means an increase in the total bonding surface area that would consequently lead to an increase in retention.[49] However, a recent study contrasted with this result and found that height did not affect the bonding stability of PICN crowns.[47] A possible clarification for these conflicting results is that the studies used a diversity of Ti-bases' geometries, cements, pretreatment of bonding surfaces, and crown materials which would have influenced their bonding strength and stability and how they behaved with different heights. Some researchers recommended that 3-mm-height Ti-bases should be used cautiously in the posterior region,[12] and others prescribed to have a Ti-base height of more than 3.5 mm to reduce the risk of debonding.[49] Therefore, as the restorative space allows for taller Ti-bases, they should be used. Additionally, it is highly advocated to evaluate the crown height space pre-surgically to allow for adequate Ti-base abutment height of more than 3.5 mm at the time of restoration.[49] However, further laboratory and clinical studies are required to set the critical height of Ti-base where below which it is risky.

If Ti-base geometry or design could affect the bonding stability or strength to ceramic crowns, straight-screw channel Ti-bases exhibited higher bond strength than angled-screw channel ones luted to zirconia crowns.[45] This is attributed to the larger access hole, the fewer axial wall, and thus the less surface area of the angled-screw channel base compared with the straight one.[45] Since limited evidence is available about the angled-screw channel Ti-bases, further research is required.

Regarding the effect of design of Ti-bases supporting zirconia multi-unit FDPs, cylindrical Ti-bases offered higher bonding stability than conical ones, as shown by one in vitro study.[21] However, another study[22] demonstrated that both designs of titanium cylinders demonstrated comparable retentive strength to zirconia FDPs when luted with self-adhesive resin cement. While it is advocated to use non-engaging cylindrical Ti-bases to support zirconia multi-unit FDPs because of the higher bonding stability and the better passivity of fit,[21] further research is required to address this issue.

Concerning the influence of the mechanical pretreatment of Ti-bases, smooth bases behaved differently to micro-grooved ones when they were sandblasted. Whereas an increase in the bond strength was found when smooth Ti-bases were roughened with air abrasion,[19,20,28,35,46] with 50µm Al_2O_3 performing more favorably,[19] sandblasting of micro-grooved Ti-bases with 50µm Al_2O_3 significantly decreased the bond strength to zirconia copings.[18,30] This could be explained by the fact that sandblasting of smooth Ti-bases would increase the roughness of surface and thus increases the surface area involved in micromechanical interlocking with resin cement. Additionally, the physicochemical alteration of the bonding surfaces may enhance the wettability of the bonding agents.[50,51] However, after sandblasting of micro-grooved bases, part of the alumina particles may remain inside the Ti-base's retentive microgrooves; thus, weakening the bond between resin cement and Ti-base.[18] Change in Ti-base geometry and increase in luting cement gap might also contribute to this weakening effect.[18,30] Coating the Ti-bases with titanium nitride to enhance esthetics might also enhance the bonding strength to zirconia copings.[40] However, still more clinically relevant data should be obtained using different designs of Ti-bases with different particle sizes of alumina to evaluate their impact on bonding of ceramic restorations to Ti-bases.

Regarding the impact of mechanical pretreatment of zirconia copings, it has been shown that sandblasting the zirconia with 110µm Al_2O_3 increased the bond strength to Ti-bases compared with no mechanical pretreatment.[17] However, sandblasting alone without primer application was not adequate to reduce the adhesive failures at zirconia/resin interface, concluding that zirconia-resin bonding is the weakest point. This might be due to the higher hardness of zirconia compared with titanium, thus the less effectiveness of sandblasting.[17] Therefore, combination of mechanical and chemical pretreatments of both bonding surfaces led to the most effective bonding.[17] One to two- bar pressure was utilized mostly to avoid microcracks of zirconia copings. Further in vitro and in vivo research are required to evaluate the performance of different surface pretreatments with different particle sizes and resin luting agents in ceramic-titanium bonding.

Apart from the mechanical pretreatment of the bonding surfaces, it has been shown that chemical pretreatment alone with application of a primer did not significantly enhance the bond strength of ceramic copings without priori mechanical pretreatment, suggesting that combination of mechanical and chemical pretreatments of both bonding surfaces led to the most effective bonding.[17,30,34,35] However, an MDP-based or phosphate ester monomer-based primer has been found to be effective for enhancing the bond strength.[17,30,34,35] This could be justified by the issue that MDP is a bifunctional molecule comprising a phosphate group that bonds to zirconia and titanium, and a methacrylate group that has been shown to bond to resin cements.[52] Similarly, the phosphate ester group in the phosphate monomer-based primers has been shown to bond firmly to hydroxyl groups of zirconia.[53] However, further research is required.

The type of resin cement may affect the bonding of ceramic restoration to Ti-bases.[18,20,22,23,32,33,38,42] For instance, phosphate monomer-based resin cements provided higher bond strength than non-phosphate containing cements;[18] because those phosphate monomers make firm covalent bonds with hydroxyl groups of zirconia.[54] In addition, DMA/HEMA-based resin cements offered higher bond strength than Bis-GMA/TEGDMA-based cements.[33] This might be attributed to the longer application time of MDP monomer allowing for adequate vaporization, the reduced particle size of ≤3.0µm, the lesser volume of inorganic fillers ≤ 36%, and the self-curing mode of DMA/HEMA-based cements compared with Bis-GMA/TEGDMA-based cements.[33] Furthermore, self-etch resin cement accompanied by an MDP-based primer offered higher bond strength than self-adhesive resin cement without a primer.[20] This might be due to the presence of acidic monomers such as 10-MDP in the self-adhesive cement structure instead of being present in the primer, having an undesirable effect on its polymerization.[55] A further issue is that a reduced degree of conversion has already been proved for self-adhesive resin cement compared with the adhesive one, affecting its mechanical properties.[56] Resin cement accompanying an MDP-based primer with higher pH produced higher bond strength than resin cement with lower pH MDP-based primer.[42] This could be explained by the fact that the lower pH primer would hasten the silanol hydrolysis and the condensation course,[57] thus reducing the bonding strength of the cement. On the other hand, some studies reported that the type of resin cement had no significant effect on the bond strength,[17,28,29,48] while other studies showed that the bond strength relied on the utilized cement type in connection with ceramic restorative material.[41,44] Therefore, they recommended utilizing a definite bonding system with specific ceramic restorative material.[41,44] However, no recommendation could be given for the best luting agent based on the restorative material, and further research is needed.

If the type of ceramic restorative material affected the bonding stability or strength to Ti-bases, LD revealed superior bonding stability[15] and strength[7,34] compared to PICN and zirconia materials. This finding could be explained by the differences in the chemical composition of those ceramic materials.[7] Etching LD would partially dissolve the glass leaving microscopic pores that would improve the micromechanical retention with the resin cement, and a phosphate monomer-based primer would enhance the chemical bonding with the etched glass ceramics. PICN material nearly lacks the disilicate component present in LD, making acid etching less effective, while a phosphate monomer-based primer is still effective in augmenting the chemical bonding. Nonetheless, zirconia oxide ceramics that would be sandblasted to enhance the micromechanical retention still have weak chemical bonding.[7] It appears that etchable ceramics could be a good option for single implant restorations. However, further laboratory and clinical research about the ceramic/Ti-base bonding stability might be conducted.

The axial luting space thickness may affect the bond strength between zirconia copings and Ti-bases.[32,36] An increase of axial luting space thickness from 25 to 50µm or from 50 to 75µm has shown to reduce the bond strength.[36] This could be explained by the fact that when luting space increased, the degree of micro-mechanical locking decreased; thus, the bond would rely mainly on the chemical bonding and on the cohesive strength of the cement itself.[32] Consequently, some researchers advocated that when CAD-CAM single-implant ceramic restorations are made, the luting space thickness should be checked prior to workflow to be less than 75 µm at the axial wall of the Ti-base.[36] However, further evidence is still needed to assess its effect on different designs of Ti-bases bonded to different ceramic materials and different restorations.

Prior to cementation, it is advocated to avoid contamination of Ti-bases because it has been shown to affect the bond strength; however, if it occurred, any of the cleaning methods including 1-minute water spray active rinsing, application of suspension of zirconium oxide particles, or re-sandblasting could be used, except the alcohol bath.[39] This is because alcohol might fix saliva proteins to the bonding surfaces and does not assist in their elimination.[58]

After cementation and prior to connection of the luted restorations to their respective implants intraorally, it has been shown that different decontamination methods including steam autoclaving did not affect the bond strength between ceramic copings and Ti-bases.[31,33] Interestingly, autoclaving may enhance the bond strength of zirconia copings when using self-cure resin cement,[29] self-adhesive resin cement with non-treated Ti-bases,[20] or self-cure or dual-cure resin cements, with higher values for self-cure, when luting LD and PICN crowns.[48] However, it may negatively affect marginal integrity.[48] The authors attributed those findings to the fact that autoclaving may increase the crosslinking of the linear polymer chains existing more in the self-cure resin cement compared with the dual-cure one; thus, increasing the bond strength.[59] Whereas the increase in the bond strength for self-adhesive resin could be explained by the issue that the extra heat curing offered by autoclaving may increase the degree of conversion of self-adhesive resin cement presenting with a late polymerization, besides the situations of no micromechanical and/or chemical surfaces pretreatment.[55] This contrasts with conventional resin cement that could reach a threshold conversion with sandblasted Ti-bases.[20] Moreover, autoclaving seems to change the physical properties of the resin cement, leading to increase of its cohesive strength and thus affecting the failure pattern analysis.[29] As autoclaving or decontamination of these restorations prior to connection to their respective implants would have a positive biological outcome on the soft tissue and on the longevity of implants, as well as it would not deteriorate the bond strength, it is recommended to use a specific decontamination protocol prior to insertion.[33] However, which protocol can enhance the longevity of the implant and at the same time does not impact the bond strength or marginal integrity most effectively must be evaluated in further studies.

Since polishing of the adhesive gap for zirconia abutments luted to Ti-bases did not affect the bond strength,[33] it is recommended to polish this gap with ceramic polishers for 10 seconds[33] to reach an optimal surface roughness of 0.2µm to reduce bacterial accumulation.[60] However, further evidence is still needed to evaluate its effect on different heights and designs of Ti-bases luted to different ceramic materials.

Regarding the observed failure patterns after pull-out test, adhesive failures at the zirconia-resin interface were frequently revealed by several studies, without[30,36] or even with mechanical pretreatment of zirconia bonding surfaces,[31,32,43] with specific types of cements,[33,38] or after autoclaving.[29] This entails that the zirconia-cement interface is generally the weakest part of the bond system. A probable explanation of this weaker bond compared with titanium interface could be the changes in the surface features of zirconia, with the surface getting rougher and softer due to low-temperature degradation.[56,61] In addition, the higher hardness and density (5.68 g/cm3) of zirconia compared with the relatively soft titanium may reduce the effectiveness of sandblasting.[32] On the other hand, other studies revealed more mixed failures with combination of mechanical and chemical surface pretreatments of both zirconia and Ti-bases,[17,34,42] with specific types of cements such as DMA/HEMA-based cement,[33,38] or with no autoclaving,[29] entailing that resin cement may provide a comparable bond to titanium and zirconia. However, those findings need to be confirmed by further investigations.

Most of the identified in vitro studies in the current review utilized the pull-out test to assess the strength of the bond between ceramic restorations and Ti-bases. Though the pull-out test is a sensitive and sophisticated technique that provides valuable information on the performance of adhesive materials,[62] the bond quality cannot be solely determined by laboratory bond strength test values.[63] A comprehensive assessment requires microscopic analysis of the fracture patterns to fully understand the results. Careful interpretation of both types of data is essential for drawing appropriate conclusions and making clinical recommendations based on the durability of the tested bonding protocols.[63] Thus, one of the limitations of this review is that several included studies (12) did not report on the fracture patterns after the test.

The analysis of various bonding protocols should consider a clinically relevant aging procedure, as this can impact the bonding durability.[12,15,23,32,37,47] Therefore, one of the inclusion criteria of this systematic review was that all samples of the included studies should be subjected to thermocycling, thermomechanical loading, and/or autoclaving before testing the bond strength. Thermocycling is commonly used in laboratory studies to test adhesive materials' performance by thermally stressing the resin interface at both surfaces with extreme temperatures like those encountered intraorally.[64]

Many included in vitro studies in this review also combined thermocycling with water storage as an aging method,[7,12,22,28,30,32,35–37,41] because water storage reduces bonding durability and the mechanical properties of adhesive materials due to hydrolytic degradation.[65,66] In addition, mechanical loading replicates the chewing forces experienced intraorally and may increase the susceptibility of adhesive systems already stressed during the thermocycling process.[12,15,23,47] Combining those approaches provides a better evaluation of the durability of different bonding protocols of ceramic restorations to Ti-bases.

Although this systematic review is a valuable addition to contemporary literature since it shed the light on this important subject, the direct application of the current data to clinical scenarios is inherently limited. The unidirectional pull-off forces used in the bonding strength tests do not accurately represent the nonaxial occlusal forces found in a patient's mouth.[23] Additionally, the lack of clear reporting data and the absence of blinding and randomization in most studies may have affected the quality of some outcomes. Several studies also did not analyze the fracture patterns microscopically after debonding, and analysis of data on multi-unit FDPs remains limited. Moreover, the risk of bias in the included studies was mostly medium (25 studies), with four presented with a high risk of bias. A further limitation of this review is the issue that a meta-analysis was not implemented due to the relative heterogeneity of the data. Lastly, this review was accomplished by only one author. To validate the clinical reliability of the bonding systems between ceramic restorations and Ti-bases, further well-designed laboratory and clinical research assessing the influence of various Ti-bases' geometries, heights, bonding protocols, pre-treatments, restorative materials, and collaboration between these factors on the bonding strength and stability are required.

Conclusions

Based on the evidence gained from the identified studies, this systematic review concluded:

1. Ti-base abutment height is an important influencing factor on the ceramic/Ti-base bond stability and strength. It is recommended to use adequate Ti-base abutment height of more than 3.5 mm, while 3-mm-height Ti-bases should be used with caution in the posterior region.
2. Combination of mechanical and chemical surface pretreatments of both bonding surfaces seems to enhance the bond strength in contrary to a sole chemical pretreatment that has a negligible influence. Interestingly, smooth Ti-bases rather than micro-grooved ones most likely benefit from sandblasting pretreatment for enhancing ceramic/Ti-base bonding performance. Therefore, it is advocated to combine the mechanical and chemical pretreatments of zirconia copings and smooth Ti-bases with 110µm Al_2O_3 and 50µm Al_2O_3, respectively.
3. It appears that etchable ceramics such as lithium disilicate may provide a more effective bonding performance to Ti-bases compared with zirconia, and thus could be a good option for single-implant restorations. While the type of resin bonding system may affect the bonding performance, the interaction of some cements with definite ceramic materials could enhance the bond strength.
4. Other factors such as Ti-base design, luting space thickness, polishing of the adhesive gap, and autoclaving could be potential influencing factors on the ceramic/Ti-base bonding performance; however, inadequate evidence is available. More forthcoming studies are required to support these conclusions.

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