Journal of Fatima Jinnah Institute of Dental Sciences
https://jfjids.com/index.php/jfjids/index
VOL 01 ISSUE 01 2025

Comparative Evaluation of Contemporary Dental Biomaterials Used in Restorative Dentistry: A Clinical and Laboratory-Based Study

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Abstract:
Contemporary restorative dentistry relies on biomaterials that must balance mechanical performance, adhesion, aesthetics, biocompatibility, and long-term clinical stability. This scholarly article presents a comparative framework for evaluating direct and indirect restorative biomaterials—resin composites, glass ionomer cements (GIC), resin-modified GIC (RMGIC), CAD/CAM resin-matrix ceramics/hybrid ceramics, lithium disilicate glass-ceramics, and zirconia—through a combined laboratory and clinical lens. Laboratory assessment emphasizes flexural strength, fracture toughness, wear, polymerization shrinkage, marginal integrity, and bonding behavior, while clinical evaluation focuses on survival/failure patterns (fracture, secondary caries, debonding, wear, marginal discoloration), patient-reported outcomes, and operator-dependent factors. Evidence suggests posterior resin composites show favorable annual failure rates in many settings, but risk increases with restoration size and patient caries risk. Glass ionomer materials remain valuable for high-caries-risk patients and cervical lesions due to fluoride release and chemical bonding, with ongoing evidence syntheses supporting their clinical longevity across indications. For indirect restorations, lithium disilicate and zirconia demonstrate strong medium-term survival in systematic reviews and cohort evidence, with zirconia often showing slightly higher survival in some comparisons. The study concludes with an evidence-guided material selection algorithm that aligns material choice with load, esthetic demand, bonding substrate, and patient risk profile.
Keywords: *Dental biomaterials, resin composite, glass ionomer cement, lithium disilicate, zirconia, CAD/CAM, bond strength, clinical longevity*

Introduction

Restorative dentistry has moved from "one-material-fits-all" approaches to patient- and site-specific selection of biomaterials. Modern clinical expectations include minimally invasive preparations, durable adhesion to enamel/dentin, highly natural aesthetics, and predictable longevity under complex oral conditions (thermal cycling, moisture, pH fluctuation, occlusal load, and biofilm activity). Materials now span direct restoratives (placed intraorally in a single visit) and indirect restoratives (manufactured extraorally using pressing or CAD/CAM). Each class has trade-offs: resin composites offer high aesthetics and conservative preparations but remain sensitive to polymerization shrinkage stress and technique; GIC/RMGIC provide fluoride release and chemical bonding but may show lower strength in high-load regions; and ceramics such as lithium disilicate and zirconia deliver excellent strength/aesthetics but require appropriate bonding/cementation protocols and thickness design. A clinically useful evaluation must therefore combine **laboratory-based performance indicators** with **clinical outcome patterns** (survival, failure modes, repairability, and patient satisfaction), ensuring the final selection is evidence-based and context-aware.

Classification of Contemporary Restorative Biomaterials

Contemporary restorative biomaterials are broadly classified into **direct** and **indirect** materials based on the method and location of fabrication. **Direct restorative materials** are placed and polymerized intraorally in a single clinical visit, allowing conservative tooth preparation and immediate restoration of form and function. These include **resin-based composites**, **glass ionomer cements (GICs)**, **resin-modified glass ionomer cements (RMGICs)**, and **compomers**. Resin composites are further categorized into **microfilled**, **microhybrid**, and **nanohybrid composites** according to filler size and distribution. Microfilled composites provide superior polishability and aesthetics, making them suitable for anterior restorations, but they exhibit lower mechanical strength. Microhybrid and nanohybrid composites combine fine and nano-sized fillers to achieve a balance between strength, wear resistance, and aesthetics, and are therefore widely used in both anterior and posterior restorations. **Conventional GICs** chemically bond to tooth structure and release fluoride, making them ideal for cervical lesions, atraumatic restorative treatment (ART), and high-caries-risk patients, although their lower strength limits use in stress-bearing areas. **RMGICs** incorporate resin components into GICs, improving mechanical properties and handling while maintaining fluoride release, and are commonly used in cervical restorations, liners, and bases. **Compomers**, which combine features of composites and GICs, offer improved aesthetics over GICs with limited fluoride release and are often indicated for pediatric dentistry and low-stress restorations.In contrast, **indirect restorative materials** are fabricated extraorally—either in a dental laboratory or via CAD/CAM systems—and subsequently cemented to the tooth. These materials are preferred for extensive tooth loss, high occlusal load situations, and cases requiring superior mechanical strength and long-term durability. **CAD/CAM resin-matrix ceramics or hybrid ceramics** consist of a polymer-infiltrated ceramic or ceramic-filled resin matrix, offering elasticity closer to dentin, easier milling, and good repairability; they are commonly indicated for inlays, onlays, and partial-coverage restorations. **Lithium disilicate glass-ceramics** are etchable ceramics known for their excellent aesthetics, translucency, and relatively high strength, making them suitable for veneers, inlays, onlays, and single-unit crowns in both anterior and posterior regions. **Zirconia**, a polycrystalline ceramic, exhibits exceptional flexural strength and fracture toughness, and is primarily indicated for posterior crowns, bridges, and high-load restorations where durability is paramount, although aesthetic outcomes depend on translucency grade and veneering strategy. Together, this classification framework assists clinicians in selecting restorative biomaterials based on clinical indication, functional demand, aesthetic requirements, and patient-specific risk factors.

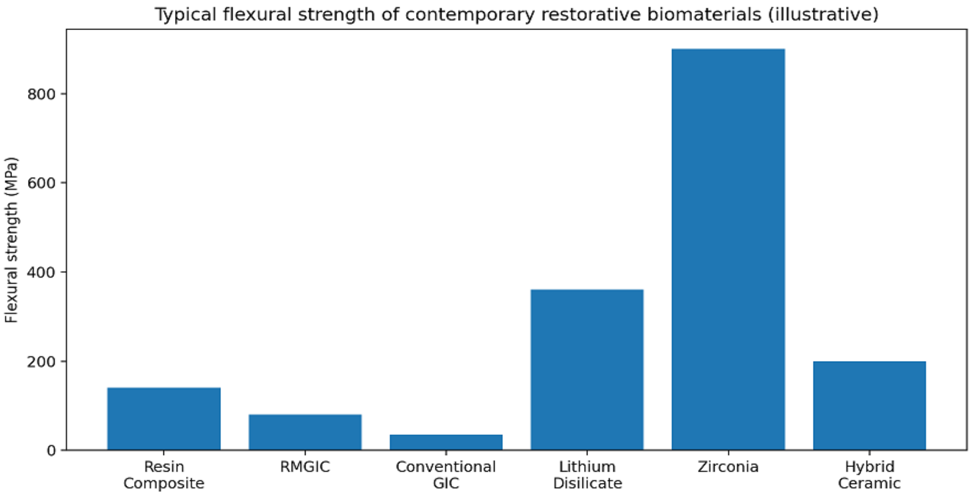
Adhesion Science and Interfacial Integrity

Adhesion science is fundamental to the long-term success of adhesive restorative dentistry, as the durability of the tooth–restoration interface largely determines marginal integrity, resistance to microleakage, and restoration longevity. Contemporary dental adhesive systems are commonly classified into **etch-and-rinse**, **self-etch**, and **universal (multi-mode)** adhesives, each differing in their interaction with enamel and dentin. **Etch-and-rinse adhesives** involve a separate phosphoric acid etching step that removes the smear layer and demineralizes enamel and dentin, creating a porous collagen network that allows resin infiltration and formation of a well-defined **hybrid layer**. These systems generally provide strong and durable enamel bonds; however, they are highly technique-sensitive, particularly with respect to **dentin wetness**. Over-drying can collapse exposed collagen fibrils, reducing resin penetration, while over-wetting can dilute the adhesive and compromise polymerization, both of which negatively affect bond strength.

Self-etch adhesives, in contrast, combine conditioning and priming steps by using acidic monomers that partially demineralize the tooth surface while simultaneously infiltrating it with resin. This approach preserves the smear layer as part of the bonding interface and reduces technique sensitivity by eliminating the need for precise moisture control. Although self-etch systems generally produce a thinner hybrid layer and slightly lower enamel bond strength compared with etch-and-rinse systems, they often demonstrate more consistent dentin bonding and reduced postoperative sensitivity. **Universal adhesives** represent an evolution of adhesive technology, as they can be applied in etch-and-rinse, self-etch, or selective-etch modes. Their formulation typically includes functional monomers such as 10-MDP, which chemically bond to hydroxyapatite, enhancing interfacial stability and potentially improving long-term bond durability across different substrates. The integrity of the hybrid layer is influenced not only by adhesive strategy but also by biological factors, particularly **matrix metalloproteinase (MMP) activity** within dentin. Acid etching can activate endogenous MMPs and cysteine cathepsins, leading to gradual collagen degradation within the hybrid layer and subsequent bond deterioration over time. This degradation explains the observed reduction in **aged bond strength** compared with **immediate bond strength**, especially in etch-and-rinse systems. Aging protocols such as **thermocycling** and **long-term water storage** are commonly used in laboratory studies to simulate oral conditions, revealing hydrolytic breakdown of resin components and collagen matrices. Self-etch and universal adhesives, which maintain more residual hydroxyapatite around collagen fibrils and enable chemical bonding, tend to show better resistance to hydrolytic degradation. Overall, understanding adhesion mechanisms and interfacial integrity is essential for optimizing adhesive selection and clinical protocols to achieve durable, long-lasting restorative outcomes.

Marginal Adaptation and Microleakage

Marginal adaptation refers to the intimate fit between a restorative material and the prepared tooth surface, while **microleakage** describes the passage of fluids, bacteria, ions, and oral debris along the tooth–restoration interface. Inadequate marginal adaptation is a multifactorial problem, with one of the primary causes being **polymerization shrinkage stress** in resin-based materials. During curing, volumetric shrinkage generates tensile stresses at the bonded interface, which can exceed the bond strength and lead to gap formation. This effect is strongly influenced by the **configuration factor (C-factor)**—the ratio of bonded to unbonded surfaces—where cavities with high C-factors (e.g., Class I and Class V) restrict material flow and amplify interfacial stress. **Inadequate or non-uniform curing**, caused by insufficient light intensity, short exposure time, improper curing distance or angulation, and increased restoration thickness, further compromises marginal adaptation by leaving under-polymerized resin that is mechanically weak and more susceptible to degradation and wear. A variety of **laboratory methods** are used to assess marginal integrity and microleakage. **Dye penetration techniques** are among the most widely used due to their simplicity and low cost; they involve immersion of restored teeth in dye solutions to visualize leakage pathways at the margins. However, these methods are qualitative and may overestimate leakage. **Scanning electron microscopy (SEM)** provides high-resolution imaging of marginal gaps and interfacial defects, allowing detailed assessment of adaptation at the micrometer level, though it is destructive and limited to surface evaluation. **Micro–computed tomography (micro-CT)** has emerged as a powerful non-destructive tool, enabling three-dimensional visualization and quantification of internal gaps and voids without sectioning the specimen. Each method contributes complementary information, and combined approaches are often used to improve reliability of results. Clinically, poor marginal adaptation and microleakage have significant consequences for both tooth structure and restoration longevity. Marginal gaps facilitate **extrinsic staining**, leading to aesthetic deterioration, particularly in anterior restorations. Fluid movement within interfacial gaps can cause **postoperative sensitivity**, especially when dentin is involved. Most importantly, microleakage creates a favorable environment for bacterial colonization, increasing the risk of **secondary (recurrent) caries**, which remains one of the leading causes of restoration failure. Over time, these processes can result in marginal breakdown, restoration fracture, or the need for premature replacement. Therefore, optimizing cavity design, adhesive selection, curing protocols, and material handling is essential to minimize marginal gaps and microleakage, ultimately improving the clinical success of restorative treatments.



Polymerization, Curing Protocols, and Depth-of-Cure

Polymerization quality is a critical determinant of the mechanical performance, biocompatibility, and clinical longevity of resin-based restorative materials. Adequate curing depends on multiple interrelated factors, including **light-curing irradiance**, **exposure time**, and the **distance and angulation** of the curing light tip relative to the restoration surface. Higher irradiance and sufficient exposure time increase the degree of monomer conversion; however, light intensity rapidly decreases as the distance between the curing tip and restoration increases or when the tip is angled obliquely. In deep or proximal cavities, limited access often results in non-uniform light distribution, producing gradients in polymerization with a well-cured superficial layer and an inadequately cured deeper layer. Such variations directly compromise the **depth-of-cure**, particularly in conventional composites with higher opacity or darker shades. To manage polymerization shrinkage stress and ensure adequate curing, clinicians traditionally employ **incremental layering techniques**, placing composite in 2-mm layers to allow sufficient light penetration and controlled polymerization. Incremental layering improves depth-of-cure, reduces C-factor-related stress, and enhances marginal adaptation, but it is time-consuming and technique-sensitive. **Bulk-fill composites** were introduced to simplify placement by allowing curing depths of 4–5 mm through modified resin matrices, optimized photoinitiator systems, and increased translucency. While bulk-fill strategies can reduce chair time and shrinkage stress, their clinical success remains highly dependent on correct curing protocols, including extended exposure times and appropriate light output to ensure complete polymerization throughout the bulk.

Under-curing has well-documented adverse effects on restoration performance. Insufficient polymerization results in reduced hardness, lower wear resistance, and increased susceptibility to **occlusal wear and marginal breakdown**, especially in posterior restorations subjected to high functional loads. Marginal degradation associated with under-cured resin facilitates microleakage and accelerates secondary caries development. Additionally, residual unreacted monomers from inadequately cured composites can leach into the oral environment, potentially causing **biological**

concerns such as pulpal irritation, cytotoxicity, and allergic reactions. Over time, under-polymerized resin matrices also exhibit increased water sorption and hydrolytic degradation, further compromising mechanical stability. Therefore, adherence to evidence-based curing protocols—optimized irradiance, adequate exposure time, minimal curing distance, and correct angulation—is essential to achieve sufficient depth-of-cure and ensure durable, clinically successful resin restorations.

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Clinical Longevity and Failure Patterns in Direct Restorations

The clinical longevity of **direct posterior resin composite restorations** is influenced by material properties, operator technique, patient-related risk factors, and restoration design. Long-term clinical studies generally report favorable survival rates for posterior composites; however, **fracture** and **secondary (recurrent) caries** remain the most common causes of failure. Fractures may occur within the restorative material or at the tooth–restoration interface and are often associated with high occlusal loads, parafunctional habits, inadequate polymerization, or insufficient remaining tooth structure. Secondary caries typically develops at restoration margins as a result of microleakage, marginal breakdown, or persistent cariogenic biofilm, and is particularly prevalent in patients with high caries risk and suboptimal oral hygiene. Restoration **size and location** play a decisive role in determining failure risk. Small to moderate Class I and Class II restorations generally demonstrate high survival rates, whereas **large, multi-surface restorations** show significantly increased failure due to greater polymerization shrinkage stress, higher C-factor, and reduced cusp support. Deep proximal boxes with gingival margins on dentin or cementum are especially vulnerable to marginal degradation and recurrent caries. Similarly, restorations in molars are exposed to greater occlusal forces than premolars, increasing the likelihood of bulk fracture or marginal chipping. Clinical evidence also supports the growing emphasis on **repair rather than complete replacement** for localized defects such as marginal staining or small fractures, as repair preserves tooth structure, reduces treatment time, and extends restoration service life. Overall, careful case selection, conservative cavity design, appropriate material choice, and regular maintenance are essential to optimize the longevity of direct posterior composite restorations.

Comparative Table (Clinical + Laboratory Snapshot)

Material class	Typical indications	Key advantages	Common limitations / failure risks	Handling notes
Resin composite (nanohybrid/bulk-fill)	Anterior/posterior direct restorations	High aesthetics; conservative; repairable	Shrinkage stress → marginal gaps; technique sensitive; fracture in large restorations	Isolation critical; appropriate curing and incremental strategy
Conventional GIC	ART, cervical lesions, high-caries-risk cases	Fluoride release; chemical bonding	Lower strength/wear resistance; moisture sensitivity early	Protect during initial set; surface coating helpful
RMGIC	Cervical lesions, liners/bases, moderate load sites	Better strength than GIC; fluoride release	Lower aesthetics vs composite; wear under heavy load	Light-assist curing; finishing timing matters
CAD/CAM resin-matrix ceramic / hybrid ceramic	Inlays/onlays, partial coverage	Good milling; easier intraoral repair; shock absorption	Aging/water sorption; bonding protocol critical	Sandblast + silane/universal primer per manufacturer
Lithium disilicate	Veneers, inlays/onlays, single crowns	Excellent aesthetics; strong glass-ceramic; etchable	Fracture if thin under high load; needs proper bonding	HF etch + silane; adhesive resin cement often preferred
Zirconia	Crowns/bridges, high-load posterior	Very high strength; good survival in many cohorts	Bonding more complex; esthetics (opacity)	Air abrasion + MDP primer; choose cementation by retention form

Clinical Role of Glass Ionomer and RMGIC

Glass ionomer cements (GICs) and **resin-modified glass ionomer cements (RMGICs)** remain clinically important because they combine **chemical adhesion**, **fluoride release**, and relatively good **moisture tolerance**—features that are especially useful when ideal isolation is difficult. GICs chemically bond to enamel and dentin through ionic interaction with calcium in hydroxyapatite, which can reduce reliance on complex adhesive steps and makes them practical for **cervical lesions**, **root/cervical caries**, and community settings. Their ongoing, rechargeable **fluoride release** is linked to a preventive effect at restoration margins; a recent systematic review and meta-analysis found GIC restorations showed a superior preventive effect against secondary caries compared with amalgam and a broadly similar effect compared with resin composites in both primary and permanent teeth. RMGICs add resin components (and light-assisted setting), improving early strength and handling while still retaining fluoride release and chemical bonding, so they are widely used for **non-carious cervical lesions (NCCLs)**, **liners/bases**, and moderate-load restorations where moisture control is not perfect. Evidence syntheses specifically comparing cervical restorations indicate that GIC/RMGIC options are clinically competitive in retention and overall performance for NCCLs in many trials and reviews. In terms of **indications**, both materials are strongly aligned with **high-caries-risk** patients, **pediatric dentistry** (where cooperation and moisture control may be challenging), and **geriatric dentistry** (root exposure, xerostomia, and higher caries susceptibility). They are central to **ART (Atraumatic Restorative Treatment)** and minimally invasive community dentistry, where the material's tolerance to less-than-ideal isolation is a practical advantage; a systematic review of ART restorations reported generally satisfactory outcomes, with survival at common follow-ups (e.g., 6–24 months) remaining within acceptable ranges across included studies. At a higher level, an umbrella review evaluating GIC longevity across primary and permanent teeth supports that GICs can achieve clinically meaningful service when used in appropriate indications, while emphasizing that outcomes depend on cavity type, patient risk, and operator technique. Overall, the clinical "sweet spot" for GIC/RMGIC is **disease control + adequate function**: when caries prevention and reliable bonding under moisture challenges matter more than maximizing high-load posterior strength, these materials often provide a strong, evidence-supported option.

CAD/CAM Hybrid Ceramics and Resin Blocks

CAD/CAM resin-matrix ceramics (hybrid ceramics) represent an intermediate class between conventional resin composites and traditional ceramics, combining a polymer matrix with a high ceramic filler content or a polymer-infiltrated ceramic network. Compared with **traditional ceramics** such as lithium disilicate or feldspathic porcelain, hybrid ceramics exhibit a lower elastic modulus that is closer to dentin, allowing better stress absorption under occlusal load and potentially reducing the risk of catastrophic fracture. From a manufacturing perspective, resin-matrix ceramics are generally **easier and faster to mill**, producing fewer chipping defects and less bur wear due to their lower brittleness. Finishing and polishing are also simpler and can often be completed chairside without glazing, whereas traditional ceramics typically require more elaborate finishing protocols, including firing or glazing, to achieve optimal surface smoothness and strength. A major clinical advantage of hybrid ceramics is their **repairability**. Because of their resin component, intraoral repairs using adhesive resin composites are more predictable and conservative compared with traditional ceramics, which often require more aggressive surface treatments or complete replacement when chipping or marginal defects occur. In terms of **wear behavior**, resin-matrix ceramics tend to be more enamel-friendly, causing less antagonist enamel wear than harder traditional ceramics such as zirconia, while still maintaining acceptable wear resistance themselves. This makes them particularly attractive for partial-coverage restorations, inlays, and onlays in patients with moderate occlusal forces or parafunctional risks. Regarding **medium-term clinical performance**, available clinical studies and systematic reviews generally report satisfactory survival rates for hybrid ceramic restorations over follow-up periods of approximately 3–5 years, with failure modes more commonly related to debonding or surface wear rather than bulk fracture. In contrast, traditional ceramics often demonstrate higher strength and long-term durability in high-load situations but at the cost of greater brittleness and more complex repair options. Consequently, CAD/CAM hybrid ceramics occupy a valuable clinical niche where a balance between mechanical resilience, ease of fabrication, and conservative long-term maintenance is desired.

Indirect ceramic selection in restorative dentistry most often comes down to **lithium disilicate** (a glass-ceramic) versus **zirconia** (a polycrystalline ceramic), and they differ in predictable ways across strength, translucency, complications, cementation, and survival. **Strength-wise**, zirconia is generally the tougher, higher-strength option and is preferred when occlusal loads are heavy (posterior crowns, parafunction, limited remaining tooth structure), while lithium disilicate has lower strength than zirconia but still provides strong performance for single crowns/onlays when thickness and bonding are appropriate. **Translucency and aesthetics** tend to favor lithium disilicate because it transmits light more like enamel; zirconia translucency has improved with newer "high-translucency" grades, but it often remains less translucent than lithium disilicate, especially in demanding anterior cases. In terms of **chipping risk**, this is most relevant for *veneered* zirconia (where porcelain chipping has historically been a complication), whereas **monolithic** (full-contour) zirconia reduces chipping/fracture complications; similarly, lithium disilicate failures are more likely to be bulk fracture if thickness/design or bonding is inadequate, rather than "chipping" in the classic veneered-zirconia sense. **Cementation strategies** also differ: lithium disilicate is an *etchable* glass-ceramic, so durable adhesion typically relies on hydrofluoric acid etching + silane + resin cement, making bonding comparatively straightforward and strong; zirconia is *not etchable* in the same way, so bonding is optimized via surface roughening (commonly air abrasion) plus an **MDP-containing primer/adhesive** and resin cement when adhesive bonding is needed, although conventional cements may still be used when retention form is ideal. Finally, **survival outcomes** at around 5 years are generally high for both materials in evidence syntheses; a recent systematic review/meta-analysis reports lithium disilicate and zirconia single crowns achieving **five-year survival comparable to metal-ceramic crowns**, with monolithic designs helping reduce technical complications. Cohort evidence also shows strong 5-year performance, with one 2025 clinical comparison reporting **~94% survival for zirconia vs ~89% for lithium disilicate** (difference not statistically significant in that study), suggesting both can be reliable when case selection and protocols are correct.

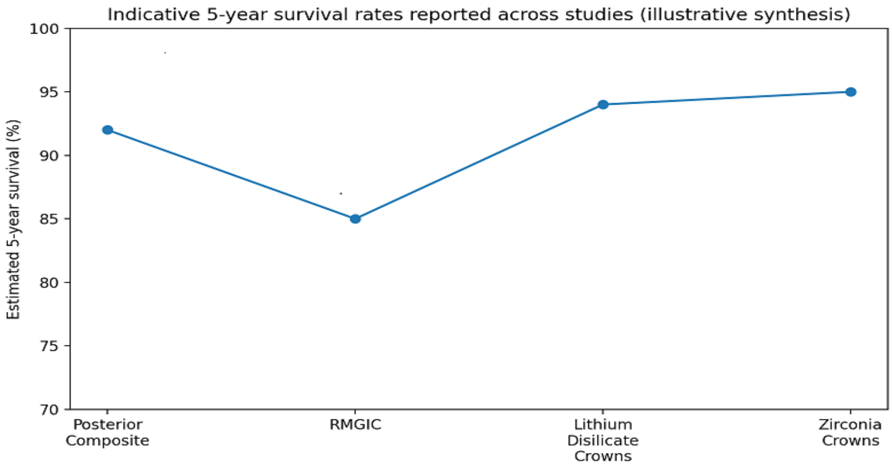
Evidence-Guided Material Selection Algorithm

An evidence-guided material selection algorithm integrates patient-specific risk factors with site-specific functional and esthetic demands to optimize restorative outcomes. **Caries risk** is a primary decision node: in patients with high or uncontrolled caries activity, materials with fluoride release and chemical adhesion—such as glass ionomer cement (GIC) or resin-modified GIC—are often preferred, particularly for cervical or root-surface lesions, whereas low-caries-risk patients are better candidates for resin composites or ceramic restorations. **Occlusal load and tooth position** further refine selection; anterior teeth and premolars with lower functional stress favor highly esthetic materials such as nanohybrid composites or lithium disilicate, while molars and stress-bearing posterior regions typically require materials with higher strength and fracture resistance, such as posterior composites for moderate defects or zirconia for extensive indirect restorations.

Available enamel and bonding substrate play a critical role in adhesive success. When sufficient enamel is present, adhesive restorations such as composite or lithium disilicate bonded with resin cement offer excellent marginal integrity and longevity. In contrast, margins predominantly on dentin or cementum reduce bonding predictability and may favor self-adhesive strategies or materials less sensitive to moisture, such as RMGICs or monolithic zirconia with conventional cementation when retention form allows. **Isolation quality** is another key determinant; in situations where rubber dam placement or moisture control is compromised, fluoride-releasing, moisture-tolerant materials are more reliable than technique-sensitive adhesive systems.

Margin location and esthetic priority must also be balanced. Supragingival margins in the esthetic zone benefit from materials with superior polishability and translucency, such as nanohybrid composites or lithium disilicate. Subgingival margins, especially in posterior regions, may justify the use of zirconia or RMGIC due to their tolerance to challenging clinical conditions.

Parafunctional habits (e.g., bruxism) shift the algorithm toward high-strength, fracture-resistant options such as monolithic zirconia or reinforced posterior composites, while avoiding brittle or thin glass-ceramic designs. Finally, **repairability needs** influence long-term management; patients likely to benefit from conservative maintenance may be better served with direct composites or CAD/CAM hybrid ceramics, which allow predictable intraoral repair, rather than ceramics that often require full replacement. When these variables are systematically considered, clinicians can apply evidence-based reasoning to select restorative materials that align biological, mechanical, and patient-centered outcomes.



Summary

Contemporary restorative biomaterials differ in ways that become clinically meaningful when matched against patient risk and restoration design. Posterior resin composites can demonstrate low annual failure rates in many cohorts, but failures concentrate in larger restorations and caries-susceptible patients, making risk stratification essential. Glass ionomer systems maintain a strong role where fluoride release and chemical bonding provide preventive benefits, and high-level reviews continue to evaluate their longevity across both primary and permanent dentitions. For indirect options, lithium disilicate and zirconia are both associated with strong medium-term clinical survival, with evidence indicating broadly comparable outcomes and sometimes slightly higher survival for zirconia in specific cohorts. CAD/CAM resin-matrix ceramics and hybrid ceramics offer a "middle ground" of aesthetics and repairability, supported by clinical performance reviews, but require careful surface treatment and bonding protocols. Overall, the most defensible selection strategy is a combined **clinical-laboratory decision model**: use laboratory properties to anticipate mechanical behavior and wear, and use clinical evidence to anticipate failure modes and maintenance burden—then tailor the final choice to isolation quality, margin location, occlusal load, and caries risk.

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