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Current status of adhesive luting in indirect dental zirconia restorations

UPDATE

Estado actual de la fijación adhesiva en restauraciones indirectas de zirconia dental

Estado atual da colagem em restaurações dentárias indiretas de zircônia

Abstract

» **Objective.** To review the state of the art regarding the different adhesion strategies of dental zirconia to tooth tissues, as well as the adhesive agents used and the techniques available in clinical practice.

» **Materials and Methods.** A narrative review of the literature was carried out by consulting the PubMed and BVS Odontología databases.

» **Results.** The initial search yielded a total of 1,556 records. Thirty-five studies met the inclusion criteria and were incorporated into the qualitative analysis. Various mechanical treatments have been proposed for the internal conditioning of zirconia surfaces including sandblasting with aluminum oxide particles, tribochemical silica coating, laser irradiation, chemical etching and the application of low-fusing porcelain. The use of cleaning agents to eliminate surface contaminants after intraoral try-ins has also been reported. In addition, different primers containing functional phosphate monomers have been evaluated. Finally, dual-cure and self-cure resin cements appear to be the most commonly used materials for adhesive cementation to zirconia.

» **Conclusions.** Currently, there is no definitive consensus on the ideal adhesive protocol for zirconia restorations. However, several studies propose the ALPC concept (Airborne-particle abrasion, Cleaning, Primer, and Resin cement) as an effective strategy to achieve reliable adhesive luting of this type of restoration.

Keywords: Dental ceramics, Dental adhesion, Dental cements, Cementation, 10-MDP.

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Resumen

» **Objetivo.** Revisar el estado del arte sobre las distintas estrategias de adhesión de la zirconia dental a los tejidos dentarios, así como los agentes adhesivos empleados y las técnicas disponibles en la práctica clínica.

» **Material y métodos.** Se llevó a cabo una revisión narrativa de la literatura mediante la consulta de las bases de datos PubMed y BVS Odontología.

» **Resultados.** La búsqueda inicial arrojó un total de 1556 registros. 35 registros cumplieron con los criterios de inclusión y fueron incorporados al análisis cualitativo. Para el acondicionamiento interno de la superficie de zirconia se han propuesto diversos tratamientos mecánicos como el arenado con partículas de óxido de aluminio, el recubrimiento triboquímico con sílice, la irradiación láser, el grabado químico y la aplicación de porcelana de baja fusión. También se ha reportado el uso de agentes limpiadores destinados a eliminar contaminantes superficiales tras la prueba intraoral. Por otro lado, se han evaluado distintos imprimadores que contienen monómeros fosfatados funcionales. Finalmente, los cementos resinosos de activación dual y química parecen ser los más utilizados en la práctica clínica para la cementación adhesiva a zirconia.

» **Conclusiones.** Actualmente, no existe un consenso definitivo respecto al protocolo adhesivo ideal para restauraciones de zirconia. Sin embargo, diversos estudios proponen el protocolo ALPC (Arenado, Limpieza, Primer y Cemento resinoso) como una estrategia eficaz para lograr una fijación adhesiva confiable de este tipo de restauraciones.

Palabras clave: Cerámica dental, Adhesión dental, Cementos dentarios, Cementado, 10-MDP.

Resumo

» **Objetivo.** Revisar o estado da arte sobre as diferentes estratégias de adesão da zircônia dental aos tecidos dentários, bem como os agentes adesivos utilizados e as técnicas disponíveis na prática clínica.

» **Materiais e métodos.** Foi realizada uma revisão narrativa da literatura por meio da consulta às bases de dados PubMed e BVS Odontologia.

» **Resultados.** A busca inicial resultou em um total de 1556 registros. 35 estudos atenderam aos critérios de inclusão e foram incorporados à análise qualitativa. Diversos tratamentos mecânicos foram propostos para o condicionamento interno da superfície da zircônia incluindo jateamento com partículas de óxido de alumínio, revestimento triboquímico com sílica, irradiação a laser, ataque químico e aplicação de porcelana de baixa fusão. Também foi relatado o uso de agentes de limpeza destinados à remoção de contaminantes superficiais após provas intraorais. Além disso, foram avaliados diferentes primers contendo monômeros fosfatados funcionais. Finalmente, os cimentos resinosos de ativação dual e química parecem ser os mais utilizados na prática clínica para a cimentação adesiva da zircônia.

» **Conclusões.** Atualmente, não há consenso definitivo quanto ao protocolo adesivo ideal para restaurações em zircônia. No entanto, diversos estudos propõem o protocolo ALPC (Abrasão com partículas, Limpeza, Primer e Cimento resinoso) como uma estratégia eficaz para alcançar uma adesão confiável desse tipo de restauração.

Palavras-chave: Cerâmica dental, Adesão dentária, Cimentos dentários, Cimentação, 10-MDP.

Introduction

The growing demand for aesthetic dental restorations has significantly driven the evolution and development of a wide variety of restorative materials.[1,2] In this context, metal-free ceramics have become the materials of choice over traditional metal-ceramic materials, owing to their ability to more faithfully mimic the natural appearance of the tooth.[3–5] Moreover, these ceramics offer important advantages in terms of biocompatibility and long-term chemical stability, which has considerably expanded their range of indications in current dental clinical practice.[5,6]

Zirconium dioxide (ZrO_2), commonly known as zirconia, is a crystalline form of zirconium and belongs to the ceramic family.[7] It is a highly resistant and biocompatible ceramic material that has gained considerable popularity in contemporary restorative dentistry due to its outstanding mechanical and aesthetic properties.[7–9] These characteristics position zirconia as one of the biomaterials of choice for the fabrication of definitive indirect aesthetic restorations, both single-unit and multi-unit restorations, used primarily in the posterior region, as well as for implant-supported rehabilitations.[1,3] In addition, this material has evolved into several formulations, depending on powder composition, sintering additives, heat treatments, and other processing factors.[10]

However, achieving effective and durable adhesion between zirconia and natural tooth surfaces remains challenging. This is due to the material's low surface energy and chemical stability, which make it resistant to hydrofluoric acid etching and conventional silanization, methods used for other types of ceramics.[11,12] To overcome these limitations, various strategies have been developed, including specific surface treatments, adhesive systems, and chemical and mechanical bonding agents, with the aim of achieving a strong and stable bond.[13]

Despite these advances, controversy remains regarding which strategies are most effective for achieving reliable adhesive luting between zirconia restorations and tooth structures.[13,14] These difficulties are associated with the inherent characteristics of this ceramic material, such as its low surface energy and lack of reactive groups.[15,16] Understanding the fundamental principles of adhesion to zirconia is crucial for the clinical success and longevity of restorations.[3,17] Therefore, the aim of this study was to identify and analyze the different strategies for adhesion to zirconia described in the literature, as well as the adhesive agents and techniques currently available in clinical practice.

Methodology

A narrative literature review with a descriptive approach was conducted using the PICO strategy. The population (P) included teeth restored with fixed prostheses or indirect zirconia restorations requiring an adhesive protocol for clinical cementation. The intervention (I) encompassed different techniques for internal conditioning of zirconia and the use of adhesive agents, such as sandblasting, tribochemical

coating, laser irradiation, chemical etching, application of low-fusing porcelain, cleaning agents, and primers containing phosphate monomers. The comparison (C) was established between these techniques and cementation systems, both individually and in combination, with an emphasis on the ALPC Concept: Airborne-particle abrasion, Cleaning, Primer, and Resin Cement. The outcome (O) of interest was adhesion efficacy, considering bond strength, long-term stability, and clinical applicability.

The literature search was carried out in the Medline database, via PubMed, and in the Virtual Health Library in Dentistry (BVS Odontología). The search was supplemented by reviewing the references of the included studies.

The search strategy used MeSH descriptors in English, including "zirconium," "dental bonding," "dental restoration, permanent," "dental adhesives," "dental cements," "cementation," and "resin cements," along with their Spanish-language equivalents. Keywords were combined using the Boolean operators AND and OR (**Table 1**).

Table 1. Search strategy in PubMed and BVS Odontología

PubMed	Zirconium AND (Bonding OR Permanent Dental Restoration OR Dental Adhesives OR Dental Cements OR Cementation OR Resin Cements)
BVS Odontología	Zirconia AND (adhesión dental OR restauración dental permanente OR adhesivos dentales OR cementos dentales OR cementado OR cementos resinosos)

The inclusion criteria were as follows:

1. studies or protocols on adhesion to zirconia surfaces;
2. availability of the full text;
3. *in vitro* studies, clinical trials, and systematic reviews with meta-analyses;
4. articles written in English or Spanish; and
5. publications issued between January 2018 and May 2025.

Conversely, the following were excluded:

1. previously published narrative or systematic literature reviews;
2. letters to the editor;
3. adhesion studies or protocols focused on dental tissues, namely enamel and dentin; and
4. studies addressing the bonding of other types of dental ceramics, including metal-ceramics, lithium disilicate, among others.

Selection of the included studies was performed independently by two researchers (CR and GG). In the first stage, titles and abstracts were evaluated. Subsequently, the selected articles were read in full to confirm their relevance, taking into account the previously reported inclusion and exclusion criteria. Relevant data from each publication were recorded, including the first author's last name and year, study title, study type, and main findings (**Table 2**).

Results

The initial keyword search yielded 1,556 records. Search filters and duplicate removal were then applied, resulting in 1,548 records. Of these, 58 records were selected based on title and abstract for full-text reading. Finally, based on the selection criteria, 35 records were included for qualitative analysis in this review (Figure 1).

Of the total records included, 33 (94.3%) were *in vitro* studies, one was a meta-analysis of *in vitro* studies (2.9%), and one was a clinical study (2.9%). The included studies primarily evaluated adhesion and bond durability to zirconia, considering factors such as fracture resistance, marginal adaptation, the effects of contamination and cleaning, surface modifications, chemical interaction with functional monomers, and the comparative performance of different resin-based and conventional cements (Table 2).

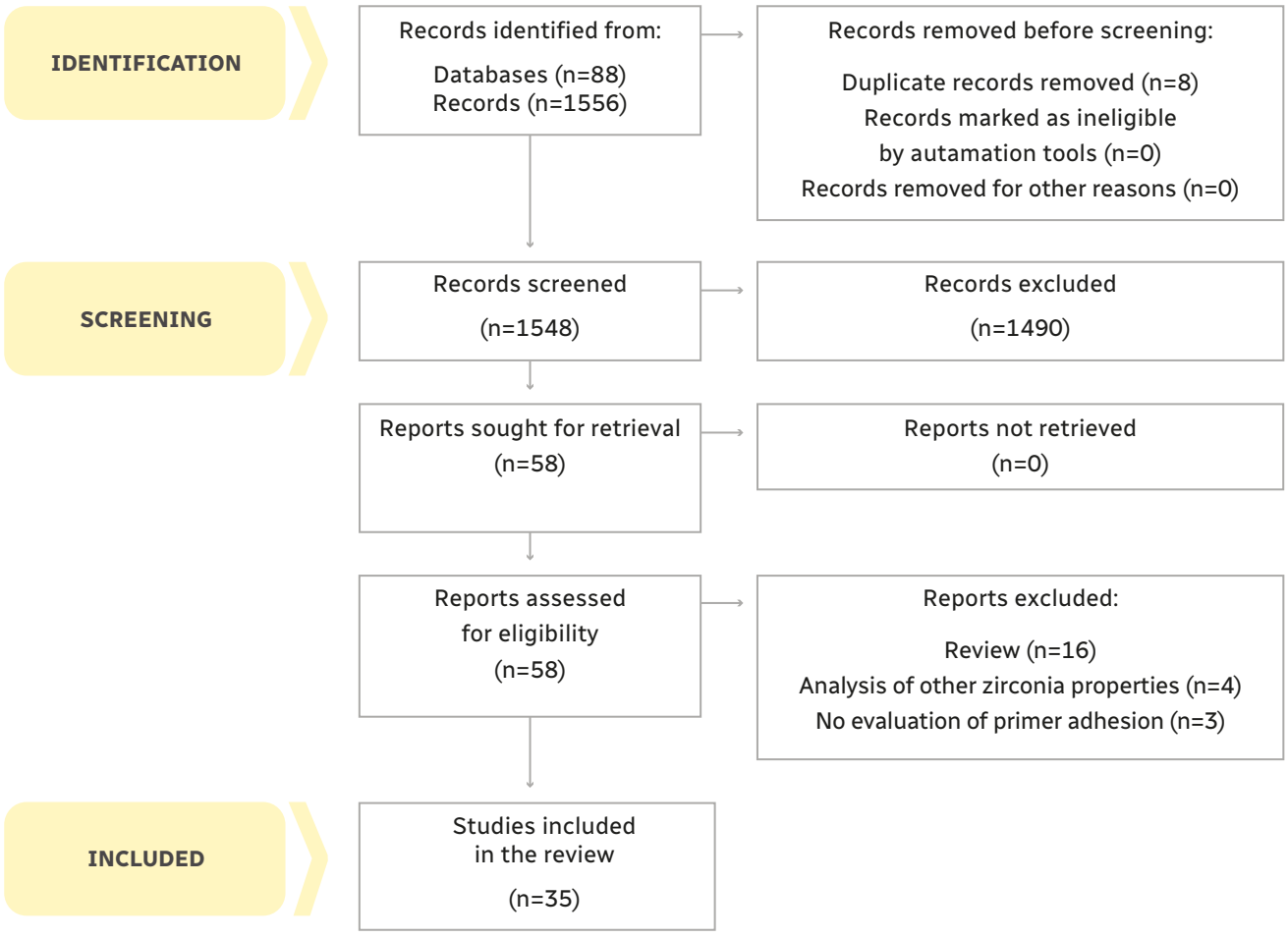


Figure 1. Diagram of the record search and selection process.

Table 2. Information on the included studies (n=35)

Author, year	Study title	Study type	Main findings
Genc, 2025	Effects of Cleaning Protocols on Resin Bond Strength to Saliva-Contaminated Monolithic Zirconia	*In vitro*	Specific cleaning protocols significantly improve resin adhesion to saliva-contaminated Zr.
Yenamandra, 2024	Effect of Various Surface Treatments of Zirconia on its Adhesive Properties to Dentin: An *In Vitro* Study	*In vitro*	Different surface treatments increase the adhesion of Zr to dentin.
Demir, 2024	Bonding Effectiveness of Saliva-Contaminated Monolithic Zirconia Ceramics Using Different Decontamination Protocols	*In vitro*	Some decontamination protocols effectively promote the adhesive capacity of Zr after contamination.
Hajjaj, 2022	Effect of Different Cleaning Methods on Shear Bond Strength of Resin Cement to Contaminated Zirconia	*In vitro*	Certain cleaning techniques maintain or improve the shear bond strength of resin cement to contaminated Zr.
Piulachs, 2023	*In vitro* comparative study between adhesion forces obtained on zirconia ceramic micromechanically treated with femtosecond laser (1027 nm), carbon dioxide laser (10,600 nm), and aluminum-oxide particles	*In vitro*	Laser treatments produce variations in adhesive strength, with significant differences among the methods evaluated.
Siwen, 2017*	Effects of different surface modifications on micro-structure and adhesion of zirconia ceramic: an *in vitro* study	*In vitro*	Surface modifications affect the microstructure and improve adhesion to Zr to varying degrees.
Noronha, 2020	Effect of zirconia decontamination protocols on bond strength and surface wettability	*In vitro*	Some decontamination protocols improve bond strength and surface wettability of Zr.
Angkasith, 2016*	Cleaning Methods for Zirconia Following Salivary Contamination	*In vitro*	Certain cleaning methods are effective in removing salivary contaminants and preserving Zr adhesion.
Chen, 2025	Nonthermal Atmospheric Plasma Promotes Bonding Between Adhesive Monomers and Zirconia	*In vitro*	Nonthermal atmospheric plasma significantly increases adhesion between adhesive monomers and Zr.
Khanlar, 2022	Effect of Air-Particle Abrasion Protocol and Primer on The Topography and Bond Strength of a High-Translucent Zirconia Ceramic	*In vitro*	The abrasion protocol and use of primer positively influence the topography and adhesive bond strength of Zr.

Tyor, 2023	Fracture resistance of monolithic translucent zirconia crown bonded with different self-adhesive resin cement: influence of MDP-containing zirconia primer after aging	*In vitro*	Fracture resistance is improved by the use of an MDP-containing primer in adhesively cemented translucent Zr crowns.
Li, 2020	High bonding strength between zirconia and composite resin based on combined surface treatment for dental restorations	*In vitro*	The combination of surface treatments achieves high adhesion between Zr and composite resin.
Kessler, 2024	Influence of additive and subtractive zirconia and lithium disilicate manufacturing on tensile bond strength and surface topography	*In vitro*	The manufacturing method affects bond strength and surface topography in Zr and lithium disilicate.
Gonçalves, 2024	Exploring Zirconia Adhesion: Pre and Postsintering Physical Surface Treatment, Chemical Treatment, and Cement Interactions	*In vitro*	Different physical and chemical treatments performed before and after sintering affect adhesion and interaction with cements.
Ruales-Carrera, 2019	Adhesion behavior of conventional and high-translucent zirconia: Effect of surface conditioning methods and aging using an experimental methodology	*In vitro*	Surface conditioning methods and aging affect adhesion in conventional and high-translucency Zr.
Le, 2019	Bond strength between MDP-based cement and translucent zirconia	*In vitro*	MDP-based cement showed good adhesion to translucent Zr.
Santos Silva, 2024	Influence of Different Surface Treatments on the Bond Strength of Yttria-Stabilized Tetragonal Zirconia Ceramic	*In vitro*	Several surface techniques significantly influence the bond strength of Zr.
You, 2024	Surface property changes observed in zirconia during etching with high-concentration hydrofluoric acid over various immersion times	*In vitro*	Hydrofluoric acid etching alters surface properties and may improve adhesion when properly controlled.
Sevilla, 2023	Effect of Surface Treatments with Low-Pressure Plasma on the Adhesion of Zirconia	*In vitro*	Low-pressure plasma improves Zr adhesion by modifying its surface without damaging the material.
Kang, 2022	Innovation Glass-Ceramic Spray Deposition Technology Improving the Adhesive Performance for Zirconium-Based Dental Restorations	*In vitro*	Spray deposition technology improves adhesive performance in Zr-based dental restorations.
Rosa, 2024	A comprehensive study on MDP effects: Microshear bond strength and fatigue resistance in 4YSZ ceramics	*In vitro*	MDP improves bond strength and fatigue resistance in Zr ceramics.
Lopes, 2023	Are Universal Adhesives Effective for Bonding to Zirconia in the Long Term?	*In vitro*	Universal adhesives show variable long-term effectiveness in bonding to Zr.
Icochea, 2024	Evaluation of single-step self-etching ceramic primer and zirconia primer for bonding to zirconia-reinforced lithium silicate ceramic	*In vitro*	The single-step self-etching primer showed adhesive performance similar to that of the specific Zr primer.

Lima, 2023	Bonding Efficacy of Universal Resin Adhesives to Zirconia Substrates: Systematic Review and Meta-Analysis	Meta-analysis	Universal adhesives appear to be effective for bonding to Zr.
Moradi, 2021	Effects of Universal Adhesive on Shear Bond Strength of Resin Cement to Zirconia Ceramic with Different Surface Treatments	*In vitro*	Universal adhesive improves shear bond strength with different surface treatments in Zr.
Afrasiabi, 2018	The effect of Z-primer on the shear bond strength of zirconia ceramic to dentin: *in vitro*	*In vitro*	The use of Z-primer increases the adhesive strength of Zr to dentin.
Al-Akhali, 2021	Influence of elapsed time between air-borne-particle abrasion and bonding to zirconia bond strength	*In vitro*	The time elapsed between abrasion and cementation affects adhesive bond strength in Zr.
Torres, 2021	Glass Ionomer Versus Self-adhesive Cement and the Clinical Performance of Zirconia Coping/Press-on Porcelain Crowns	Clinical	Self-adhesive cement showed better performance than glass ionomer in Zr crowns.
Khanlar, 2022	The effects of different silicatization and silanization protocols on the bond durability of resin cements to new high-translucent zirconia	*In vitro*	Different silicatization and silanization protocols affect bond durability in translucent Zr.
Ríos, 2018	Comparative study of displacement resistance of four zirconia cements	*In vitro*	Differences in displacement resistance were observed among four cements for Zr.
Vivek, 2022	Comparison of Zirconia to Dentin Bonding Using Resin-Based Luting Cements and Resin-Modified Glass-Ionomer Cement: *In vitro*	*In vitro*	Resin-based cements showed better adhesion to Zr compared with resin-modified glass ionomer cements.
Wongsirisuwan, 2024	Influence of light-polymerizing units and zirconia on the physical, chemical and biological properties of self-adhesive resin cements	*In vitro*	The polymerization unit and the presence of Zr affect the properties of self-adhesive resin cements.
Yang, 2018	Effects of Luting Cements and Surface Conditioning on Composite Bonding Performance to Zirconia	*In vitro*	Cement type and surface conditioning affect composite adhesion to Zr.
Imbery, 2021	Microshear bond strength of resin luting agents to monolithic zirconia	*In vitro*	Shear bond strength was evaluated, showing differences according to the luting agent used.
Yoshida, 2021	Effect of 10-Methacryloyloxydecyl Dihydrogen Phosphate Concentrations in Primers on Bonding Resin Cements to Zirconia	*In vitro*	The concentration of MDP in primers directly influences the adhesive strength of cements to Zr.

* Studies included from the gray literature because they were considered relevant. Zr: Zirconia.

Development and discussion

Unlike silica-based ceramics, also known as glass ceramics, zirconia is not susceptible to hydrofluoric acid etching or silanization because of its high crystalline content, which hinders adhesion.[11,12] Initially, zirconia was cemented conventionally; however, recent studies have explored methods to achieve adhesive cementation without compromising its structure.[13] Strategies such as surface treatments, specific adhesive systems, and chemical and mechanical bonding agents have been developed to optimize adhesion and improve retention, resistance to microleakage, and restoration durability.[13,14] However, the most effective technique for achieving reliable adhesion remains a matter of debate. Therefore, this literature review aimed to analyze the available evidence on this topic.[14]

Adhesive luting

Adhesive luting is a technique used in dentistry for the definitive placement of indirect dental restorations.[18] It involves the use of adhesive agents and cements that create a micromechanical and/or chemical bond with both the tooth structure and the restoration, thereby improving retention and fracture resistance. For this purpose, surface treatments are performed on both structures.[19] Although this technique offers several advantages, it requires multiple steps, is technique-sensitive, and may be susceptible to contamination, which may lead some practitioners to prefer conventional cementation.[20]

Nevertheless, adhesive luting provides a stronger and more durable bond, reducing the risk of detachment or fracture.[19] It also allows for greater preservation of tooth structure, as it requires less invasive preparation than conventional cementation.[20,21] However, this technique requires precision, optimal cleaning and drying conditions, and involves higher material costs.[21] Among its main advantages are the superior aesthetic properties of resin-based cements compared with conventional cements, such as glass ionomer or zinc phosphate cements.[1,3] This may be attributed not only to the translucency of the material, but also to the variety of available shades and its lower solubility, which may offer certain long-term advantages.[2,6]

Resin cements minimize leakage in ceramic restorations, although most of these findings come from *in vitro* studies on glass ceramics.[22] Proper adhesive protocols improve bonding between the restorative material and the tooth, marginal adaptation, prevention of microleakage, and fracture resistance.[11,21] The longevity of bonded ceramic restorations depends on the composition of the resin cement and the pretreatment methods applied.[13,17]

When analyzing the different strategies for adhesive luting to zirconia described in the literature, the following aspects should be considered: cleaning of the internal surface, treatment of the internal surface, and selection of the resin-based luting agent.

Cleaning of the internal surface

For effective adhesion, it is essential to work on a contaminant-free surface. During clinical procedures, restorations may become contaminated with blood, saliva, and other substances, which interfere with the adhesion mechanism.[23] Cements and primers contain phosphate groups that interact with the zirconia surface.[24] When contaminants are present, they occupy the sites where phosphate monomers should interact, rendering these monomers inactive. Therefore, proper cleaning of the zirconia surface is crucial for the durability of the restorative treatment.[23–25]

Simple methods such as cleaning with water (H_2O), hydrogen peroxide (H_2O_2), ethanol, acetone, phosphoric acid, or ultrasonic cleaning have shown the poorest results in contaminant removal.[26] In contrast, mechanical cleaning by sandblasting with aluminum oxide (Al_2O_3) particles has proven effective, although repeated use may weaken the structure of the zirconia restoration, according to several *in vitro* studies.[25–28]

Chemical cleaning with specific products such as Ivoclean (Ivoclar Vivadent), Katana Cleaner (Kuraray Noritake Dental), or ZirClean (BISCO Dental) appears to be a viable option, as it is practical, preserves the internal topography of zirconia, and is cost-effective.[26,29] Ivoclean is an alkaline solution (pH=13) containing zirconium oxide particles, which attract and remove contaminants during subsequent rinsing.[29] ZirClean, an alkaline gel containing potassium hydroxide (pH=13), removes phosphate contaminants in a similar manner.[26] Katana Cleaner, which contains an MDP salt, has surfactant properties that make it useful for both extraoral and intraoral cleaning.[26]

Some studies suggest that airborne-particle abrasion with aluminum oxide particles and the use of Ivoclean are the most effective techniques for restoring adhesion between zirconia and the bonding agent, whereas ZirClean has yielded the poorest results.[23,26] According to the literature, cleaning should be performed before priming with the adhesive system. If phosphoric acid or Ivoclean is applied after priming, the MDP coating may be removed, reducing bond strength.[30]

An *in vitro* study reported increased bond strength when a ceramic primer containing 10-MDP was applied before zirconia was exposed to contaminants.[31] If zirconia treated with 10-MDP becomes contaminated with saliva, a quick rinse with water is sufficient to restore adhesion.[31] This is because priming creates a water-repellent surface, making it difficult for saliva, which is 99% water, to interfere. However, Hajjaj and Alzahrani concluded that this method does not maintain the bond strength between zirconia and resin cement.[26]

Finally, nonthermal atmospheric plasma has been proposed as a promising technique for cleaning zirconia, although its clinical application is complex. This technique has shown highly effective results in contaminant removal.[32]

Internal surface treatment

Pretreatment of the zirconia surface is performed to improve its topography at the microscopic level. Its objective is to increase surface energy and surface wettability by creating roughness.[15,16,30] The absence of surface treatment on zirconia has been shown to result in lower bond strength.[30] Several studies agree that, to obtain durable bonds between resin and zirconia, both mechanical and chemical treatments are required.[33,34]

- **Micromechanical treatment**

Several methods are available for mechanical surface treatment, including sandblasting with aluminum oxide particles, tribochemical silica coating, laser irradiation, chemical etching, application of low-fusing porcelain, selective infiltration etching, plasma spraying, and zirconia ceramic powder coating, among others.[35]

Sandblasting is a process in which high-velocity aluminum oxide particles impact the zirconia surface, creating surface roughness.[36] Although this treatment improves wettability, it may also damage the surface and generate defects or cracks that affect the mechanical properties of zirconia.[35] To avoid this, sandblasting should be performed using appropriate parameters, such as a pressure of 2 to 2.5 bar, 50 µm particles, a distance of 10 mm, and an angle of 75–90 degrees, for 5–10 seconds.[13,30] Treatment with aluminum oxide particles has shown favorable results compared with tribochemical treatment using silica-coated particles.[37] For example, one study found that sandblasting with 50 µm aluminum oxide particles at low pressure produced the best results in terms of bond strength compared with untreated groups.[38]

Therefore, sandblasting with aluminum oxide particles is considered the most effective treatment for increasing zirconia roughness, regardless of whether conventional or high-translucency zirconia is used.[38,39] However, increasing particle size or pressure may damage the zirconia surface and reduce its bond strength.[39] In contrast, other studies found that neither particle size nor pressure had a significant impact on bond strength.[40] Despite the negative effects of the time elapsed between sandblasting and primer application, many clinicians choose to have sandblasting performed by the dental laboratory because of the difficulty of having a sandblaster available in their offices.[41]

Silica tribochemical coating (STC) is another treatment method that uses silica-coated alumina particles. These particles impact the zirconia surface and create a silica layer that enables bonding with silane.[37] This improves adhesion to both the composite and zirconia.[37] STC can be performed using systems such as Rocatec (3M ESPE), which uses 110 µm silica-coated alumina particles, or CoJet Sand (3M ESPE), which uses 30 µm particles. Although this method does not produce a completely uniform surface, it is more resistant to thermocycling than other treatments.[30,34,38]

Another alternative treatment is the use of glass beads instead of alumina particles, which reduces damage to zirconia. However, this treatment has proven less effective in creating the necessary roughness, and the bond strengths obtained are similar to those of untreated zirconia.[33]

Laser treatment of the zirconia surface has also been proposed as an alternative method, but it has not been shown to be as effective as sandblasting. High-intensity laser irradiation may damage the material, whereas low-intensity laser irradiation does not improve adhesion.[42,43]

Zirconia is an inert material and therefore cannot be etched with hydrofluoric acid.[30] However, some acid solutions combining hydrofluoric and nitric acids have been proposed for conditioning the zirconia surface. These treatments, however, are not as effective as other methods and may also be potentially hazardous.[44]

Low-pressure plasma has shown favorable results in improving adhesion without increasing roughness. Plasma activates the zirconia surface and increases its hydrophilicity, thereby improving adhesion. However, plasma treatment requires specialized equipment, and its effectiveness depends on several factors, such as the type of gas used and exposure time.[45,46]

Plasma treatment combined with sandblasting has shown the best results in terms of bond strength, although the available studies are *in vitro* and do not account for clinical variables.[46] Another emerging technique is glass-ceramic spray deposition (GCSD), which consists of spraying glass-ceramic powder onto zirconia and then sintering it, creating a dense lithium disilicate layer that improves bonding to resin cement.[47] These new techniques, such as plasma treatment and GCSD, improve the adhesion of zirconia to resin. However, they require expensive equipment and complex procedures that are difficult to standardize and are not suitable for routine clinical use.[46,47]

- **Chemical treatment**

Most of the studies reviewed recommend combining mechanical and chemical treatments to achieve the best results in zirconia bonding.[24,30,38] Although sandblasting modifies the zirconia surface, it is not sufficient on its own to significantly improve bonding to the ceramic material. For this reason, it is essential to combine these treatments with chemical promoters capable of enhancing adhesion. Among these, primers containing functional monomers stand out, particularly 10-MDP (*10-methacryloyloxydecyl dihydrogen phosphate*), which is known for its ability to form stable chemical bonds with dental zirconia.[48]

10-MDP has a terminal phosphoric acid group that interacts with zirconia, forming P–O–Zr bonds, while the other end of the molecule contains a vinyl group that allows copolymerization with the resin cement. These two functional groups are separated by a carbon chain, which determines properties such as the compound's viscosity, rigidity, hydrophobicity, and solubility.[35]

Specific zirconia primers are available on the market, such as Z-Prime Plus (BISCO Dental) and Peak ZM (Ultradent). According to the manufacturer, Z-Prime Plus significantly improves bond strength to materials such as zirconia, alumina, and metals due to its combination of two active monomers: MDP, a phosphate monomer, and BPDM, a carboxylate monomer.[49] This product should be applied in one to two coats, uniformly wetting the surface and then drying it with compressed air for 3–5 seconds. Peak ZM, which also contains 10-MDP, improves the chemical bond between the resin and the zirconia surface.[49] Ultradent recommends applying this primer to a previously sandblasted surface, using compressed air for 3 seconds, and then drying for another 3 seconds at full pressure.[49]

The methacrylate-functional silane monomer, γ-MPTS, is a coupling agent widely used in dentistry because it improves surface wettability. However, silanes cannot react directly with zirconia. Therefore, a ceramic primer containing MDP is required, since conventional coupling agents cannot bond to metal oxide ceramics.[33]

Some recent commercial adhesive primers combine silane, γ-MPTS, with phosphoric acid-functional monomers to simplify clinical procedures and improve adhesion to different ceramic materials.[50] These products have been shown to perform better than silane primers alone. However, the isolated application of MDP has proven more effective for bonding zirconia to resin cement than primers combining MDP with silane.[51] Monobond N (Ivoclar Vivadent) is an example of a universal primer that facilitates bonding between resin cements and all materials used in indirect restorations. Its composition includes silane methacrylate, phosphoric acid methacrylate, and sulfide methacrylate. For use, a thin layer is applied to the pretreated surfaces, left to act for 60 seconds, and then the excess is removed with compressed air.[50]

Universal adhesive systems have been developed to simplify clinical procedures. These systems contain chemical promoters and allow the restoration to be prepared without the need for additional components. Most of these adhesives contain 10-MDP and have been widely studied in recent years.[49] The application of a universal adhesive containing 10-MDP has been shown to increase adhesion to zirconia after sandblasting, and some studies suggest that these adhesives could even replace mechanical treatment and primer application.[49,52] Light-curing the adhesive before cement application showed no significant differences in adhesion.[40] One study showed that the use of a universal adhesive containing MDP, combined with mechanical treatment, produces a durable bond by promoting a water-resistant chemical interaction with metal oxides.[38]

Several commercial brands offer universal adhesives, such as Single Bond Universal (3M ESPE), All-Bond Universal (BISCO Dental), and Tetric N-Bond Universal (Ivoclar Vivadent). These adhesives are self-etching systems that contain both an acidic primer and an adhesive in a single bottle. Among them, All-Bond Universal is the most alkaline, with a pH of 3.5 according to the manufacturer, making it more suitable for use with dual-cure cements.[52] The manufacturer recommends applying

a thin layer to the pretreated surface, air-drying to remove excess solvent, and then light-curing for 10 seconds. If light-curing is not desired, Z-Prime Plus is suggested instead.[49,52] Single Bond Universal, in turn, contains 10-MDP, dimethacrylate resins, HEMA, Vitrebond™ copolymer, among other components. This improves adhesion to materials such as zirconia and alumina and allows bonding to glass ceramic surfaces without the need for an additional primer. Manufacturers agree that primers and cements from the same commercial brand should preferably be used to avoid interactions that could affect treatment effectiveness.[53]

The use of a 10-MDP-based primer may increase bond strength with both self-adhesive resin cements, whether based on 10-MDP or other functional monomers, and traditional resin cements.[54] It is important to use a flowable cement to take advantage of the effects of sandblasting, regardless of the type of resin used.[30] Immediate priming of zirconia after sandblasting has also been recommended, as bond strength decreases significantly when too much time elapses between the two treatments.[55] On high-strength ceramic surfaces without any pretreatment, the resin–ceramic interface has been observed to show wide gaps. In addition, alumina particle abrasion followed by the application of a 10-MDP-containing primer significantly improves the adhesive interface.[51]

Finally, according to the literature, the two most commonly used methods to improve adhesion are sandblasting with alumina abrasion followed by chemical treatment with a phosphate monomer such as 10-MDP, and tribochemical silica coating followed by silanization.[33,37]

Luting agents

One of the main advantages of oxide-based ceramics over silica-based ceramics is that they do not necessarily require adhesive cementation for the definitive placement of full-coverage restorations. They can be conventionally cemented, provided that the retention and fit of the restoration are adequate.[3,8] Conventional cements, such as glass ionomer and resin-modified glass ionomer cements, are suitable for zirconia restorations when abutment preparation conditions and material thickness allow.[56] One study suggests that resin-modified glass ionomer cements and self-adhesive resin cements offer similar clinical results for the cementation of zirconia crowns.[57] However, it has also been suggested that the adhesive capacity of glass ionomer to zirconia is minimal or nonexistent.[58]

The use of resin may be indicated to improve retention and flexural strength, especially in newer generations of highly translucent zirconia, which are less resistant.[33] In terms of adhesive strength to dentin, an *in vitro* study suggests that resin cements may yield better results than resin-modified glass ionomers.[59] Resin cements can be broadly divided into two main categories: traditional resin cements and self-adhesive resin cements.[60] With traditional resin cements, bond strength depends on the effectiveness of the preliminary treatments. These cements are more fluid, which favors penetration into surface microporosities and ensures

greater long-term strength.[60] Self-adhesive resin cements are designed to bond to the tooth structure through a one-step protocol, without the need for etching, rinsing, or priming.[18]

All self-adhesive cements primarily contain predominant acidic functional monomers and conventional dimethacrylate monomers. The most commonly used acidic monomers in these cements include bis-2-methacryloxyethyl acid phosphate (BMP), 10-MDP, 4-methacryloxyethyl trimellitic anhydride (4-META), glycerol pyromellitate dimethacrylate (PMGDM), 2-methacryloxyethyl phenyl hydrogen phosphate (Phenyl-P), and dipentaerythritol pentaacrylate monophosphate (PENTA).[18,60] According to several studies, self-adhesive cements containing 10-MDP provide higher bond strength values. However, other studies have not shown a clear difference among the different cement categories.[30,58] The low initial pH and high hydrophilicity of self-adhesive cements favor surface demineralization, similar to what occurs with self-etching adhesives. The predominant acidic functional monomers may chemically interact with zirconia and with the hydroxyapatite of the tooth structure.[61-63]

The use of Panavia SA Cement Automix (Kuraray Noritake Dental) is recommended because of its simplified application technique, which does not require coupling agents and therefore reduces the risk of errors during cement handling.[12] In addition, this cement showed the best results in terms of retention strength compared with Multilink Automix (Ivoclar Vivadent) and RelyX Ultimate (3M ESPE). However, no significant differences were found among the three self-adhesive cements, all of which showed highly acceptable performance.[58]

Regarding fracture resistance, poorer results were found when Calibra Universal self-adhesive cement (Dentsply Sirona) was used. These findings may be attributed to the fact that this cement contains PENTA as the predominant monomer, resulting in high viscosity that prevents effective wetting of the bonding surface and alters micromechanical interpenetration.[34] In addition, PENTA has been suggested to have lower bonding energy and lower chemical affinity for hydroxyapatite than MDP. In contrast, no significant differences were observed among the other cements used: RelyX U200, Panavia SA Cement Plus, and Multilink Speed.[34] According to some authors, the type of cement affects stress distribution within the tooth–restoration complex, helping to dissipate occlusal forces applied to the restoration and redirect them away from the tooth–restoration interface.[59,64]

Self-adhesive cements can bond to zirconia, but they are not capable of maintaining stable long-term adhesion on their own. For this reason, the combination of mechanical conditioning and chemical promoters is essential.[57] It has also been shown that combining a 10-MDP-containing primer with self-adhesive cements significantly improves the fracture resistance of monolithic zirconia crowns. The application of a primer to zirconia increases the bond strength of self-adhesive cement to the ceramic surface due to the synergistic effect of 10-MDP and acidic

functional monomers.[34] One study reported that increasing the concentration of 10-MDP could improve the bond strength of resin cement to zirconia.[65]

Because zirconia is an opaque dental ceramic, it should ideally be cemented with a dual-cure or self-curing resin cement. Highly translucent zirconia can be cemented with light-curing cements, provided that they are used in thin layers.[66]

Final considerations

Adhesive luting protocols successfully applied to conventional zirconia are also effective for high-translucency zirconia. In addition, surface treatment through sandblasting, the application of special primers containing phosphate monomers, and the use of composite resin cements provide durable long-term bond strengths.[67]

A three-step technique has been suggested in the literature to achieve a high-strength and durable bond between resin and zirconia, known as the "APC Concept."[68] The first step, "A," refers to sandblasting the zirconia surface with aluminum oxide particles or silica-coated aluminum oxide particles. The second step, "P," refers to applying a specific 10-MDP-containing primer to prime the zirconia surface. The final step, "C," refers to selecting the resin cement to be used, which may be either dual-cure or self-curing.[68] Following this approach, and incorporating new information on the importance of cleaning the zirconia surface, this technique could be updated as the "ALPC Concept," in which the "L" step would involve the use of specific cleaning agents for the zirconia surface (**Figure 2**).

In clinical practice, different situations may arise that modify the application of the ALPC Concept. If the dentist has a sandblaster in the office, the usual procedure is to first perform the intraoral try-in, followed by sandblasting and then primer application, without the need for intermediate cleaning, since sandblasting removes saliva and other contaminants. When sandblasting is performed in the laboratory, the use of cleaning agents is essential if the restoration is tried in the mouth before priming. In a less common scenario, the restoration may be sandblasted and conditioned before the clinical try-in. In this case, salivary contamination has a lower impact, since the primer has already established adhesion to zirconia; rinsing with water followed by drying is sufficient before continuing with the adhesive protocol.[66–69]

Although this review provides a broad and up-to-date overview of adhesion to zirconia, some limitations inherent to the available literature should be acknowledged. Most of the retrieved studies were *in vitro* and showed marked methodological heterogeneity in terms of experimental designs, conditioning protocols, and evaluation methods, which makes it difficult to establish a definitive consensus. Nevertheless, one of the strengths of this work lies in having compiled the most recent evidence, including relevant clinical data in the discussion. This allowed consistent trends and points of convergence in adhesive protocols to be identified.

In this regard, it is important to note that *in vitro* studies provide valuable information on adhesion mechanisms, but they do not reach the same level of clinical validity as controlled trials or longitudinal evaluations in patients. Therefore, further high-quality clinical research is essential to confirm and validate the findings obtained in the laboratory. Even so, the available evidence clearly indicates that the success of adhesive cementation depends largely on following the recommended protocols and correctly applying the products and materials indicated by manufacturers. When these aspects are fulfilled, the longevity and clinical performance of zirconia restorations are significantly improved.



Figure 2. ALPC Concept for adhesive luting of indirect zirconia restorations.

Conclusions

There is no definitive consensus on the ideal adhesive protocol for zirconia restorations.

Most of the studies analyzed agree on recommending a combination of mechanical and chemical pretreatments on the zirconia surface.

The most commonly used mechanical treatment is sandblasting with aluminum oxide particles.

The application of primers containing 10-MDP after mechanical treatment improves bond strength to zirconia, whether through specific primers or universal adhesive systems.

Self-adhesive resin cements can bond to zirconia. However, on their own, they do not maintain stable long-term adhesion. Therefore, when these cements are selected, it is essential to combine mechanical conditioning with the use of chemical promoters.

Adhesive luting protocols that have been successful for conventional zirconia have also proven effective for high-translucency zirconia.

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Data availability

The complete dataset supporting the results of this study is published within the article.

Conflict of interest

The authors declare that there are no potential conflicts of interest.

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Author contributions and collaboration

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1. Project Administration
2. Funding Acquisition
3. Formal Analysis
4. Conceptualization
5. Data Curation
6. Writing - Review and Editing
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