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Review Article

Marginal integrity of direct restorations and factors influencing microleakage

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ABSTRACT

Marginal integrity is a fundamental determinant of the clinical performance and longevity of direct dental restorations, as it influences the stability of the interface between restorative materials and dental hard tissues. Maintaining an effective marginal seal is essential for preventing microleakage, which involves the penetration of bacteria, fluids, and dissolved substances along the tooth-restoration interface. Microleakage may contribute to marginal discoloration, postoperative sensitivity, pulpal irritation, and secondary caries, potentially compromising restorative outcomes. Several factors influence marginal adaptation, including restorative material composition, polymerization shrinkage, adhesive system characteristics, cavity configuration, and clinical application techniques. Resin-based composites demonstrate favourable aesthetic and mechanical properties; however, polymerization contraction may generate interfacial stresses that promote marginal gap formation. Bulk-fill composites and glass ionomer-based materials exhibit different handling characteristics, bonding mechanisms, and dimensional behaviours, which can affect marginal performance. Adhesive effectiveness is influenced by dentin moisture conditions, surface preparation, and proper application protocols, while inadequate light curing may compromise polymerization efficiency and interfacial stability. Environmental conditions within the oral cavity, including thermal fluctuations, mechanical loading, moisture exposure, and chemical degradation, may accelerate deterioration of the adhesive interface over time. Clinical management of marginal defects requires careful assessment of restoration integrity, caries activity, and patient-related risk factors. Minor marginal irregularities do not necessarily indicate restorative failure and may be managed through monitoring, polishing, sealing, or localized repair when clinically appropriate. Preventive strategies emphasize adequate isolation, appropriate material selection, optimized bonding procedures, controlled polymerization, and regular clinical evaluation. Preservation of existing restorations through minimally invasive interventions can reduce unnecessary removal of healthy teeth and support long-term oral health. Understanding the interactions between restorative materials, clinical techniques, and environmental influences remains essential for minimizing microleakage, maintaining marginal integrity, and improving the durability and predictability of direct restorative treatments across different clinical situations and patient populations.

Keywords: Marginal integrity, Microleakage, Direct dental restorations, Adhesive systems, Polymerization shrinkage

INTRODUCTION

Direct dental restorations play a fundamental role in restorative dentistry by re-establishing the function, aesthetics, and structural integrity of teeth affected by dental caries, fractures or other structural defects. Continuous advancements in restorative materials and adhesive technologies have contributed to improvements in the clinical performance and longevity of these restorations. Resin-based composites, glass ionomer cements (GICs) and resin-modified glass ionomer cements (RMGICs) are among the most frequently used materials due to their favourable clinical properties and ability to preserve healthy tooth structure through minimally invasive restorative approaches. Among these options, resin-based composites have become particularly popular because of their superior aesthetic characteristics, favourable mechanical properties and capacity to achieve micromechanical adhesion to dental hard tissues through appropriate adhesive systems. Nevertheless, despite substantial progress in material formulations and restorative procedures, achieving and maintaining optimal marginal integrity remains a significant challenge that may affect the long-term clinical success of direct restorations.[1]

Marginal integrity describes the degree of adaptation and continuity at the interface between a restorative material and the surrounding tooth structure. Establishing an effective marginal seal is essential to limit the penetration of oral fluids, microorganisms, and other substances along the tooth–restoration interface. Disruption of this seal may result in microleakage, which is defined as the clinically undetectable movement of bacteria, fluids, molecules, or ions through microscopic spaces between the restoration and cavity walls. Microleakage has been associated with several undesirable clinical consequences, including marginal discoloration, postoperative sensitivity, pulpal irritation and an increased potential for secondary caries under favourable conditions for disease development. Therefore, the formation of a stable and durable adhesive interface is an important consideration in enhancing restoration performance and preserving the integrity of the remaining dental tissues.[2]

The marginal adaptation of direct restorations is influenced by several material-related, technique-sensitive, and cavity-specific factors. These include the composition and mechanical behaviour of restorative materials, polymerization shrinkage, adhesive system performance, cavity configuration, and the methods used for material placement and curing. Polymerization shrinkage represents a particular concern in resin-based composite restorations, as the volumetric contraction occurring during polymerization may generate stresses within the material and at the bonded interface. When these stresses exceed the capacity of the adhesive interface to withstand them, interfacial separation and marginal gap formation may occur, potentially facilitating microleakage. Additionally, cavity depth and geometry, the relative proportions of enamel and dentin at the cavity margins, moisture control, and light-curing protocols may influence the quality of marginal adaptation and the long-term stability of the adhesive interface. Consequently, appropriate restorative material selection and meticulous application techniques are essential to reduce interfacial defects and improve marginal sealing.[1,3]

The long-term integrity of direct restorations is further challenged by the complex conditions of the oral environment. Repeated temperature fluctuations, cyclic mechanical stresses generated during mastication, continuous exposure to saliva and chemical degradation may progressively compromise the physical properties of restorative materials and the stability of their bonded interfaces. Over time, these factors may contribute to marginal deterioration, reduced adaptation, and potential impairment of restoration performance. Furthermore, patient-specific factors, such as oral hygiene practices, individual caries risk, dietary patterns, and occlusal loading, can substantially influence the clinical longevity of restorations. Importantly, the detection of marginal defects or microleakage does not necessarily indicate immediate restorative failure, because restoration survival is determined by a complex interaction of biological, mechanical, material-related and clinical factors. A comprehensive understanding of these influences is therefore essential for optimizing restorative strategies, improving marginal adaptation, minimizing microleakage and promoting the long-term functional and aesthetic success of direct dental restorations.[3,4]

REVIEW

Marginal integrity is a critical determinant of the clinical performance, durability, and long-term success of direct dental restorations. Maintaining a stable and effective seal at the interface between the restorative material and surrounding tooth structure is influenced by several interrelated factors, including the physicochemical properties of restorative materials, polymerization shrinkage, adhesive performance and restorative application techniques.

Among these factors, polymerization shrinkage is recognized as a significant challenge in resin-based composite restorations, as the volumetric contraction occurring during the curing process can generate stresses within the restorative material and along the bonded interface. These stresses may compromise marginal adaptation and contribute to the formation of interfacial gaps, particularly when they exceed the capacity of the adhesive bond to withstand them. The magnitude and distribution of polymerization-induced stresses are influenced by various factors, including cavity configuration, restorative material composition, elastic modulus, and polymerization conditions. Therefore, careful selection of restorative materials, combined with appropriate placement and curing techniques, is essential for minimizing shrinkage-related stresses, maintaining marginal integrity, and reducing the potential for microleakage.[5]

Adhesive systems are equally important in establishing and preserving marginal integrity by promoting effective bonding between restorative materials and dental hard tissues. Achieving a reliable and durable bond to enamel and dentin is fundamental to maintaining the stability of the tooth–restoration interface and resisting the mechanical, thermal and chemical challenges encountered in the oral environment. However, the effectiveness of adhesive systems may vary according to their chemical composition, bonding strategies, application protocols and interactions with the underlying dental substrates. Factors such as inadequate moisture control, improper adhesive application, incomplete solvent evaporation and progressive degradation of the adhesive interface may compromise bond durability and increase susceptibility to marginal leakage.

Furthermore, variations in the clinical performance of different adhesive systems emphasize the importance of selecting suitable bonding agents and following manufacturer-recommended application procedures. Accordingly, optimizing adhesive protocols alongside effective management of polymerization-related stresses represents an important strategy for improving marginal adaptation, limiting microleakage, and enhancing the long-term clinical performance of direct dental restorations.[6]

RESTORATIVE MATERIALS AND MARGINAL INTEGRITY

The composition and physicochemical properties of restorative materials play a fundamental role in determining their ability to achieve and maintain adequate adaptation to cavity walls. Resin-based composites are widely employed in direct restorative procedures because of their favourable mechanical properties, superior aesthetic characteristics and compatibility with contemporary adhesive systems. Despite these advantages, dimensional changes associated with polymerization may adversely affect marginal integrity, particularly in restorations involving extensive dentin margins, where bonding may be more challenging. The polymerization behaviour and resulting stress distribution of resin composites are influenced by several material-related factors, including inorganic filler content, organic resin matrix composition, and viscosity. Variations in these characteristics can affect material flow, adaptation to cavity surfaces, and the development of interfacial stresses during polymerization. An experimental investigation comparing bulk-fill composites, self-adhesive composites, alkasite restorative materials, and high-viscosity glass ionomer cements reported differences in marginal and internal adaptation among the evaluated materials. These findings highlight the influence of material composition, physical properties, and handling characteristics on the quality of the tooth–restoration interface.[7]

Conventional resin-based composites are typically applied using an incremental placement technique to promote adequate light penetration, facilitate polymerization, and improve adaptation within the prepared cavity. In contrast, bulk-fill resin composites have been introduced to simplify restorative procedures by allowing the placement and curing of thicker increments, thereby reducing the number of clinical steps required. These materials incorporate modifications in their formulations, such as alternative photo-initiator systems, increased translucency and stress-modulating components, to enhance curing efficiency and manage polymerization-related contraction stresses.

Nevertheless, the effectiveness of bulk-fill composites in maintaining marginal integrity is influenced by material formulation, cavity characteristics, and light-curing protocols. A systematic review and meta-analysis evaluating the clinical performance of conventional and bulk-fill resin composites identified variations in marginal degradation under different clinical conditions, without demonstrating consistent superiority of either restorative approach. These observations indicate that the long-term marginal performance of resin composite restorations depends on multiple interacting factors rather than the placement technique alone.[8]

The viscosity and flow characteristics of restorative materials represent additional factors influencing their adaptation to cavity walls, particularly in areas with complex anatomical configurations or limited accessibility. Flowable resin composites possess relatively low viscosity, which facilitates their placement and adaptation to irregular cavity surfaces, internal line angles, and proximal gingival margins. However, differences in filler loading and resin matrix composition may affect their mechanical behaviour, polymerization shrinkage, and resistance to functional stresses. Consequently, the advantages associated with improved flow and handling must be considered alongside the material's physical and mechanical limitations. Microcomputed tomography investigations assessing the interfacial adaptation of different bulk-fill composite formulations have revealed variations in marginal adaptation, suggesting that restorative materials within the same classification may exhibit different performance characteristics. Such findings are particularly important in posterior restorations, where cavity configuration, restricted access, and the difficulty of achieving intimate adaptation along proximal surfaces may increase the likelihood of interfacial imperfections.[9]

Glass ionomer-based restorative materials exhibit distinct bonding and interfacial characteristics compared with resin-based composites, primarily because their adhesion to dental hard tissues involves chemical interactions with the mineral components of enamel and dentin. Their ability to release fluoride and their relatively favourable performance under certain moisture-control conditions make them valuable restorative options in selected clinical situations, particularly when achieving ideal isolation is challenging. However, conventional glass ionomer cements remain sensitive to moisture

contamination and dehydration during the early stages of setting and generally demonstrate lower mechanical strength and wear resistance than resin-based composites. Resin-modified glass ionomer cements were developed to address some of these limitations through the incorporation of polymerizable resin components, improving handling characteristics, early strength development, and clinical versatility. Nevertheless, polymerization-related dimensional changes, water interactions, and long-term interfacial stability remain important considerations when evaluating their marginal performance. A systematic review comparing ion-releasing restorative materials with conventional composite restorations investigated differences in clinical outcomes, including marginal integrity, emphasizing the importance of material-specific properties and clinical conditions in determining restorative success.[10]

FACTORS INFLUENCING MICROLEAKAGE

Microleakage in direct dental restorations is a multifactorial phenomenon influenced by the complex interactions among cavity configuration, adhesive application techniques, polymerization conditions and environmental factors within the oral cavity. The geometry of the prepared cavity plays a significant role in determining the magnitude and distribution of polymerization-induced stresses at the tooth–restoration interface. One of the principal factors affecting stress development is the cavity configuration factor (C-factor), defined as the ratio of bonded to unbonded surfaces within a prepared cavity. Restorations with a higher C-factor exhibit a greater proportion of bonded surfaces, which limits the capacity of resin-based composites to undergo deformation and flow during polymerization. This restriction may increase contraction stresses at the adhesive interface, potentially resulting in interfacial separation, marginal gap formation, and subsequent microleakage. Feilzer et al demonstrated that cavity configuration significantly affects the development of polymerization stresses, particularly when the availability of unbonded surfaces for stress relaxation is limited. Consequently, deep cavity preparations and complex restorative configurations may present additional challenges in achieving and maintaining adequate marginal adaptation, emphasizing the importance of appropriate restorative techniques and effective management of polymerization-related stresses.[11]

Moisture control during adhesive application is another critical factor influencing the quality, durability, and stability of the resin–dentin interface. Unlike enamel, dentin is a heterogeneous, hydrated tissue composed of mineralized components, an organic collagen matrix, and dentinal fluid, making adhesive bonding particularly sensitive to variations in surface moisture. Following acid etching, excessive dehydration of dentin may cause the exposed collagen network to collapse, reducing the interfibrillar spaces required for adequate resin monomer infiltration and compromising the formation of a uniform hybrid layer. Conversely, excessive moisture may interfere with adhesive monomer penetration, solvent evaporation, and subsequent polymerization, potentially resulting in an inadequately infiltrated and mechanically weakened adhesive interface. Kanca demonstrated that appropriately moist dentin surfaces achieved higher bond strengths than excessively dried substrates under the experimental conditions investigated, highlighting the importance of maintaining suitable dentin hydration during adhesive procedures. These findings emphasize the relationship between moisture control, resin infiltration, and the formation of a stable adhesive interface, particularly in restorations involving cervical or gingival margins extending beyond the cementoenamel junction, where bonding to dentin or cementum may be more challenging.[12]

Light-curing procedures also play an essential role in determining the degree of polymerization, mechanical properties, and long-term performance of resin-based restorative materials. Adequate polymerization depends on several factors, including the irradiance and spectral emission of the light-curing unit, exposure duration, distance and orientation of the curing tip, restoration thickness, and compatibility between the emitted light and the photoinitiator system of the restorative material. Inadequate light exposure or insufficient energy delivery may result in incomplete conversion of resin monomers, potentially compromising the mechanical strength, wear resistance, and chemical stability of the restoration. Price et al emphasized that the effectiveness of light curing is influenced not only by the output characteristics of the curing unit but also by light distribution, clinical exposure conditions, and the optical properties of restorative materials. Furthermore, increased restoration thickness, restricted accessibility, and variations in light transmission may contribute to nonuniform polymerization, particularly in deep or proximal regions of the cavity. Such variations may influence the mechanical behaviour of the restorative material and its ability to maintain marginal stability under functional loading. Therefore, appropriate light-curing protocols are essential for achieving adequate polymerization and supporting the long-term integrity of the tooth–restoration interface.[13]

The long-term durability of the adhesive interface is further influenced by continuous exposure to moisture and the complex physical, chemical, and mechanical conditions of the oral environment. Water sorption and diffusion within the adhesive layer may contribute to hydrolytic degradation of resin components, while incomplete resin infiltration into demineralized dentin can leave collagen fibrils insufficiently protected and susceptible to progressive deterioration. These processes may compromise the structural integrity of the hybrid layer, reduce bond strength, and increase the permeability of the adhesive interface over time. Hashimoto et al investigated the durability of resin–dentin bonds following prolonged water storage and reported reductions in bond strength associated with structural changes and deterioration at the bonded interface.

Progressive adhesive degradation may reduce the ability of the interface to withstand functional stresses and facilitate the penetration of oral fluids and other substances through microscopic interfacial defects. In addition, repeated occlusal loading, thermal fluctuations, and exposure to acidic conditions may contribute to the deterioration of restorative materials and their adhesive interfaces. These effects are particularly relevant at dentin margins, where the hydrated nature of the substrate and the susceptibility of the hybrid layer to moisture-related degradation can present additional challenges to maintaining a durable marginal seal.[14]

CLINICAL IMPLICATIONS AND PREVENTION

Marginal deterioration in direct dental restorations represents a significant clinical concern, as alterations at the tooth–restoration interface may develop progressively without producing noticeable symptoms during their initial stages. Clinical manifestations of marginal deterioration may include marginal discoloration, detectable interfacial gaps, postoperative sensitivity, and the development of secondary carious lesions adjacent to existing restorations. However, the presence of marginal staining or minor surface irregularities does not necessarily indicate active carious disease or justify immediate restorative replacement. The revised World Dental Federation (FDI) criteria provide a standardized framework for assessing the clinical quality of restorations based on functional, biological, and aesthetic parameters, facilitating a more systematic evaluation of restorative performance. Clinical decision-making should therefore involve a comprehensive assessment of the location, severity, and extent of marginal defects, together with evidence of caries activity and the overall structural and functional condition of the restoration. Additional diagnostic information obtained through appropriate radiographic examination, combined with individual patient-related factors such as caries risk and oral hygiene status, may further guide decisions regarding continued monitoring, refurbishment, localized repair, or complete replacement. This comprehensive approach supports evidence-informed clinical decisions while minimizing unnecessary intervention and preserving the remaining healthy tooth structure.[15]

Preventive strategies for maintaining marginal integrity primarily focus on identifying and controlling the biological, behavioural, and clinical factors associated with restorative deterioration and failure. Individualized caries risk assessment, dietary modification, effective plaque control, and regular clinical follow-up are essential components of preventive management, particularly in patients with an increased susceptibility to secondary carious lesions around existing restorations. Contemporary restorative dentistry increasingly emphasizes minimally invasive approaches that prioritize the preservation of sound dental tissues and the selective removal of carious tissue when clinically indicated. Consensus recommendations presented by Schwendicke et al support conservative caries management strategies aimed at avoiding unnecessary removal of healthy or remineralizable dental tissues while establishing conditions favourable for effective restorative treatment. Furthermore, the position of cavity margins, accessibility of the operative field, and ability to maintain adequate moisture control can substantially influence the effectiveness of adhesive procedures and the quality of the resulting marginal seal. Integrating preventive measures with careful restorative planning may therefore contribute to reducing the likelihood of recurrent disease, improving restoration longevity, and maintaining the structural integrity of the remaining tooth.[16]

The clinical management of defective restoration margins requires careful evaluation of the extent of deterioration and the functional condition of the existing restoration to determine whether conservative intervention is appropriate. Localized marginal defects may be managed through refinishing, polishing, sealing, or repair when the remaining restorative material and surrounding dental tissues retain sufficient structural integrity. Repair procedures generally involve appropriate preparation of the existing restorative surface, followed by mechanical and/or chemical conditioning and adhesive application to establish a durable bond between the original restoration and the newly applied restorative material. Loomans and Özcan described clinically applicable repair strategies for different restorative substrates, highlighting the importance of material-specific surface treatment protocols and the characteristics of the existing defect. Procedures such as surface roughening, thorough cleaning, and appropriate chemical conditioning may improve interfacial adhesion and enhance repair bond strength. Nevertheless, the predictability of restorative repair depends on several factors, including the type and condition of the original restorative material, defect accessibility, available bonding surfaces, and compatibility of the selected repair materials. When clinically appropriate, localized repair represents a conservative treatment option that may extend restoration service life while reducing unnecessary removal of sound dental tissue.[17]

Complete restoration replacement may be indicated when extensive secondary caries, major structural fractures, significant loss of retention, or widespread marginal deterioration compromises the clinical serviceability of the existing restoration and cannot be managed predictably through conservative treatment. However, removal and replacement of an existing restoration frequently result in additional loss of dental tissue, potentially increasing cavity dimensions, reducing the volume of remaining tooth structure, and complicating subsequent restorative procedures. For this reason, the Academy of Operative Dentistry European Section has emphasized the importance of critically evaluating defective restorations before selecting replacement as the preferred treatment approach. Conservative management strategies, including refurbishment and repair, should be considered whenever they can predictably restore acceptable function and clinical performance. Treatment

decisions should also account for the size and location of the restoration, extent of marginal deterioration, accessibility of defective areas, occlusal loading conditions, and individual patient-related factors, including caries activity and plaque-control practices. Defects involving proximal or subgingival margins may present additional challenges because of restricted access, difficulties in moisture control, and limitations in achieving reliable adhesive bonding. Accordingly, a patient-centred and minimally invasive treatment approach is essential for balancing restorative longevity, preservation of dental tissues, and long-term oral health outcomes.[18]

CONCLUSION

Marginal integrity plays a crucial role in the long-term success and durability of direct dental restorations. Microleakage is influenced by restorative material properties, polymerization shrinkage, adhesive techniques, and clinical conditions. Appropriate material selection, effective bonding procedures, and careful restorative techniques can minimize marginal defects and improve restoration longevity. Regular clinical evaluation and preventive measures are essential for maintaining marginal adaptation, reducing secondary complications, and preserving tooth structure.

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