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ADVANCES IN BONDING TECHNIQUES FOR ZIRCONIA: A LITERATURE REVIEW OF SURFACE TREATMENTS AND ADHESIVE SYSTEMS"

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ABSTRACT

Zirconia (zirconium dioxide, ZrO_2) has become a popular material in dentistry due to its excellent mechanical properties, biocompatibility, and aesthetics. However, bonding to zirconia presents challenges due to its chemical inertness. This literature review explores recent advances in zirconia bonding, including mechanical and chemical surface treatments, adhesive systems, and a comparative analysis of resin and glass ionomer cements. The primary goal is to evaluate these bonding methods' efficacy and clinical impact. Studies indicate that combining airborne-particle abrasion and laser treatments with chemical methods, such as silica coating and acidic primers, enhances zirconia bonding. Resin cements with phosphate ester-based adhesives like MDP demonstrate superior bond strength and durability over glass ionomer cements. Although resin cements necessitate a more complex bonding protocol, their enhanced longevity makes them the preferred choice in clinical practice for zirconia restorations. Continuous research into zirconia bonding refines these techniques, expanding zirconia's applications and improving clinical outcomes.

Aim of the Stud: The main aim of this review is to evaluate recent advancements in bonding techniques for zirconia, with an emphasis on the efficacy of different surface treatments and adhesive systems. Additionally, the study aims to compare resin and glass ionomer cements regarding bond strength, durability, and clinical suitability, providing clinicians with a comprehensive understanding of each approach's strengths and limitations.

Materials and Methods: This literature review is based on a comprehensive search of peer-reviewed articles. Databases including PubMed, Google Scholar, and Web of Science were searched using keywords such as "zirconia bonding," "surface treatments," "resin cements," "glass ionomer cements," "MDP primers," and "adhesive systems." Inclusion criteria were studies focused on zirconia bonding techniques, comparisons between resin and glass ionomer cements, and investigations into bond longevity. Studies outside this range or lacking empirical evidence were excluded to ensure relevance and rigor in the findings.

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This literature review analyzed 22 references categorized by study type to ensure a comprehensive understanding of zirconia bonding techniques.

1. **In Vitro Experimental Studies:** A majority of the references (14 studies) were in vitro experiments evaluating bond strength, surface treatments, and adhesive properties under controlled laboratory conditions [3,6,7,10,16,19,20,22].
2. **Literature Reviews and Systematic Reviews:** Two references comprised a systematic review and an updated literature review, which provided an overview and synthesis of existing research on zirconia bonding and adhesive methods [8,11].
3. **Clinical Studies:** Four studies used simulated clinical conditions, such as thermocycling and aging processes, to assess the durability of zirconia bonds in environments mimicking intraoral conditions [5,13,14,18].
4. **Case-Based and Applied Research:** Two references focused on practical applications of zirconia bonding in clinical settings, examining specific bonding protocols and materials for different zirconia generations [4,9].

KEYWORDS: Advances in Bonding Techniques, Zirconia,Surface Treatments,Adhesive Systems

INTRODUCTION

Zirconia (zirconium dioxide, ZrO_2) is a popular material in restorative dentistry because of its high strength, durability, biocompatibility, and aesthetic appeal [1,2,3]. Nevertheless, zirconia's chemical inertness poses challenges for achieving a durable bond, especially when compared to other dental materials [4,5]. Recent studies have focused on developing mechanical and chemical surface treatments and advanced adhesive systems to enhance zirconia bonding efficac^y [6,9,8]. This review investigates these advancements, exploring how different methods affect bond strength, longevity, and clinical performance. The study further compares the properties and suitability of resin cements versus glass ionomer cements in bonding with zirconia, given their distinct bonding mechanisms and durability [9,10].

Historical Development of Zirconia Bonding Techniques

The methods for bonding to zirconia have evolved significantly over the past two decades, spurred by zirconia's introduction to restorative dentistry in the 1990s [5,11]. Early techniques relied heavily on mechanical retention due to zirconia's resistance to conventional etching. Over time, air-borne-particle abrasion and silica-coating methods gained traction, creating micro- retentive surfaces and enabling chemical adhesion with silane primers [5]. In the early 2000s, the development of phosphate monomers, such as MDP, marked a breakthrough by allowing chemical bonding to zirconia's crystalline structure [9,12]. Today, combining mechanical and chemical treatments provides clinicians with more reliable bonding protocols for zirconia restorations.

Comparative Analysis of Different Zirconia Generations

Zirconia ceramics are available in various forms, primarily based on yttria content, which affects their physical properties and bonding compatibility. The most common are 3Y-TZP (3 mol% yttria), known for high strength but limited translucency, and newer generations like 4Y-TZP and 5Y-TZP, which offer greater translucency but lower strength [1,13]. Studies indicate that 3Y-TZP requires aggressive mechanical treatments (e.g., airborne-particle abrasion) to enhance bond strength, whereas

4Y-TZP and 5Y-TZP can benefit from gentler chemical surface treatments due to their modified microstructures [2,14]. Resin cements with MDP demonstrate strong chemical bonds with all zirconia types, though surface treatment choice should align with each generation's specific properties to ensure optimal adhesion [3,15].

Surface Treatments

Surface treatment is fundamental in zirconia bonding, as untreated zirconia exhibits low adhesive capabilities due to its high crystalline content [2,15]. Surface treatments can be divided into mechanical and chemical methods, each enhancing bond strength through unique mechanisms.

Mechanical Surface Treatments:

Airborne-Particle Abrasion: Airborne-particle abrasion is one of the most common techniques, utilizing alumina particles to roughen the zirconia surface and increase micromechanical retention [4,15,16]. Variations in particle size, pressure, and application duration affect bond strength. Studies by Łagodzińska et al. found that smaller particles (e.g., 50 μm) generate an ideal roughness, resulting in better bonding performance compared to larger particles [16]. This technique allows for increased surface area and mechanical interlocking, which is crucial for adhesive retention [7].

Laser Treatment: Laser treatments, including Er and Nd lasers, create micro-retentive features on zirconia surfaces, promoting adhesion without causing excessive thermal damage [6,10,17].

Hatami et al. showed that laser-treated surfaces improve bonding by generating surface micro-roughness, facilitating better interlocking with adhesive materials [6,18]. Compared to airborne-particle abrasion, laser treatments offer precision in modifying surface topography, preserving zirconia's structural integrity while achieving the desired roughness for optimal adhesion [12].

Chemical Surface Treatments:

Silica Coating: Silica coating, typically applied through tribochemical methods, enhances zirconia's chemical bonding capabilities by creating a silica-rich layer compatible with silane coupling agents [3,13]. Yang et al. reported that silica-coated zirconia displayed significantly improved bond strength, especially when used with silane-based primers, which act as a bridge between zirconia's inorganic surface and resin-based cements [19,20]. This treatment is effective in creating a chemical bond and complements other surface treatments [17,21].

Acid Etching and Phosphate Primers: While conventional acid etching does not significantly impact zirconia surfaces, phosphate-based primers such as MDP (10-methacryloyloxydecyl dihydrogen phosphate) have been shown to form stable chemical bonds with zirconia [7,9]. Tsuo et al. confirmed that MDP primers create robust chemical bonds through phosphate groups, resulting in increased bond strength [2,9,11]. The MDP monomer's molecular structure enables it to bond strongly with zirconia's surface, making it integral to achieving durable bonds in clinical practice [7].

Adhesive Systems

The choice of adhesive system is critical for long-lasting zirconia restorations, with resin cements generally outperforming glass ionomer cements.

Resin Cements

Self-Adhesive Resin Cements: Self-adhesive resin cements simplify bonding by eliminating the need for separate etching and priming steps. Research by Fouad et al. indicated that self-adhesive resin cements containing MDP provide reliable zirconia bonding, even without additional surface treatments [4,10,17]. This feature makes them attractive for clinical use where a streamlined bonding protocol is beneficial [7].

Dual-Cure Resin Cements: Dual-cure resin cements offer the advantage of both light and chemical curing, ensuring full polymerization in areas with limited light exposure, such as posterior restorations. Ozcan et al. found that dual-cure cements containing MDP exhibit superior durability and bond strength compared to light-cure-only systems [8,11,22]. These cements are preferred in complex restorations due to their adaptability to various clinical conditions [5].

Glass Ionomer Cements (GICs)

Glass ionomer cements are widely used for their ease of handling, chemical bond to tooth structure, and fluoride release, which can be beneficial for caries prevention [5,8]. However, GICs have limitations in bonding to zirconia due to the material's lack of ionic bonding sites [1].

Bonding Mechanism: GICs bond to tooth structure through ionic interactions with calcium ions in hydroxyapatite; however, this mechanism does not effectively bond with zirconia, which lacks similar chemical interaction sites [2,13,21]. Additional treatments, such as airborne-particle abrasion combined with MDP primers, are often necessary to improve bond strength between GICs and zirconia [1,14].

Mechanical Properties: GICs generally exhibit lower compressive and tensile strengths compared to resin cements, which impacts their long-term durability in zirconia restorations. De Angelis et al. noted that, while GICs provide acceptable initial bond strength, their long-term mechanical properties are weaker compared to resin cements when bonded to zirconia [2,5,10].

Challenges and Limitations in Zirconia Bonding

Despite advancements, zirconia bonding still faces challenges that affect clinical success. Moisture sensitivity is a common issue, as contamination by saliva or blood can hinder adhesive performance[2,19]. Technique sensitivity is another factor, with varying requirements for surface preparation, primer application, and resin curing depending on the type of zirconia and adhesive system [11,21]. These factors underscore the need for careful handling and strict protocol adherence to maximize bond durability and patient outcomes [22,10]. Furthermore, environmental conditions, such as long-term exposure to moisture and temperature fluctuations, may degrade bond strength, especially in GICs [2,14].

RESULTS

Recent studies highlight significant improvements in zirconia bonding with advanced surface treatments and adhesive systems. Mechanical treatments such as airborne-particle abrasion and laser modification enhance bond strength through micro retentive features, while chemical treatments like silica coating and phosphate-based primers (e.g., MDP) further strengthen the bond [9,16,17,19,]. Resin cements, particularly those containing MDP, consistently demonstrate greater bond strength and durability compared to glass ionomer cements [4,5,7]. While GICs can achieve adequate initial bond strength with enhanced surface treatments, their long-term durability generally remains inferior to resin cements [1,15].

DISCUSSION

Bond Strength and Durability

Resin Cements: Studies consistently show that resin cements, especially those containing MDP, provide superior bond strength and long-term durability on zirconia [2,3,7]. Yue et al. found that MDP creates a durable bond with zirconia, offering robust adhesion superior to GICs [7,20]. The strong chemical interaction between MDP and zirconia improves clinical performance and makes resin cement the preferred choice for zirconia bonding [8,11].

Glass Ionomer Cements: Although GICs are simpler to handle, they exhibit lower bond strength to zirconia than resin cements, even when MDP primers are used [1,13]. Turker et al. reported that despite surface treatments, GICs' bond strength remains significantly lower than resin cements due to its less effective ionic bonding mechanism [1,17]. This limitation affects GICs' use in long-term zirconia restorations, as the bond is more susceptible to degradation under clinical conditions [14,15].

Handling and Clinical Application

Resin Cements: Resin cements require a more complex protocol, involving multiple steps such as surface treatment, primer application, and careful handling. However, the strength and longevity of the bond justify this complexity in clinical scenarios where durability is paramount [5,12,21].

Glass Ionomer Cements: GICs are easier to handle and have a simplified bonding protocol, making them attractive in clinical situations requiring a straightforward approach [1,13].

However, their limited durability and lower bond strength make them less suitable for demanding restorations [10].

Mechanisms of Bonding Chemical Bonding

Phosphate Ester-Based Adhesives: Phosphate ester monomers such as MDP enhance zirconia bonding by forming a durable chemical bond with the surface. Yue et al. highlighted that phosphate groups react with zirconia, creating a stable chemical interface that significantly improves bond strength [7].

Silane Coupling Agents: While traditionally used for silica-based ceramics, silane agents are effective on zirconia when combined with silica coating or specific primers. Zhang et al. demonstrated that silane-treated zirconia surfaces, especially when pre-treated with silica, exhibit enhanced bonding with resin cements [13].

Mechanical Interlocking

Surface Roughening: Mechanical surface treatments like airborne-particle abrasion create micro retentive features that enhance micro-mechanical interlocking. Łagodzińska et al. showed that increasing surface roughness improves the mechanical retention of adhesive systems to zirconia [16].

Laser Treatments: Lasers such as Er can create controlled micro-roughness on zirconia surfaces, promoting mechanical interlocking without excessive damage. Hatami et al. found that laser-treated zirconia surfaces had improved bond strength due to the enhanced microtopography [6].

Clinical Protocol Recommendations

For optimal bonding, clinicians are advised to use a combination of mechanical and chemical surface treatments, especially airborne-particle abrasion and MDP-based primers [8,12]. Resin cement, particularly those with dual-cure capabilities, provide robust bonding with durable performance in posterior and load-bearing restorations [10,22]. GICs may be used in simpler cases or where fluoride release is beneficial, though additional surface treatment may be required to strengthen the bond to zirconia [13,11].

Future Trends and Emerging Technologies in Zirconia Bonding

The field of zirconia bonding continues to evolve with advancements in surface modification and adhesive chemistry. Emerging technologies like plasma treatments and nanocoating are under investigation for enhancing zirconia's bonding properties while simplifying clinical procedures [12,21]. Digital dentistry, including CAD/CAM technology, has also enabled more precise surface modifications and bonding protocols tailored to individual patient needs, reducing chair time and improving adhesive success rates [3,18].

Patient Outcomes and Satisfaction with Zirconia Restorations

Successful zirconia bonding directly impacts patient satisfaction by ensuring long-lasting restorations with minimal maintenance. Studies highlight that strong zirconia bonds reduce failure rates, enhance aesthetic outcomes, and provide stability under functional loads [5,7,8].

The biocompatibility and high durability of zirconia restorations have made them a preferred choice among patients seeking both aesthetic appeal and longevity in dental restorations [1,11,14].

Future Directions

Despite significant advancements, the field of zirconia bonding still presents opportunities for research and development aimed at enhancing clinical efficacy and simplifying application protocols. Future directions in zirconia bonding research include:

Development of Simplified, High-Performance Bonding Protocols

As techniques and materials advance, one focus is to develop simplified protocols that require fewer steps without compromising bond strength and durability. Currently, bonding protocols for zirconia, especially with resin cements, can be technique-sensitive and time-consuming [1,17]. Research into "one-step" or universal bonding agents that combine mechanical and chemical bonding properties could improve clinical efficiency and reduce the potential for technique errors, thus increasing the overall success rate of zirconia restorations [3,7].

Advances in Nanotechnology and Surface Modification

Emerging technologies such as plasma treatments and nanocoatings are promising areas for zirconia surface modification. These treatments aim to increase surface energy and bonding efficacy without altering zirconia's structural integrity [12]. Plasma technology, for example, can be used to etch or coat zirconia surfaces with nanoscale particles, allowing better adhesion with MDP-based and other resin-based adhesives [21]. Nanocoating's that provide antimicrobial properties are also under investigation to enhance zirconia's long-term clinical performance by reducing biofilm formation [10].

Exploration of Digital Dentistry and CAD/CAM Technology

Digital workflows and CAD/CAM technologies have revolutionized restorative dentistry, offering precision in design and manufacturing. Future research may explore CAD/CAM- integrated surface treatments tailored to specific restoration sites and patient needs. This could enable a higher degree of customization in surface topography for optimized adhesion, reducing the need for additional mechanical or chemical treatments [3,18]. Additionally, CAD/CAM integration could enable automated bonding protocols, reducing chair time and improving consistency in clinical outcomes [14].

Investigating Alternative Adhesive Systems and Monomer Chemistries

While MDP remains the primary monomer for zirconia bonding, new monomers and functional groups are under development to provide even stronger and more durable bonds. Research into novel primers with enhanced resistance to hydrolytic degradation and improved bonding to all- ceramic surfaces may allow for stronger and more resilient bonding, particularly in high-stress regions [9,20]. Future formulations that combine multiple monomer chemistries could provide universal applicability across diverse restorative materials, simplifying adhesive selection for clinicians [2,15].

Studies on Clinical Outcomes and Patient Satisfaction

Finally, additional clinical studies assessing the impact of new bonding protocols on patient outcomes would provide valuable data on the long-term performance and durability of zirconia restorations. These studies should focus on patient-reported outcomes, including aesthetics, comfort, and maintenance needs, alongside mechanical evaluations such as bond strength retention, resistance to wear, and fracture rates over time [5,8,11]. Such data will help clinicians make informed decisions about which techniques provide the best outcomes in real-world settings.

CONCLUSION

The development of effective bonding techniques for zirconia has progressed significantly, addressing challenges presented by the material's high crystallinity and chemical inertness. Advances in surface treatment methods, including airborne-particle abrasion, laser modification, and chemical treatments such as silica coating and MDP-based primers, have proven critical in enhancing zirconia's bond strength. These methods improve surface roughness and promote chemical adhesion, laying the foundation for stronger and more durable bonds.

Among adhesive systems, resin cements—particularly those containing the phosphate monomer MDP—consistently demonstrate superior bond strength and longevity compared to glass ionomer cements (GICs). The chemical affinity between MDP and zirconia allows for durable bonding, rendering resin cements the preferred choice in clinical settings. While GICs offer simplicity and fluoride release, their bond strength and durability are generally inferior, limiting their applicability for load-bearing zirconia restorations.

This review underscores that, while mechanical and chemical surface treatments combined with advanced adhesive systems have improved zirconia bonding significantly, there remain challenges such as moisture sensitivity, technique sensitivity, and the need for streamlined clinical protocols. For clinicians, adhering to these precise bonding protocols is essential to achieving optimal results with zirconia restorations.

In summary, the continuous refinement of zirconia bonding techniques—combining innovative surface treatments and adhesive systems—holds the potential to expand the material's applications and improve clinical outcomes, making zirconia an increasingly versatile and reliable option in restorative dentistry.

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