International Journal of Dental Sciences
www.dentaljournal.in
E-ISSN: 2663-4708, P-ISSN: 2663-4694
Received: 30-08-2025; Accepted: 29-09-2025; Published: 14-10-2025
Volume 7, Issue 4, 2025, Page No. 50-57

Microleakage in dental composites-present and future directions- A review

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Abstract

Microleakage remains a significant clinical concern in restorative dentistry, particularly in relation to resin composite restorations. It is defined as the passage of bacteria, fluids, molecules, or ions between the cavity wall and the restorative material, leading to adverse outcomes such as postoperative sensitivity, marginal staining, recurrent caries, and eventual restoration failure. Despite advancements in adhesive systems, polymerization shrinkage and the complex bonding mechanism between composite and tooth structure continue to challenge the achievement of an ideal marginal seal.

Keywords: Polymerisation shrinkage, c factor, marginal integrity, composites

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- Importance in composite resin restorations

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Clinical Implications and Correlation with Restoration Longevity
- Relevance of *in vitro* microleakage studies to clinical failure
- Importance in high-risk patients and deep lesions

Future Perspectives and Research Directions
- Advanced bonding chemistries (e.g., MDP, bioactive adhesives)
- Need for standardization in microleakage research protocols

Conclusion

Introduction

Microleakage is the clinically undetectable passage of bacteria, fluids, molecules, or ions between a restorative material and the cavity wall. It remains a significant concern in composite resin restorations, potentially leading to secondary caries, pulpal irritation, staining, and postoperative sensitivity [1]. Microleakage most commonly occurs when the gingival margin of any restoration is placed below the cementoenamel junction because bonding to dentin is less predictable than enamel due to its complex pattern and lower mineral content [2],Composite resins, while offering aesthetic and conservative treatment options, are particularly susceptible to microleakage due to polymerization shrinkage and the complex dynamics at the tooth-restoration interface. As adhesive dentistry evolves, understanding the mechanisms, contributing factors, and clinical implications of microleakage is critical for achieving long-lasting restorations.

Historical Background and Early Investigations

Early research into microleakage primarily focused on amalgam and silicate cement restorations. Buonocore's 1955 study on acid etching marked the inception of adhesive dentistry, laying the groundwork for resin-based restorations. In the 1970s and 80s, dye penetration methods (silver nitrate, methylene blue) were commonly employed to assess leakage *in vitro*, revealing consistent issues with marginal gaps in composites. Kidd (1976) emphasized the lack of correlation between microleakage and caries but acknowledged its role in pulpal irritation. Subsequent work by Going and others in the 1980s reinforced the variability in microleakage based on bonding techniques and cavity design. These early studies, though methodologically limited, highlighted polymerization shrinkage as a core problem, setting the stage for the development of new adhesives, materials, and evaluation protocols.

Polymerization Shrinkage and Adhesive Failures

Resin composites typically undergo polymerization shrinkage of about 2%–5%, generating stresses that can surpass the adhesive bond strength. This may result in interfacial gaps, marginal deterioration, and eventual microleakage [3]. The extent of shrinkage is influenced by factors such as the resin matrix formulation, filler loading, and curing dynamics. Flowable composites, though offering superior cavity adaptation, exhibit greater shrinkage, whereas highly filled composites contract less but adapt poorly to cavity walls [5]. Bulk-fill resins are marketed as shrinkage-reducing alternatives, yet investigations by Campodonico and Garcia indicate that marginal sealing is still problematic, particularly in cavities with a high configuration factor. Additionally, rapid, high-intensity curing amplifies stress development; hence, soft-start and pulse-delay protocols are advocated [6]. Adhesive breakdown, whether from incomplete hybrid layer formation or moisture interference, further increases the likelihood of leakage, especially at deeper dentin margins.

Effect of Adhesive Systems and Techniques

The choice of adhesive system and its clinical application play a pivotal role in determining microleakage. Etch-and-rinse adhesives achieve strong and predictable enamel bonds but are prone to nanoleakage in moist dentin. Self-etch systems simplify procedures, yet their performance on uncut enamel is often suboptimal. According to Van Meerbeek *et al*. (2011) and Perdigão (2010), maintaining hybrid layer integrity, ensuring proper solvent evaporation, and achieving sufficient polymerization are essential for long-term success. Recent studies report that selective enamel etching and universal adhesives applied in a two-step approach yield improved marginal adaptation. Errors such as incomplete solvent evaporation or excessive drying of dentin may collapse collagen fibrils, hindering resin penetration [9]. Furthermore, functional monomers like MDP incorporated into universal adhesives have been shown to enhance the durability of dentin bonds (Yoshida *et al*., 2012)

Adhesive Systems and Bonding Strategies

Microleakage is strongly affected by the adhesive strategy and its interaction with tooth structures. Total-etch (etch-and-rinse) systems employ phosphoric acid conditioning followed by primer and adhesive placement. This approach eliminates the smear layer and exposes the collagen framework, enabling micromechanical retention through hybrid layer development. Nonetheless, excessive etching or dehydration can collapse collagen fibrils, thereby weakening the bond and promoting leakage [11]. In contrast, self-etch systems were introduced to simplify bonding by combining etching and priming into a single step. These agents modify the smear layer rather than completely removing it, integrating it into the hybrid zone while maintaining collagen architecture and lowering technique sensitivity. Although they minimize postoperative sensitivity and are gentler on dentin, their reduced effectiveness on enamel surfaces often results in compromised marginal sealing over time.

The Hybrid Layer: Formation, Function, and Relevance to Microleakage

The hybrid layer is a micromechanical and biochemical interface that forms between demineralized dentin and resin adhesive. It was first described by Nakabayashi *et al*. (1982), who demonstrated that hydrophilic monomers could infiltrate etched dentin and polymerize within the exposed collagen network, forming a resin-reinforced zone that bonds resin to dentin [12]. This zone is crucial for sealing dentin tubules, resisting fluid movement, and preventing bacterial microleakage.

In total-etch systems, phosphoric acid completely removes the smear layer and demineralizes the underlying dentin, exposing a collagen scaffold. Adhesive monomers like HEMA must infiltrate this scaffold before polymerization; failure to do so results in a weak or incomplete hybrid layer, leading to nanoleakage and long-term bond degradation [13]. In contrast, self-etch systems create a thinner, more superficial hybrid layer, partially dissolving the smear layer and incorporating it, reducing technique sensitivity but potentially weakening the mechanical retention [14].

The quality and stability of the hybrid layer are determinants of long-term adhesion and resistance to microleakage. Hydrolytic degradation, collagen fibril collapse, and matrix metalloproteinase (MMP) activation contribute to hybrid layer breakdown over time, especially in overly wet or dry bonding environments [15]. Strategies like using MMP inhibitors (e.g., chlorhexidine) and crosslinking agents (e.g., carbodiimide) are being explored to stabilize the hybrid layer and improve adhesive longevity.

Composite Types and Placement Techniques

The type and handling of composite resins are fundamental factors influencing microleakage, a key cause of marginal failure, secondary caries, and postoperative sensitivity. The evolution of composite resins has led to the development of flowable, nanohybrid, and bulk-fill composites, each with distinct characteristics affecting adaptation and sealing ability.

Flowable Composites

Flowable composites possess low viscosity due to their reduced filler content (37–53% by volume), allowing better adaptation to internal cavity walls, especially in narrow or intricate spaces [16], However, this benefit is offset by their increased polymerization shrinkage and reduced mechanical properties, which contribute to micro gaps and leakage at the margins . They are often used as a liner beneath more filled composites to improve adaptation but not recommended alone in stress-bearing zones.

Nanohybrid Composites
Nanohybrids incorporate nano-sized and micro-sized filler particles, offering improved strength, and better marginal adaptation due to enhanced filler loading (up to ~70%) [17]. Their balanced viscosity helps maintain shape during placement while adapting well to the cavity. They exhibit moderate polymerization shrinkage but have shown superior long-term marginal integrity in comparison to micro hybrids or flowables [18].

Bulk-Fill Composites
Bulk-fill composites are designed to be placed in increments of up to 4–5 mm in depth and cured in one step. This reduces clinical chair time and technique sensitivity. They employ modified resin matrices, low-stress monomers, and improved initiator systems to reduce polymerization stress and improve depth of cure . However, deeper regions of restorations, particularly in Class II proximal boxes, may be inadequately cured or poorly adapted to cavity walls, especially when high-viscosity bulk fills are used without a liner, leading to increased microleakage [19].

Incremental vs Bulk Placement
The incremental layering technique (placing 2 mm layers) minimizes polymerization shrinkage stress, improves light penetration, and reduces C-factor (bonded to unbonded surface ratio), leading to lower marginal leakage [20]. On the contrary, while bulk-fill techniques increase efficiency, they carry higher risk of incomplete polymerization, especially at deeper cavity margins and in areas with complex geometry [21].

Effect of Viscosity and Filler Load
Composites with higher viscosity may not adapt well to internal cavity irregularities, increasing voids and microleakage. In contrast, lower-viscosity composites, while adapting better, can exhibit higher shrinkage, highlighting the need to balance filler content, handling properties, and clinical application [22].

4. Cavity Configuration (C-Factor)
Microleakage in composite restorations is heavily influenced by polymerization stress, which is directly affected by the Cavity Configuration Factor (C-Factor). A higher C-Factor increases stress concentration at the bonded interfaces, which can compromise marginal adaptation and seal integrity, leading to microleakage [23].

Definition and Mathematical Model
C-Factor is defined as the ratio of bonded to unbonded (free) surfaces in a dental cavity. It reflects the configuration of a preparation and how it affects stress development during polymerization shrinkage of resin composites [24].

C-Factor= number of bonded surface /numbers of unbonded surface
For example
- A Class I cavity with 5 bonded and 1 unbonded surface has a C-Factor of 5.0
- A Class IV restoration with 1 bonded and 4 free surfaces has a C-Factor of 0.25

Higher C-Factor = more constraint on composite shrinkage = more internal stress = greater potential for microleakage.

Stress Development in High vs Low C-Factor Cavities
In cavities with high C-Factors (e.g., Class I, II), the polymerization of composite leads to shrinkage stress that pulls the material inward toward the bonded walls. Since the material cannot flow freely due to the high number of bonded surfaces, this results in gap formation, especially at the margins and base of the cavity, predisposing the site to microleakage [23, 24].
In contrast, low C-Factor cavities allow more flow and compensation during polymerization shrinkage, reducing internal stress and maintaining a better marginal seal [3]. These findings are consistent across several microleakage studies using dye penetration, SEM, and micro-CT analysis.

Stress-Reducing Strategies (Oblique Layering, Liners)
To counteract the effects of high C-Factor configurations, various stress-reducing techniques have been proposed
- **Oblique Layering:** Composite is applied in smaller oblique increments (2 mm or less), ensuring that each layer bonds to only two opposing cavity walls. This lowers the effective C-Factor per increment, allowing polymerization shrinkage to be more effectively dissipated [25].
- **Use of Liners:** Applying a flowable resin liner or resin-modified glass ionomer cement (RMGIC) at the base of the cavity acts as a stress-absorbing layer, compensating for shrinkage-induced stress and enhancing marginal adaptation [26].
- Soft-start or pulse-delay curing techniques have also been found to allow more initial flow of resin before hardening, reducing marginal gaps in high C-Factor cavities [27].

These methods, when combined, significantly lower microleakage and improve the long-term performance of composite restorations.

Strategies to Minimize Microleakage
Microleakage continues to be a persistent challenge in composite restorations. Several clinical and material-based strategies have been proposed to mitigate micro gaps at the tooth-restoration interface. These include the use of liners, Immediate Dentin Sealing (IDS), bioactive materials, and optimized curing protocols.

1. Use of Liners (GICs, Flowable Composites)
Liners serve as intermediate stress-relieving layers between dentin and composite, absorbing polymerization stress and improving marginal adaptation. Resin-modified glass ionomer cements (RMGICs) and flowable composites are the most commonly used liners.
- RMGICs bond chemically to dentin and offer fluoride release, making them effective for Class II and V restorations. They form a hybrid ion-exchange layer with dentin, enhancing the seal [1].
- Flowable composites exhibit lower modulus of elasticity and better adaptability to cavity walls. When placed in a 0.5–1 mm layer, they significantly reduce microleakage, especially in deep or high C-factor cavities [26]

Studies show that both materials reduce gap formation at the gingival margin, especially in areas lacking enamel [27].

2. Immediate Dentin Sealing (IDS)

Immediate Dentin Sealing (IDS) involves applying a dentin bonding agent directly after tooth preparation but before impression taking or temporary restoration. This technique ensures optimal bonding under freshly cut dentin, preserving the collagen matrix and reducing bacterial infiltration [28].

- IDS improves bond strength, reduces fluid movement in dentinal tubules, and minimizes nanoleakage
- Research has shown that restorations using IDS show significantly less microleakage and better long-term stability than those with delayed bonding

IDS is particularly beneficial in indirect restorations and deep cavities, where traditional bonding may be compromised.

3. Use of Bioactive Restorative Materials

Bioactive materials such as ACTIVA™ BioACTIVE Restorative, Cention N, and Biodentine™ have emerged as alternatives due to their ability to interact with tooth structures.

1. These materials release and recharge calcium, phosphate, and fluoride ions, promoting remineralization and formation of hydroxyapatite at the interface.
2. They form a chemical seal with dentin, reducing microleakage compared to conventional composites, especially in cervical areas [29].

Although early in adoption, bioactive materials show promising results in reducing leakage, particularly where moisture control is difficult.

4. Influence of Curing Protocols (Soft-start, Pulse-cure)

Polymerization shrinkage stress is influenced by the curing protocol, which in turn affects marginal integrity.

- Soft-start curing begins with low light intensity followed by a higher intensity phase. This allows for more composite flow before gelation, reducing stress at bonded interfaces [30].
- Pulse-cure technique involves intermittent light pulses, permitting relaxation of polymer chains and improved adaptation.

Both techniques are superior to conventional high-intensity curing in terms of reducing marginal gap formation and preserving bond strength over time [29, 30].

Clinical Implications and Correlation with Restoration Longevity

Microleakage is a critical factor in the long-term success and failure of composite restorations. Although primarily assessed *in vitro*, microleakage has significant clinical consequences that contribute to restoration failure, recurrent caries, postoperative sensitivity, and pulpal complications. This section explores how microleakage translates from laboratory studies to real-world outcomes.

1. Relevance of *In vitro* Microleakage Studies to Clinical Failure

In vitro studies on microleakage are widely used to evaluate the sealing ability of dental materials and techniques. These studies typically involve dye penetration, bacterial infiltration, or fluid filtration methods to simulate marginal leakage.

- **Controlled environment:** *In vitro* settings allow isolation of variables such as material type, curing protocol, or bonding technique, helping to predict clinical behaviour.

- **Predictive validity:** Although they do not perfectly replicate the oral environment (saliva, thermal cycling, masticatory forces), these studies have been shown to strongly correlate with marginal integrity and bond durability over time.

Limitation: *In vitro* microleakage does not account for dynamic oral factors like occlusal loading, biofilm activity, and patient-specific factors (e.g., bruxism, poor hygiene).
Still, high leakage observed in lab tests often predicts early marginal breakdown and secondary caries in clinical settings, especially in cervical margins and Class II restorations [30].

2. Studies Linking Microleakage to Recurrent Caries and Pulp Inflammation

Microleakage plays a direct role in the initiation of recurrent caries, particularly at cervical and proximal margins where enamel is thin or absent. Leakage allows bacterial and toxin ingress, which can [31].

- Demineralize adjacent tooth structure
- Cause acidic pH fluctuations, encouraging caries
- Trigger inflammatory pulpal responses

Evidence from clinical studies

- In deep lesions close to the pulp, even minute leakage can lead to chronic inflammation and pulp necrosis if left untreated

Thus, microleakage has a pathophysiological connection to both biological and mechanical failures of restorations [32]

3. Importance in High-Risk Patients and Deep Lesions

In patients with high caries risk, compromised saliva flow, poor oral hygiene, or acidogenic diets, the consequences of microleakage are amplified. These groups include

- Paediatric patients
- Elderly individuals with root exposure
- Xerostomia patients (e.g., post-radiation, Sjögren's syndrome)
- Bruxers or those with abfraction lesions

Deep lesions

- Restorations involving deep Class II, Class V, or near-pulpal Class I cavities are more vulnerable due to
- High C-factor (cavity configuration)
- Thinner enamel/dentin
- Difficulty in moisture control
- Greater risk of pulpal exposure

Even slight leakage in these cases can compromise pulpal health, necessitating endodontic intervention.

Methods To Detect Microleakage

Methods for Evaluating Microleakage

Radioisotope method

Various radioactive isotopes such as ^45Ca, ^131I, ^35S, ^22Na, ^32P, ^86Rb, and ^14C have been applied in leakage studies. Detection is usually carried out using autoradiography, which visualizes isotope penetration at restoration margins [33]. These tracers can infiltrate defects ≥40 nm, a sensitivity beyond that of bacterial models. Compared with dyes, isotopes often provide clearer evidence of leakage [34]. However, the drawbacks include radiation exposure and the inability of autoradiographs to present three-dimensional (3D) leakage patterns.

Acetate peel technique

Füsun *et al*. introduced the acetate peel technique as a quick way to obtain sequential surface replicas from etched teeth. Acetate films reproduce tooth surfaces at micron resolution, enabling analysis of tissue and interfacial leakage [35]. Mohapatra and Sivakumar further highlighted its simplicity, low cost, and stability for storage. Yet, the fragility of peels may introduce artifacts and misinterpretations [36].

Dye penetration

Dye staining is the most widely used leakage test. Solutions such as 0.5% basic fuchsin, 2% methylene blue, and 50% silver nitrate are commonly employed to mark leakage pathways [37]. The technique is inexpensive, reproducible, and free from radiation hazards. Nevertheless, the reliability may vary depending on dye type, particle size, and chemical interactions with dentin. For example, Wu and Cobb favored silver nitrate due to its strong optical contrast and nanoscale penetration capacity [38]. Silver nitrate has been extensively used to evaluate nanoleakage and highlight discrepancies between demineralization depth and resin infiltration. Studies caution against highly concentrated (≥50%) silver nitrate, as it lowers solution pH and may cause unwanted diffusion [39]. Costa *et al*. showed that even 5% silver nitrate immersion for 24 hours can detect compromised margins in composites [40]. Since dye distribution differs across sections, multi-surface scoring methods and multiple sectioning (as suggested by Raskin *et al*.) are preferred over single-surface analysis [41, 42]. Gale and Darvell later proposed a grinding and reconstruction approach, revealing higher leakage values in 3D assessments than in 2D ones [43]. Majety and Pujar further recommended complete restoration removal to assess overall leakage [44]. Microscopy remains central for evaluation, with recent advances adopting µCT, confocal laser scanning microscopy (CLSM), and optical coherence tomography (OCT) for improved accuracy [45].

Three-dimensional techniques

Gale *et al*. first described a 3D approach involving sequential slicing and computer-based reconstruction [46]. This method provides a more comprehensive view than 2D sectioning and allows volumetric leakage analysis [47]. However, it is destructive, subjective, and may alter restoration integrity during sectioning.

Microcomputed tomography (µCT)

µCT adapts medical imaging principles to dental research, producing 3D reconstructions at micron resolution without specimen destruction [48, 49]. De Santis *et al*. pioneered its application for leakage evaluation [50]. Since then, µCT has been employed to assess adhesive interfaces, stressed dentin, and *in vivo* restoration margins [51, 52]. Özkan *et al*. advocated µCT as an alternative to histological methods for *in vitro* studies [53]. Eden *et al*. successfully used µCT for *in vivo* Class II composite restorations in primary molars [54]. When combined with silver nitrate immersion, µCT accurately quantified marginal leakage. Despite these advantages, µCT alone cannot fully replace histological validation [55].

Confocal laser scanning microscopy (CLSM)

CLSM enables non-destructive imaging of subsurface structures up to 100 µm deep [56]. Tangsgoolwatana *et al*. compared CLSM with autoradiography, finding strong agreement between fluorescent dye and isotope studies [57]. Grobler *et al*. confirmed CLSM's ability to visualize resin tag formation, hybrid layers, and bonding agent penetration in detail [58].

Optical coherence tomography (OCT)

OCT generates real-time 3D images of dental tissues *in vivo*, supporting diagnosis of caries, periodontal disease, and cancer while also evaluating restoration margins [59]. It detects voids and interfacial gaps using reflected infrared light, similar to ultrasound echo principles. Bakhsh *et al*. validated OCT for quantifying tooth–restoration gaps, while Nazari *et al*. applied it to flowable composites, showing high accuracy in identifying voids and interfacial defects [60]. Overall, OCT offers a noninvasive and highly precise approach for leakage assessment.

Future Perspectives and Research Directions

1. Advanced Bonding Chemistries (e.g., MDP, Bioactive Adhesives)

Future adhesive systems aim to go beyond simple micromechanical retention and chemical adhesion. A prominent development is functional monomers like MDP (10-Methacryloyloxydecyl dihydrogen phosphate), which form stable chemical bonds with calcium in hydroxyapatite, improving long-term durability of the bond interface [61]. Studies have shown that MDP-containing adhesives offer superior resistance to hydrolytic degradation and better marginal sealing over time [62]. In parallel, bioactive adhesives which release ions such as fluoride, calcium, and phosphate are being developed to not only seal margins but promote remineralization and inhibit bacterial infiltration. Products incorporating nanohydroxyapatite, bioactive glass, and antibacterial agents (e.g., quaternary ammonium compounds) show promise in reducing microleakage and extending the functional life of restorations

2. Need for Standardization in Microleakage Research Protocols

Despite the wealth of published data, a major limitation in microleakage literature is the lack of standardization in testing protocols, making inter-study comparisons difficult. Studies vary in terms of dye types, immersion durations, thermocycling cycles, sectioning methods, and scoring systems. To advance the field, there is a growing consensus that ISO-standardized testing frameworks must be adopted universally. Moreover, new methods such as micro-CT, confocal laser scanning microscopy, and finite element analysis (FEA) are becoming the gold standard due to their

non-invasive, precise, and reproducible measurement capabilities. Establishing uniform guidelines will not only enhance reproducibility but also bridge the gap between *in vitro* studies and clinical relevance, ensuring better translation of research findings into practice.

The clinical significance of microleakage extends far beyond laboratory testing. It is a primary contributor to restoration failure through

- Recurrent caries
- Postoperative sensitivity
- Pulpal inflammation
- Compromised bond durability

Conclusion

Understanding and managing microleakage is especially crucial for long-term success in high-risk patients and deep lesions. Dentists must integrate material science with clinical protocols to reduce leakage and improve restoration longevity.

Microleakage remains a critical factor affecting the long-term success and reliability of composite restorations. Through decades of research, our understanding has evolved—from early observations in amalgam and silicate cements to the current era of nanohybrid, bulk-fill, and ormocer-based composites combined with sophisticated adhesive strategies.

Recent studies affirm that material selection, bonding technique, cavity design, and placement protocol play a pivotal role in minimizing microleakage. Total-etch adhesives, when applied correctly, still offer superior marginal sealing—particularly in enamel-rich margins—while universal adhesives have shown reliable outcomes across varied etch modes. Use of RMGIC liners, especially beneath bulk-fill composites like SDR, provides an effective barrier against microleakage in deep proximal margins. Furthermore, emerging materials like fiber-reinforced composites and bioactive restoratives show promising potential in enhancing marginal integrity and reducing leakage-related failure.

Clinically, minimizing microleakage is not merely a matter of product choice—it involves a careful integration of material science, adhesion strategy, and clinical execution. Techniques such as incremental placement, soft-start curing, and immediate dentin sealing (IDS) have shown added value in stress reduction and long-term sealing. High C-factor cavity designs and polymerization stress remain challenging, yet they can be effectively managed with oblique layering and low-viscosity flowable liners.

However, much of the evidence remains *in vitro*, and its direct translation to clinical settings requires further validation. Future research must focus on long-term, *in vivo* trials that assess how modern materials and bonding techniques perform under biological and mechanical challenges over time. There is also a need for standardized microleakage evaluation methods to ensure consistency across studies.

In conclusion, controlling microleakage is a multidimensional task rooted in scientific understanding and precise clinical practice. As restorative materials and adhesive systems continue to evolve, the goal remains clear: to achieve durable, leakage-free restorations that ensure pulpal health, structural integrity, and restoration longevity

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