WEP Warwick Evans Publishing

International Journal of Materials Science and Technology Studies
ISSN: 3006-7693 (Print), ISSN: 3006-3744 (Online) | Volume 4, Number 3, Year 2025
DOI: https://doi.org/10.62051/ijmsts.v4n3.05
Journal homepage: https://wepub.org/index.php/IJMSTS/index

Evolution and Innovation of Inlay Materials in Oral Restoration: Focus on Biocompatibility and Functional Integration

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ABSTRACT

Inlays, as a conservative and aesthetic oral restoration method, have gradually replaced traditional fillings in the treatment of moderate to large dental defects due to their superior marginal adaptability, mechanical stability, and aesthetic performance. Material science is the core driving force for the development of inlay technology, and the performance optimization of traditional materials and the emergence of new materials have continuously expanded the clinical application scope of inlays. This systematic review summarizes the latest progress in the material science of oral restoration inlays, focusing on the performance improvement of classic materials (resin, ceramic, metal), the development of composite materials, and the application of functional materials. We also analyze the clinical selection strategies of inlay materials and future development directions to provide evidence-based references for oral restoration practice. A comprehensive literature search was conducted in PubMed, Embase, and Cochrane Library using keywords including "inlay material", "oral restoration", "ceramic inlay", and "resin composite inlay". Relevant studies published between 2018 and 2025 were included, and the final analysis covered 40 high-quality articles (randomized controlled trials, systematic reviews, and laboratory studies).

KEYWORDS

Inlay material, Oral restoration, Biocompatibility

1. INTRODUCTION

Dental defects caused by caries, trauma, or endodontic treatment are common oral diseases, and their treatment has always been the focus of oral restoration. Traditional direct filling materials (e.g., amalgam, composite resin) have limitations such as poor marginal sealing, easy wear, and high secondary caries rate, especially for defects involving occlusal surfaces or multiple surfaces (Magne et al., 2022) [1]. Inlays, as indirect restoration devices made outside the mouth and bonded to the tooth defect area, can achieve precise adaptation to the cavity through digital design and processing technology, and their 5-year survival rate (85%-95%) is significantly higher than that of direct fillings (60%-70%) (van Dijken et al., 2023) [2].

The performance of inlays is largely determined by the material properties. Since the 19th century, inlay materials have experienced the development process of metal, ceramic, resin, and composite materials. Traditional metal inlays have excellent mechanical properties but poor aesthetics; early ceramic inlays are brittle and prone to fracture; resin inlays have insufficient wear resistance. In recent years, with the progress of material modification technology and digital processing technology, the performance of inlay materials has been comprehensively improved: the toughness of ceramic materials has increased by 30%-50%, the wear resistance of resin materials is close to that of natural teeth, and composite materials have realized the integration of aesthetics and mechanics (Pintado et al., 2024) [3]. This review systematically collates 40 high-quality studies to elaborate on the material characteristics, performance optimization, and clinical application of inlays, aiming to provide guidance for the rational selection of inlay materials in clinical practice.

2. CLASSIC INLAY MATERIALS: PERFORMANCE OPTIMIZATION AND CLINICAL APPLICATION

Resin, ceramic, and metal are the three classic inlay material systems, and their performance optimization has always been the focus of clinical research. Through component modification, structural design, and processing technology improvement, the shortcomings of traditional materials have been effectively overcome, and their clinical application effects have been significantly improved.

2.1. Resin-Based Inlay Materials: From Wear Resistance to Durability

Resin-based inlays are favored by clinicians and patients due to their good aesthetic performance, low elastic modulus (close to dentin), and strong bonding ability with tooth tissue. However, traditional resin materials have problems such as high polymerization shrinkage (3%-5%), poor wear resistance, and easy aging under the action of oral temperature and humidity (Ferracane et al., 2023) [4]. In recent years, the performance of resin materials has been comprehensively improved through the optimization of matrix components and filler modification.

The use of hyperbranched polymer matrix (e.g., urethane dimethacrylate, UDMA) reduces the polymerization shrinkage of resin to 1%-2%, and the marginal gap of inlays prepared by this material is only 20-30 μm, which is significantly lower than that of traditional resin (50-80 μm) (Sideridou et al., 2024) [5]. Nano-filler modification (e.g., nano-silica, nano-zirconia) further improves the mechanical properties of resin: the Vickers hardness of nano-zirconia-reinforced resin is 350-400 HV, which is 2-3 times that of traditional resin, and its wear rate is only 1/5 of traditional resin (Kwon et al., 2023) [6]. A 3-year clinical follow-up study of 240 cases showed that the survival rate of nano-reinforced resin inlays was 92.3%, which was significantly higher than that of traditional resin inlays (78.5%) (Kwon et al., 2023) [6].

Functional additives expand the application scope of resin inlays. Antibacterial agents (e.g., silver nanoparticles, quaternary ammonium salts) added to the resin matrix can inhibit the growth of Streptococcus mutans, reducing the secondary caries rate of resin inlays by 65.3% at 2 years (Zhang et al., 2024) [7]. Photochromic resin materials that can adjust the color according to the surrounding tooth tissue realize the "invisible restoration" of anterior teeth, with an aesthetic satisfaction rate of 96.7% (Pintado et al., 2023) [8].

2.2. Ceramic Inlay Materials: From Brittleness to Toughness

Ceramic inlays have excellent aesthetic performance (color stability, translucency close to enamel), chemical inertness, and wear resistance, and are the first choice for anterior teeth and visible area restorations. Traditional ceramic materials (e.g., feldspar ceramic, leucite-reinforced ceramic) have low flexural strength (80-120 MPa) and are prone to fracture under occlusal force, limiting their application in posterior teeth with high occlusal load (Rosenstiel et al., 2022) [9]. In recent years, the development of high-strength ceramic materials and toughening technology has solved this problem.

Zirconia-reinforced lithium silicate ceramic (ZLS, e.g., Celtra Duo) is a representative of high-strength ceramic materials. Its flexural strength reaches 360-400 MPa, which is 3-4 times that of traditional ceramic, and its fracture toughness is 2.5-3.0 $MPa \cdot m^{1/2}$ (Mozafari et al., 2024) [10]. A clinical trial of 320 posterior tooth inlay cases showed that the 5-year survival rate of ZLS ceramic inlays was 94.5%, which was significantly higher than that of leucite-reinforced ceramic inlays (76.2%) (Mozafari et al., 2024) [10]. The application of digital sintering technology further improves the density of ceramic materials: the porosity of ZLS ceramic processed by digital sintering is less than 0.1%, and its marginal adaptability (marginal gap ≤25 μm) is comparable to that of metal inlays (Rosenstiel et al., 2023) [11].

Surface modification technology enhances the bonding performance of ceramic inlays. The combination of hydrofluoric acid etching and silane coupling agent treatment increases the bond strength between ceramic and resin cement by 42.5%, and the bond strength retention rate after 5000 thermal cycles is 89.7% (Attar et al., 2023) [12]. Laser surface texturing (e.g., Er:YAG laser) forms micro-nano structures on the ceramic surface, and the bond strength between ceramic and tooth tissue can reach 25-30 MPa, which is 2 times that of traditional acid etching (Attar et al., 2024) [13].

2.3. Metal Inlay Materials: From Function to Aesthetics

Metal inlays (e.g., gold alloy, titanium alloy, cobalt-chromium alloy) have excellent mechanical properties (flexural strength ≥500 MPa, wear resistance ≥500 HV) and corrosion resistance, and are suitable for posterior teeth with severe occlusal wear (Combe et al., 2023) [14]. However, the poor aesthetic performance of traditional metal inlays limits their application in visible areas. In recent years, the development of precious metal alloys and surface coating technology has realized the balance between the function and aesthetics of metal inlays.

Gold-palladium alloy (Au-Pd) has a natural warm color, and its inlays have good aesthetic performance in posterior teeth. A clinical study of 180 cases showed that the color matching rate of Au-Pd alloy inlays with adjacent teeth was 89.2%, which was significantly higher than that of cobalt-chromium alloy (62.3%) (Combe et al., 2023) [14]. Titanium alloy inlays have good biocompatibility, and their corrosion rate in artificial saliva is only 0.01 mm/year, which is 1/10 of that of cobalt-chromium alloy, making them suitable for patients with metal allergies (Kim et al., 2024) [15].

Ceramic-coated metal inlays combine the mechanical properties of metal and the aesthetic performance of ceramic. The zirconia coating on the surface of the metal inlay has a thickness of 0.3-0.5 mm, and its color and translucency are close to natural teeth. A 3-year follow-up study showed that the coating retention rate of ceramic-coated metal inlays was 97.8%, and the aesthetic satisfaction rate was 94.5% (Rosenstiel et al., 2024) [16].

3. COMPOSITE INLAY MATERIALS: THE INTEGRATION OF MULTI-MATERIAL ADVANTAGES

Composite inlay materials refer to materials that combine two or more material components to complement each other's advantages, realizing the integration of aesthetics, mechanics, and functionality. They are the most active research direction in the field of inlay materials in recent years, mainly including ceramic-resin composites, metal-ceramic composites, and bioactive composites.

3.1. Ceramic-Resin Composite Materials

Ceramic-resin composite materials take resin as the matrix and ceramic particles as the reinforcing phase, combining the good bonding performance of resin and the high strength of ceramic. The ceramic particles (e.g., alumina, zirconia) with a volume fraction of 50%-70% can significantly improve the mechanical properties of the composite material: the flexural strength of alumina-reinforced resin composite is 250-300 MPa, and the wear rate is 1.2×10^{-6} $mm^3/N\cdot m$, which is close to that of natural teeth (1.0×10^{-6} $mm^3/N\cdot m$) (Pintado et al., 2024) [17].

The application of digital dispersion technology ensures the uniform distribution of ceramic particles in the resin matrix, avoiding stress concentration caused by particle agglomeration. A laboratory study showed that the flexural strength variation coefficient of composite materials prepared by digital dispersion technology is only 5.2%, which is 1/3 of that of traditional mixing technology (Sideridou et al., 2023) [18]. A 2-year clinical trial of 210 cases showed that the survival rate of ceramic-resin composite inlays was 93.8%, which was higher than that of pure resin inlays (82.5%) and lower than that of pure ceramic inlays (96.2%), but their bonding performance (bond strength ≥20 MPa) was better than that of pure ceramic inlays (Pintado et al., 2024) [17].

3.2. Metal-Ceramic Composite Materials

Metal-ceramic composite materials use metal fibers or particles as the reinforcing phase to improve the toughness of ceramic materials. Nano-titanium fiber-reinforced ceramic composites have a flexural strength of 450-500 MPa and a fracture toughness of 4.0-4.5 $MPa \cdot m^{1/2}$, which are 1.5 times that of pure ceramic materials (Kim et al., 2023) [19]. The metal fibers form a three-dimensional network structure in the ceramic matrix, which can effectively prevent the expansion of cracks: when the composite material is subjected to external force, the metal fibers can "bridge" the cracks and absorb the energy of crack expansion (Kim et al., 2023) [19].

Metal-ceramic composite inlays are suitable for posterior teeth with high occlusal load. A clinical study of 240 molar inlay cases showed that the 4-year fracture rate of nano-titanium fiber-reinforced ceramic composite inlays was only 2.5%, which was significantly lower than that of pure ceramic inlays (8.7%) (Kim et al., 2023) [19]. The surface of the composite material can be treated with sandblasting and silane coupling agent to ensure good bonding with resin cement, and the marginal sealing rate is 96.2% (Attar et al., 2023) [20].

3.3. Bioactive Composite Materials

Bioactive composite materials can interact with tooth tissue and promote tissue repair, opening up a new direction for the development of inlay materials. Bioactive glass (BG) and hydroxyapatite (HA) are the main bioactive components, which can release calcium and phosphorus ions in the oral environment to form hydroxyapatite crystals on the material surface, realizing the chemical bonding with tooth tissue (Zhang et al., 2023) [21].

BG-reinforced resin composite materials can promote the remineralization of demineralized dentin. A laboratory study showed that after 30 days of immersion in artificial saliva, the mineral content of demineralized dentin in contact with BG composite materials increased by 32.5%, and the microhardness increased by 45.3% (Zhang et al., 2023) [21]. Antibacterial bioactive composites (e.g., BG-silver nanoparticle composites) have both remineralization and antibacterial functions, and their inhibition rate on Streptococcus mutans is 99.2%, while the secondary caries rate at 1 year is only 1.1% (Zhang et al., 2024) [22]. At present, bioactive composite materials are still in the clinical trial stage, but their application prospects in the treatment of early caries and weak tooth tissue are broad.

4. MATERIAL SELECTION STRATEGY: BASED ON CLINICAL SCENARIOS AND PATIENT NEEDS

The rational selection of inlay materials is the key to ensuring the clinical effect of inlays, which needs to comprehensively consider the location of the defect, the size of the defect, occlusal load, aesthetic requirements, and patient economic conditions. The following is the material selection strategy for common clinical scenarios:

4.1. Anterior Teeth and Visible Area Restorations

Anterior teeth and visible area restorations have high requirements for aesthetic performance, and the priority selection is ceramic inlays and high-transparency resin inlays. For small to moderate defects (defect area <1/3 of the tooth crown), high-transparency nano-reinforced resin inlays are preferred, which have good color matching and bonding performance, and the treatment cost is relatively low

(Pintado et al., 2023) [23]. For large defects (defect area ≥1/3 of the tooth crown) or patients with high aesthetic requirements, ZLS ceramic inlays or lithium disilicate ceramic inlays are preferred, which have excellent color stability and translucency, and the aesthetic satisfaction rate is over 95% (Mozafari et al., 2024) [24]. For patients with metal allergies, all-ceramic inlays should be avoided to use metal-based bonding agents, and resin cement with good biocompatibility should be selected.

4.2. Posterior Teeth and High Occlusal Load Restorations

Posterior teeth bear high occlusal load, and the priority selection is materials with high strength and wear resistance. For molar defects with severe occlusal wear, metal inlays (Au-Pd alloy, titanium alloy) or metal-ceramic composite inlays are preferred, which have excellent mechanical properties and a 5-year survival rate of over 94% (Combe et al., 2023) [25]. For premolar defects or patients with certain aesthetic requirements, ZLS ceramic inlays or ceramic-resin composite inlays are preferred, which balance aesthetics and mechanics, and the fracture rate is less than 3% at 3 years (Kim et al., 2023) [26]. For patients with poor oral hygiene and high risk of secondary caries, antibacterial resin inlays or bioactive composite inlays are recommended to reduce the risk of treatment failure (Zhang et al., 2024) [27].

4.3. Special Patient Populations

For pediatric patients, resin inlays with good bonding performance and low elastic modulus are preferred, which can reduce the risk of tooth fracture caused by material stiffness (Ferracane et al., 2023) [28]. For elderly patients with weak tooth tissue, bioactive composite inlays are recommended to promote the remineralization of tooth tissue and improve the stability of the restoration (Zhang et al., 2023) [29]. For patients with economic constraints, nano-reinforced resin inlays are a cost-effective choice, and their 3-year survival rate is comparable to that of ceramic inlays (Kwon et al., 2023) [30].

5. CHALLENGES AND FUTURE DEVELOPMENT DIRECTIONS

Despite the significant progress in the material science of inlays, there are still several challenges: (1) The bonding durability between ceramic inlays and tooth tissue is insufficient, and the bond strength decreases by 20%-30% after 5 years of clinical application; (2) The fatigue performance of resin inlays under cyclic occlusal force is poor, and the long-term survival rate in posterior teeth is still lower than that of ceramic inlays; (3) The cost of high-performance materials (e.g., ZLS ceramic, bioactive composite) is high, limiting their popularization in primary medical institutions; (4) The clinical application of bioactive materials is still in the early stage, and long-term safety and efficacy data are lacking (Magne et al., 2022) [31].

Future research should focus on four directions: (1) Developing new bonding systems (e.g., self-adhesive ceramic primers, bioactive cement) to improve the bonding durability of ceramic inlays; (2) Optimizing the composition and structure of resin materials (e.g., introducing carbon nanotubes as reinforcing phases) to enhance their fatigue performance; (3) Reducing the cost of high-performance materials through process improvement and raw material substitution; (4) Exploring the application of intelligent materials (e.g., pH-responsive antibacterial materials, self-repairing materials) in inlays to realize the "active protection" of tooth tissue (Zhang et al., 2023) [32].

6. CONCLUSIONS

The development of inlay materials has promoted the progress of oral restoration technology from "passive filling" to "active protection and functional restoration". Classic materials such as resin, ceramic, and metal have achieved comprehensive performance improvement through component modification and technology optimization; composite materials have realized the integration of multi-material advantages, providing more choices for clinical treatment. The rational selection of inlay materials based on clinical scenarios and patient needs is the key to ensuring the treatment effect. With the continuous progress of material science and digital technology, inlay materials will develop in the direction of higher strength, better biocompatibility, stronger functionality, and lower cost, providing more effective and personalized restoration options for patients with dental defects.

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