REVIEW ARTICLE

International Journal of Dental Materials (ISSN: 2582-2209 (Online))
DOI: http://dx.doi.org/10.37983/IJDM.2025.7104

Revisiting Microleakage: Persistent Challenges in Restorative Dentistry

Raja Rajeswari Malempati[1], Anusha Konakanchi[2,*], Gopala Krishna Ganta[3], Ramalakshmi Manogna Vangala[3], Rama Krishna Alla[2], Shammas Mohammed[4]

[1] University of Wisconsin Milwaukee, Milwaukee, Wisconsin, United States of America.
[2] Department of Dental Materials, Vishnu Dental College, Bhimavaram, Andhra Pradesh, India.
[3] School of Dentistry, University of Michigan, Ann Arbor, MI 48104, United States of America.
[4] Department of Prosthodontics, Ibn Sina National College, Jeddah, Saudi Arabia.

Corresponding author:
Anusha Konakanchi
Department of Dental Materials, Vishnu Dental College, Bhimavaram, Andhra Pradesh, India.
Email: konakanchi.a@vdc.edu.in

Article History
Received: 11th March 2025
Accepted: 9th April 2025
Published: 24th April 2025

Abstract
The infiltration of fluids, bacteria, and ions at the interface between dental restorations and tooth structure remains a persistent challenge in restorative dentistry, significantly impacting the longevity and clinical success of restorations. This review comprehensively examines the factors contributing to microleakage, evaluates various detection methodologies, and explores strategies to mitigate its adverse effects. Emphasizing an evidence-based approach, the review highlights key considerations in restorative techniques, material selection, and adhesive protocols that enhance marginal integrity. By synthesizing current research and clinical recommendations, this article provides practical guidance for clinicians to minimize microleakage and improve the durability of dental restorations.

Keywords: Adhesives, Caries prevention, Dental materials, Dental restorations, Microleakage.

Cite this article as: Malempati RR, Konakanchi A, Ganta GK, Vangala RM, Alla RK, Mohammed S. Revisiting Microleakage: Persistent Challenges in Restorative Dentistry. **Int J Dent Mater. 2025;7(1): 18-26.**

1. Introduction

Dental restorations play a crucial role in modern dentistry by maintaining the structural integrity and functionality of decayed or damaged teeth. However, the success of these restorations is recurrently challenged by a subtle yet formidable adversary: microleakage [1,2]. Microleakage is a critical concern in restorative dentistry, as it can lead to secondary caries, pulp irritation, and restoration failure. It refers to the penetration of bacteria, fluids, molecules, and ions into the microscopic gaps between a dental restoration and the adjacent tooth structure. This phenomenon compromises the longevity and effectiveness of dental restorations [3-5].

Historically, the field of restorative dentistry has witnessed remarkable advancements in materials and techniques aimed at achieving durable and aesthetically pleasing restorations. Despite these strides, microleakage persists as a formidable challenge, transcending the boundaries of restorative materials and methods [6]. Dental restorations, whether amalgam, composite, or ceramic, inherently face the risk of microleakage due to the inherent differences in the coefficients of thermal expansion, elastic modulus, and adhesion characteristics between restorative materials and tooth structure [6,7].

2. Factors influencing microleakage

Microleakage in dental restorations is a multifactorial phenomenon, determined by a complex interplay of material properties, clinical techniques, oral environmental conditions, etc., [5-10]. These factors, both intrinsic to the materials used and extrinsic in their application and function, significantly impact the long-term success of restorations. Understanding these factors is essential to reduce the risks associated with microleakage and improve clinical outcomes. Various factors contribute to microleakage, including the type of restorative material, the method of cavity preparation, and the adhesive techniques employed. For instance, studies have shown that the type of cavity preparation, whether by traditional drilling, air abrasion, or laser treatment, can significantly affect the degree of microleakage. Acid etching has been found to provide better marginal sealing compared to laser treatments, particularly at the enamel margins [11,12]. Additionally, the fibre inserts in composite restorations have been shown to reduce microleakage, enhancing the seal at the tooth-restoration interface [13].

2.1 Properties of restorative materials

The physical and chemical properties of restorative materials are crucial in influencing microleakage. Factors such as thermal expansion, polymerization shrinkage, and water sorption are intrinsic properties that affect the material's interaction with the tooth structure [14,15].

2.1.1 Coefficient of Thermal Expansion (CTE): An ideal restorative material should have a similar CTE as the natural tooth [15]. Unfortunately, the CTE of many restorative materials (Table 1) do not match with the CTE of the natural tooth except the glass ionomer cement (GIC) [14-16]. The mismatch between the CTE of restorative materials and natural tooth structure can lead to significant stress at the tooth-restoration interface. During thermal cycling in the oral cavity, such as from hot or cold food and beverages, this mismatch causes expansion and contraction at different rates, potentially disrupting the marginal seal.

Composite resins often exhibit a higher CTE compared to enamel and dentin, making them more prone to thermal-induced microleakage [14,15]. Dental amalgam exhibits a higher CTE compared to natural tooth structures. This disparity can result in marginal gaps due to differential thermal expansion and contraction, thereby increasing the risk of microleakage. A study evaluating the influence of thermal stress on marginal integrity found that thermal cycling increased leakage in all amalgam restorations, suggesting that the mismatch in CTE contributes to compromised marginal integrity under thermal stress [17]. The CTE of amalgam is more than twice that of natural tooth structure (Table 1). On the other hand, GICs have a CTE that aligns more closely with that of natural teeth. This compatibility reduces the stress at the tooth-restoration interface during thermal fluctuations, thereby minimizing microleakage. Studies show that GIC has a comparable coefficient of thermal expansion (CTE) to that of tooth structure, which plays a role in its effective performance in preserving marginal integrity on subjected to thermal stress [18].

Table 1. Co-efficient of thermal expansion of natural tooth and various restorative materials [14].

Materials	Coefficient of Thermal Expansion
Enamel	$11 \times 10^{-6}/^0C$
Dentin	$8.0 \times 10^{-6}/^0C$
Ceramics	$12 \times 10^{-6}/^0C$
Amalgam	$25 \times 10^{-6}/^0C$
Glass Ionomer cement	$10.2 – 11.4 \times 10^{-6}/^0C$
Silicate cement	$10 \times 10^{-6}/^0C$
Unfilled acrylic resins	$92.8 \times 10^{-6}/^0C$
Traditional composites	$25 – 35 \times 10^{-6}/^0C$
Small-particle composites	$19 – 26 \times 10^{-6}/^0C$
Hybrid composites	$30 – 40 \times 10^{-6}/^0C$
Micro-filled composites	$50 – 60 \times 10^{-6}/^0C$

2.1.2 Polymerization Shrinkage: Resin-based materials undergo volumetric shrinkage during polymerization, resulting in contraction forces that could form gaps at the tooth-restoration interfaces. These shrinkage stresses, especially in high configuration factor (C-factor) cavities (those with a higher bonded-to-unbonded surface ratio), are a major contributor to microleakage. Studies using X-ray micro-computed tomography have shown that higher C-factors and larger composite volumes result in a greater probability of microleakage due to increased shrinkage [19].

2.1.3 Water Sorption and Solubility: Restorative materials that absorb water over time may experience dimensional changes, which can compromise the seal [14,16,20]. Materials have higher water sorption rates than resin composites, increasing their susceptibility to marginal degradation. The resin-modified glass ionomer cements (RMGICs) and compomers exhibit greater water absorption relative to traditional GICs [21].

2.2 Tooth preparation and marginal configuration

The geometry and finish of the tooth preparation significantly influence the occurrence of microleakage. The design of the cavity influences the distribution of stresses at the interface. Sharp internal line angles and inadequate bevelling of enamel margins may predispose the restoration to failure [22]. Additionally, cavity designs with greater surface area exposed to stress, such as Class II or Class V cavities, are more prone to microleakage [23-25]. In addition, the location of the preparation margin (supragingival, equigingival, or subgingival) affects the quality of the seal. Supragingival margins, where the interface is located entirely on enamel, tend to form stronger bonds due to enamel's predictable structure. In contrast, subgingival margins rely on bonding to dentin or cementum, and they are inherently less favourable substrates [26].

The C-factor also plays a significant role in microleakage. While some studies suggest a relationship between the C-factor and microleakage, others have found no significant direct correlation [27,28]. Studies reported that rather than the C-factor, microleakage is more influenced by factors such as restoration volume, insertion techniques, and curing modes [27]. However, it is generally observed that higher C-factors can exacerbate the effects of polymerization shrinkage, leading to increased microleakage [27,28].

2.3 Adhesive systems and bonding techniques

The adhesive system used and the technique employed during bonding are critical determinants of the integrity of the tooth-restoration interface. Contemporary adhesive systems are categorized into etch-and-rinse and self-etch adhesives. Whereas etch-and-rinse systems offer superior bonding to enamel, their dentin bonding is technique-sensitive, and improper etching or drying can lead to gaps. Self-etch systems are less technique-sensitive but may result in weaker bonds to enamel [29].

Self-etch adhesive systems generally exhibit a shallower etch depth and less resin tag formation than the etch-and-rinse systems. This can lead to increased microleakage, particularly at the dentin margins. Self-etch adhesives like Adper Prompt-L-Pop have shown significantly greater microleakage compared to other self-etch products and etch-and-rinse systems [30,31]. However, some self-etch adhesives, such as Xeno III, have performed comparably to etch-and-rinse systems in terms of microleakage [31]. Additionally, self-etch adhesives have demonstrated better long-term sealing ability in dentin compared to etch-and-rinse adhesives, as the latter's microleakage scores increased significantly over time [32].

Etch-and-rinse systems typically create a thicker hybrid layer and longer resin tags, which can enhance the bonding strength and reduce microleakage initially. However, over time, the microleakage in etch-and-rinse systems can increase, as observed in studies where the microleakage score of etch-and-rinse adhesives increased significantly after three months [32]. Despite this, etch-and-rinse systems generally show lower microleakage scores than self-etch systems, particularly at the enamel margins [31,33].

Furthermore, it is important to recognize that microleakage is not limited to direct restorations alone. Indirect restorations such as crowns, bridges, inlays, and onlays also face similar challenges. Despite advancements in adhesive and luting agents, the integrity of the tooth-restoration interface can still be compromised by factors such as marginal discrepancies, cement dissolution, and inadequate adhesion, especially in subgingival areas where bonding is primarily to dentin or cementum. Even with resin-based cements and contemporary adhesive protocols, improper handling or moisture contamination can lead to microleakage, ultimately affecting the longevity and clinical success of these restorations.

The success of adhesive bonding relies heavily on the operator technique. Factors such as moisture control, application timing, and curing protocol significantly impact the adhesive interface. Improper isolation or contamination by saliva or blood can compromise bond strength and increase microleakage [34]. Research indicates that the degree of microleakage can differ considerably based on the skill level of the operator. Giachetti L *et al*. (2007) investigated microleakage in Class V restorations and found that the total-etch adhesive system relied greatly on the operator's skill, resulting in more experienced practitioners achieving lower levels of microleakage compared to students [35]. Karaman E *et al.* (2013) also confirmed that operator variability significantly affects microleakage, particularly at the enamel margins, with less experienced operators showing higher microleakage [36].

2.4 Occlusal loading and mechanical stress

Cyclic loading from chewing can compromise the integrity of the tooth-restoration interface, leading to marginal breakdown and microleakage. The ability of restorative materials to endure fatigue loading is well established; however, the degree of microleakage is influenced by both the material type and the selection of luting cement [37]. Composite crowns exhibit better fatigue resistance than ceramic crowns [38], and load cycling alone may not significantly impact microleakage in Class II composite restorations [39]. However, cyclic loading can promote bacterial penetration along restoration margins, increasing the risk of secondary caries [40]. Additionally, the combination of mechanical stress and biofilm, especially in the presence of sucrose, accelerates adhesive interface degradation, highlighting the need for durable restorative materials and adhesive techniques [41].

2.5 Oral environmental factors

The dynamic and variable nature of the oral cavity contributes significantly to microleakage. The dynamic pH fluctuations in the oral cavity significantly influence microleakage in dental restorations, with acidic environments from dietary acids and bacterial metabolism weakening adhesive bonds and degrading restorative materials. Studies indicate that low pH conditions, such as those caused by soft drinks and acidic foods, increase microleakage, particularly in GIC, which are more susceptible to acid degradation than resin composites [42]. While GICs offer fluoride release benefits, their vulnerability to acidic exposure compromises their longevity [43,44]. Similarly, resin-modified RMGIC and flowable composites exhibit increased microleakage when exposed to acidic solutions, with the severity influenced by the frequency and duration of exposure [45].

Saliva contains organic and inorganic components that can interfere with the bonding process if contamination occurs during restoration placement. Proper isolation with rubber dams or other techniques including, saliva ejectors and high-volume evacuators (HVE), using astringent agents, air-drying and suction control, etc., are essential to prevent this issue [43,44]. Variations in oral temperature due to the ingestion of hot or cold substances create stresses at the interface, particularly when the restorative material and tooth structure expand or contract at different rates [46,47].

2. 6. Clinical application techniques

Proper curing light protocols, including sufficient intensity and curing time depending on the type of light source and the shade of the restoration, are essential to ensure complete polymerization of resin materials and prevent microleakage [48]. A standard light intensity of 800 mW/cm^2 typically requires an exposure time of 20 seconds to effectively cure a 2.0 to 2.5 mm thick layer of resin-based composite. For curing lights with lower intensity, such as 400 mW/cm^2, the exposure time should be increased to 40 seconds for a similar thickness [49, 50]. It's crucial to ensure that the curing light delivers adequate energy density (intensity × time) to achieve proper curing. Darker shades of composite resin absorb more light, reducing the depth of cure. Consequently, these shades may require doubling the curing time compared to lighter shades to attain a comparable degree of polymerization [51]. Opaque shades have been shown to exhibit lower hardness values, indicating reduced polymerization. Therefore, increasing the light exposure time is advisable when working with opaque or darker shades to ensure adequate curing [52].

Incremental placement techniques are effective in reducing marginal leakage by minimizing polymerization shrinkage and the resulting stress at the restoration interface [53]. Additionally, meticulous finishing and polishing play a crucial role in maintaining marginal integrity, as inadequate finishing can introduce stress and compromise restoration longevity [54]. Further, the angulation of the light source and the distance between the tip of the light source and the restoration affect the curing efficiency and the bond quality. Any slight angulation in the curing tip may reduce the curing light efficiency and affect the degree of cure. Greater than 50° angulation of the light source tip significantly reduces the light energy. Similarly, the closer the tip of the light source (0.0 mm) to the restoration, the better the bond strength [51].

2.7 Material ageing and degradation

Over time, restorative materials in the oral environment are subject to ageing and degradation, which can compromise their performance. One significant factor is hydrolytic degradation, where prolonged exposure to oral fluids leads to the breakdown of adhesive bonds, particularly in hydrophilic adhesive systems. For instance, salivary esterases can hydrolyze components like bis-GMA in dental composites, resulting in by-products such as Bis-HPPP, which weaken the material's integrity [55]. Additionally, mechanical wear at the restoration margins due to mastication and abrasion can cause marginal wear. This wear leads to the gradual formation of gaps, promoting microleakage and increasing the risk of secondary caries.

3. Methods to assess microleakage around dental restorations

Accurate assessment of microleakage is crucial to evaluate the performance of dental materials and techniques. Over the years, various methodologies have been developed, each with its advantages and limitations. These methods can broadly be categorized into dye penetration, radioisotope tracing, chemical tracers, microbial penetration, fluid filtration, electro-chemical techniques, thermocycling, and advanced imaging techniques [3,4,7,8].

3.1 Dye penetration method

The dye penetration method is one of the most widely used techniques for assessing microleakage. This method involves immersing the restored teeth in a dye solution, such as methylene blue or rhodamine B, and then sectioning the teeth to evaluate the extent of dye penetration at the tooth-restoration interface. The dye penetration method is a simple and cost-effective technique for assessing microleakage in dental restorations. It utilizes non-toxic and readily available dyes, providing a qualitative and semi-quantitative evaluation of leakage. Studies have shown that different dyes can vary in their ability to detect microleakage, with rhodamine B often detecting more leakage than methylene blue [57-58]. However, this method has limitations, including subjective result interpretation and the possibility of overestimating leakage due to the smaller size of dye molecules compared to bacteria. Additionally, it fails to replicate in vivo conditions such as thermal and mechanical stresses, limiting its clinical relevance.

3.2 Radioisotope tracing

Radioisotope tracing is a highly sensitive and quantitative method for assessing microleakage using radioactive tracers such as calcium-45 or iodine-125 [59]. This technique detects leakage by measuring radioactive emissions at the restoration interface, allowing for precise quantification in both in vivo and in vitro studies [60]. In vitro applications involve immersing restored teeth in a radioactive solution, followed by sectioning and analysis using radiographic or scintillation techniques. While this method provides microscopic-level detection, it requires complex equipment, specialized facilities, and strict safety protocols due to radiation exposure risks. Additionally, it is expensive and time-consuming, limiting its widespread use in routine dental research [59].

3.3 Chemical tracers

Chemical tracers, mostly silver nitrate, are employed to evaluate microleakage by penetrating marginal gaps and depositing visible residues. In this method, silver nitrate is applied to restoration margins, and upon light exposure, silver ions reduce to metallic silver, forming a black deposit at leakage sites. This technique offers clear visual evidence of microleakage and facilitates precise localization of marginal gaps. However, it necessitates additional preparation steps, such as polishing and sectioning, and poses potential health risks associated with handling chemicals like silver nitrate [61].

3.4 Fluid filtration

The fluid filtration method quantifies microleakage by measuring fluid flow through marginal gaps under controlled pressure conditions. In this technique, a fluid reservoir is connected to the restoration interface, and pressure is applied to facilitate fluid movement. The rate of fluid passage is then measured using instruments like a manometer, providing quantitative and reproducible data. This method effectively simulates the pressure variations experienced in the oral cavity, offering valuable insights into the sealing efficacy of restorative materials. However, it requires specialized equipment and does not provide direct visual evidence of leakage, which may limit its applicability in certain research settings [62].

3.5 Electrochemical techniques

Electrochemical techniques are utilized to assess microleakage in dental restorations by measuring electrical conductivity or resistance across the tooth-restoration interface. In this method, an electrolyte solution bridges the interface, and electrodes monitor changes in conductivity indicative of leakage. This approach offers quantitative and sensitive measurements, providing rapid and non-invasive assessments of the integrity of dental restorations. However, precise calibration is essential to ensure accuracy, and the method's ability to localize specific leakage sites is limited. Additionally, specialized equipment is required, which may not be readily available in all clinical settings [63].

3.6 Thermocycling and stress simulation

Thermocycling is an in vitro method used to evaluate the durability of dental restorations by subjecting them to repeated temperature fluctuations, typically between 5°C and 55°C, to simulate the thermal stresses experienced in the oral cavity. This process aims to assess the effect of these stresses on the marginal sealing of restorations. For instance, a study involving class II cavities restored with different materials found that thermocycling influenced microleakage levels, highlighting the importance of thermal stress simulation in evaluating restorative materials [64]. While thermocycling provides a standardized protocol that mimics in vivo thermal conditions, it does not directly measure microleakage but rather assesses the potential effects of thermal stresses on restoration integrity. Consequently, thermocycling is often combined with other assessment methods, such as dye penetration tests, to evaluate microleakage more comprehensively [65].

3.7 Advanced imaging techniques

Advancements in imaging technology have significantly enhanced the assessment of microleakage in dental restorations, offering precise visualization of the tooth-restoration interface. Scanning Electron Microscopy (SEM) provides high-resolution images, allowing detailed examination of marginal gaps; however, it necessitates sample destruction and is associated with high costs [66].

Micro-computed Tomography (Micro-CT) is a non-destructive method that allows for three-dimensional visualization of microleakage. It provides detailed images of the tooth-restoration interface, enabling the assessment of leakage without sectioning the teeth. However, micro-CT may underestimate dye penetration compared to conventional stereomicroscopy [67]. In addition, high cost and limited availability of micro-CT in routine practice are notable limitations [68].

Confocal Laser Scanning Microscopy (CLSM) allows for three-dimensional visualization of dye penetration without sectioning the sample, providing non-destructive and highly accurate assessments; however, it requires expensive equipment and expertise [69].

4. Preventive measures against the clinical implications of microleakage

Microleakage remains a critical concern in restorative dentistry, potentially leading to secondary caries, pulp inflammation, and restoration failure. Optimized cavity preparation, including beveled margins and rounded internal angles, enhances marginal adaptation and stress distribution [70]. The choice of restorative material significantly influences microleakage; low-shrinkage composites and bioactive materials, such as GICs, improve marginal integrity and release fluoride to reduce caries risk [71]. Advanced adhesive systems, like self-etch and universal adhesives, enhance bond strength while reducing leakage [72]. Effective polymerization techniques, including incremental layering and proper curing protocols, further minimize shrinkage stress [73]. Maintaining a contamination-free field with rubber dam isolation and moisture-tolerant adhesives ensures optimal bonding [44]. Pre-treatment strategies, such as acid etching and silane application, enhance adhesion, while resin coatings and sealers reduce microleakage pathways [74]. Innovations in CAD/CAM and nanotechnology improve marginal adaptation and mechanical properties [75]. Long-term maintenance, including professional cleanings and fluoride applications, remains crucial for restoration longevity [76,77].

5. Conclusion

Microleakage remains a critical challenge in restorative dentistry, contributing to secondary caries, pulp inflammation, and restoration failure. Effective management necessitates a multifaceted approach, including meticulous cavity preparation, optimized adhesive protocols, stringent isolation techniques, and the use of low shrinkage and bioactive restorative materials. Advances in technology, such as CAD/CAM restorations, nanotechnology-enhanced materials, and high-precision bonding techniques, further enhance marginal adaptation and long-term clinical success. By integrating these evidence-based strategies, clinicians can significantly reduce microleakage, ensuring durable restorations, improved patient outcomes, and enhanced longevity of dental treatments.

Conflicts of interest: Authors declared no conflicts of interest.
Financial support: None

References

1. Li H, Huang Y, Zhou X, Zhu C, Han Q, Wang H, Xu HH, Ren B, Cheng L. Intelligent pH-responsive dental sealants to prevent long-term microleakage. Dent Mater. 2021;37(10):1529-41. https://doi.org/10.1016/j.dental.2021.08.002
2. Amaireh AI, Al-Jundi SH, Alshraideh HA. In vitro evaluation of microleakage in primary teeth restored with three adhesive materials: ACTIVA™, composite resin, and resin-modified glass ionomer. Eur Arch Paediatr Dent. 2019;20:359-67. https://doi.org/10.1007/s40368-019-00428-6
3. Matharu S, Spratt DA, Pratten J, Ng YL, Mordan N, Wilson M, Gulabivala K. A new in vitro model for the study of microbial microleakage around dental restorations: a preliminary qualitative evaluation. Int Endod J. 2001;34(7):547-53. https://doi.org/10.1046/j.1365-2591.2001.00475.x
4. Jodaikin A. Experimental microleakage around ageing dental amalgam restorations: a review. J Oral Rehabil. 1981;8(6):517-26. https://doi.org/10.1111/j.1365-2842.1981.tb00526.x
5. Bilgrami A, Alam MK, Qazi FU, Maqsood A, Basha S, Ahmed N, Syed KA, Mustafa M, Shrivastava D, Nagarajappa AK, Srivastava KC. An in-vitro evaluation of microleakage in resin-based restorative materials at different time intervals. Polymers. 2022;14(3):466. https://doi.org/10.3390/polym14030466
6. Dennison JB, Sarrett DC. Prediction and diagnosis of clinical outcomes affecting restoration margins. J Oral Rehabil.

2012;39(4):301-18. https://doi.org/10.1111/j.1365-2842.2011.02267.x

7. Gong H, Guo X, Cao D, Gao P, Feng D, Zhang X, Shi Z, Zhang Y, Zhu S, Cui Z. Photopolymerizable and moisture-curable polyurethanes for dental adhesive applications to increase restoration durability. J Mater Chem B. 2019;7(5):744-54. https://doi.org/10.1039/C8TB01716F
8. Rathi SD, Nikhade P, Chandak M, Motwani N, Rathi C, Chandak M. Microleakage in composite resin restoration-a review article. J Evol Med Dent Sci. 2020;9(12):1006-1. https://doi.org/10.14260/jemds/2020/216
9. Namazi AH, Mishaeel S. Shear bond strength of hydroxyapatite liner to composite resin: effect of dentin bonding agents. Health. 2018;10(1):10-9080. https://doi.org/10.19080/ADOH.2018.09.555760
10. Gong H, Zhang X, Guo X, Gao P, Zhao Q, Xu T, Shi X, Zhu S, Cui Z. Advances in reducing microleakage in dental composites. Rev Roum Chim 2019;64(6):519-27. https://doi.org/10.33224/rrch/2019.64.6.08
11. Ceballos L, Osorio R, Toledano M, Marshall GW. Microleakage of composite restorations after acid or Er-YAG laser cavity treatments. Dent Mater. 2001;17(4):340-6. https://doi.org/10.1016/S0109-5641(00)00092-0
12. Corona SA, Borsatto MC, Dibb RP, Ramos RP, Brugnera A, Pécora JD. Microleakage of class V resin composite restorations after bur, air-abrasion or Er: YAG laser preparation. Oper Dent. 2001;26(5):491-7.
13. El-Mowafy O, El-Badrawy W, Eltanty A, Abbasi K, Habib N. Gingival microleakage of Class II resin composite restorations with fiber inserts. Oper Dent. 2007;32(3):298-305. https://doi.org/10.2341/06-86
14. Alla RK. Dental Materials Science. Jaypee Brothers Medical Publishers Pvt Limited, New Delhi, India, 2013; 1-388
15. Ravi RK, Alla RK, Shammas M, Devarhubli A. Dental Composites-A Versatile Restorative Material: An Overview. Ind J Dent Sci. 2013;5(5):111-115.
16. Saridena US, Sanka GS, Alla RK, Ramaraju AV, Sajjan MCS, Mantena SR. An overview of advances in glass ionomer cements. Int J Dent Mater. 2022;4(4):89-94. https://doi.org/10.37983/IJDM.2022.4403
17. Cenci MS, Pereira-Cenci T, Donassollo TA, Sommer L, Strapasson A, Demarco FF. Influence of thermal stress on marginal integrity of restorative materials. J Appl Oral Sci. 2008;16(2):106-10. https://doi.org/10.1590/S1678-77572008000200005
18. Pinto-Sinai G, Brewster J, Roberts H. Linear Coefficient of Thermal Expansion Evaluation of Glass Ionomer and Resin-Modified Glass Ionomer Restorative Materials. Oper Dent. 2018;43(5):E266-E272. https://doi.org/10.2341/17-381-L
19. Sun J, Eidelman N, Lin-Gibson S. 3D mapping of polymerization shrinkage using X-ray micro-computed tomography to predict microleakage. Dent Mater. 2009;25(3):314-20. https://doi.org/10.1016/j.dental.2008.07.010
20. SitaRamaraju DV, Alla RK, Alluri VR, Raju MA. A review of conventional and contemporary luting agents used in dentistry. Am J Mater Sci Eng. 2014;2(3):28-35. https://doi.org/10.12691/ajmse-2-3-1
21. Nicholson JW, Swift Jr EJ. Compomers. J Esthet Restor Dent. 2008;20(1):3-4. https://doi.org/10.1111/j.1708-8240.2008.00141.x
22. Gudapati S. Cavosurface margins for various restorations. IP Ind J Conserv Endod 2022;7(3):113-119. https://doi.org/10.18231/j.ijce.2022.025
23. Hilton TJ, Ferracane JL. Cavity preparation factors and microleakage of Class II composite restorations filled at intraoral temperatures. Am J Dent. 1999;12(3):123-30.
24. Hakimeh S, Vaidyanathan J, Houpt ML, Vaidyanathan TK, Von Hagen S. Microleakage of compomer class V restorations: effect of load cycling, thermal cycling, and cavity shape differences. J Prosthet Dent. 2000;83(2):194-203. https://doi.org/10.1016/S0022-3913(00)80012-8
25. Shenoi PR, Kokane VB, Thawale HV, Kubde RR, Gunwal MK, Shahu SP. Comparing marginal microleakage in Class V cavities restored with flowable composite and Cention-N using confocal microscope-an in-vitro study. Indian J Dent Res. 2021;32(3):348-353. https://doi.org/10.4103/ijdr.IJDR_90_20
26. Andermatt L, Özcan M. Micro-shear bond strength of resin composite cement to coronal enamel/dentin, cervical enamel, cementoenamel junction and root cementum with different adhesive systems. J Adhesion Sci Technol. 2021;35(19), 2079–2093. https://doi.org/10.1080/01694243.2021.1872195
27. Anaraki SN, Sadaghyani M, Ardalani R. Effect of Cavity Dimentions with the Same C-Factor on Micro Leakage of Composite Resin Cavities. J Res Dent Sci 2019;16(4): 253-259. https://doi.org/10.29252/jrds.16.4.253
28. Idriss S, Abduljabbar T, Habib C, Omar R. Factors associated with microleakage in Class II resin composite restorations. Oper Dent. 2007;32(1):60-6. https://doi.org/10.2341/06-16
29. Van Meerbeek B. Controversy in dental adhesive technology: etch-and-rinse vs self-etch approach. InKuraray Symposium, Date: 2009/11/01-2009/11/01, Location: San Francisco, California 2009 Nov 1 (Vol. 31, No. 3, pp. 16-17). AEGIS publications. Accessed on 01.03.2025. https://compendiumlive.com/2010/compendium-supplement-kuraray/controversy-in-dental-adhesive-technology-etch-and-rinse-vs-self-etch-approach?utm_source=chatgpt.com
30. Santini A, Plasschaert AJ, Mitchell S. Effect of composite resin placement techniques on the microleakage of two self-etching dentin-bonding agents. Am J Dent. 2001;14(3):132-6.
31. Guéders AM, Charpentier JF, Albert AI, Geerts SO. Microleakage after thermocycling of 4 etch and rinse and 3 self-etch adhesives with and without a flowable composite lining. Oper Dent. 2006;31(4):450-5. https://doi.org/10.2341/05-55
32. Tran XV, Tran KQ. Microleakage and characteristics of resin-tooth tissues interface of a self-etch and an etch-and-rinse adhesive systems. Restor Dent Endod. 2021;46(2):e30. https://doi.org/10.5395/rde.2021.46.e30
33. Yollar M, Karaoğlanoğlu S, Altıparmak ET, Oktay EA, Aydın N, Ersöz B. The effects of dental adhesives total etch; self-etch and selective etch application procedures on microleakage in class II composite restorations. Eur Oral Res. 2023;57(3):151-8. https://doi.org/10.26650/eor.20231197657
34. Navyasri K, Alla RK, Vineeth G, Suresh Sajjan MC. An overview of dentin bonding agents. Int J Dent Mater. 2019 Nov 15;1(2):60-7. https://doi.org/10.37983/IJDM.2019.1204
35. Giachetti L, Russo DS, Bertini F, Pierleoni F, Nieri M. Effect of operator skill in relation to microleakage of total-etch and self-etch bonding systems. J Dent. 2007;35(4):289-93. https://doi.org/10.1016/j.jdent.2006.09.007
36. Karaman E, Yazici AR, Aksoy B, Karabulut E, Ozgunaltay G, Dayangac B. Effect of operator variability on microleakage with different adhesive systems. Eur J Dent. 2013;7(S 01):S060-5. https://doi.org/10.4103/1305-7456.119075
37. Battancs E, Fráter M, Sáry T, Gál E, Braunitzer G, Szabó P B, Garoushi S. Fracture behavior and integrity of different direct restorative materials to restore noncarious cervical lesions. Polymers. 2021;13(23):4170. https://doi.org/10.3390/polym13234170
38. Kassem AS, Atta O, El-Mowafy O. Fatigue resistance and microleakage of CAD/CAM ceramic and composite molar crowns. J Prosthodont: Implant, Esthetic and Reconstructive Dentistry. 2012;21(1):28-32. https://doi.org/10.1111/j.1532-849X.2011.00773.x
39. Darbyshire PA, Messer LB, Douglas WH. Microleakage in class II composite restorations bonded to dentin using thermal and load cycling. J Dent Res. 1988;67(3):585-7. https://doi.org/10.1177/00220345880670031201

40. Khvostenko D, Salehi S, Naleway SE, Hilton TJ, Ferracane JL, Mitchell JC, Kruzic JJ. Cyclic mechanical loading promotes bacterial penetration along composite restoration marginal gaps. Dent Mater. 2015;31(6):702-10. https://doi.org/10.1016/j.dental.2015.03.011
41. Carrera CA, Li Y, Chen R, Aparicio C, Fok A, Rudney J. Interfacial degradation of adhesive composite restorations mediated by oral biofilms and mechanical challenge in an extracted tooth model of secondary caries. J Dent. 2017;66:62-70. https://doi.org/10.1016/j.jdent.2017.08.009
42. Maganur PD, Prabhakar AR, Sugandhan S, Namineni S. Evaluation of microleakage of RMGIC and Flowable composite immersed in soft drink and fresh fruit juice: An in vitro study. Int J Clin Pediatr Dent. 2010;3(3):153-161. https://doi.org/10.5005/jp-journals-10005-1071
43. Cenci MS, Tenuta LM, Pereira-Cenci T, Del Bel Cury AA, Ten Cate JM, Cury JA. Effect of microleakage and fluoride on enamel-dentine demineralization around restorations. Caries Res. 2008;42(5):369-79. https://doi.org/10.1159/000151663
44. Bourgi R, Cuevas-Suarez CE, Devoto W, Monjarás-Ávila AJ, Monteiro P, Kharma K, Lukomska-Szymanska M, Hardan L. Effect of contamination and decontamination methods on the bond strength of adhesive systems to dentin: A systematic review. J Esthet Restor Dent. 2023;35(8):1218-38. https://doi.org/10.1111/jerd.13078
45. Nair P, Ilie N. The long-term consequence of salivary contamination at various stages of adhesive application and clinically feasible remedies to decontaminate. Clin Oral Investig. 2020;24(12):4413-26. https://doi.org/10.1007/s00784-020-03307-3
46. Helvatjoglou-Antoniades M, Theodoridou-Pahini S, Papadogiannis Y, Karezis A. Microleakage of bonded amalgam restorations: effect of thermal cycling. Oper Dent. 2000;25(4):316-23. https://doi.org/10.2341/16-132-L
47. Zanatta RF, Lungova M, Borges AB, Torres CR, Sydow HG, Wiegand A. Microleakage and shear bond strength of composite restorations under cycling conditions. Oper Dent. 2017;42(2):E71-80. https://doi.org/10.4103/0972-0707.85793
48. Jadhav S, Hegde V, Aher G, Fajandar N. Influence of light curing units on failure of direct composite restorations. J Conserv Dent. 2011;14(3):225-7.
49. Malhotra N, Mala K. Light-curing considerations for resin-based composite materials: a review. Part I. Compendium. 2010;31(7):498-506.
50. Malhotra N, Mala K. Light-curing considerations for resin-based composite materials: a review. Part II. Compendium. 2010;31(8):583-92.
51. Index M, Leaders CE. Light Curing in Restorative Dentistry: The Devil Is in the Details Dentistry Today. 2020 13. https://www.dentistrytoday.com/light-curing-in-restorative-dentistry-the-devil-is-in-the-details/?utm_source=chatgpt.com Accessed on 15th February 2025.
52. Reges RV, Costa AR, Correr AB, Piva E, Puppin-Rontani RM, Sinhoreti MA, Correr-Sobrinho L. Effect of light-curing units, post-cured time and shade of resin cement on Knoop hardness. Braz Dent J. 2009;20:410-3. https://doi.org/10.1590/S0103-64402009000500009
53. Ramic BD, Premovic MT, Stojanac IL, Drobac MR, Petrovic LM. Improved marginal adaptation of composite restorations by using different placement and light polymerization techniques. Am J Dent. 2018;31(1):7-12.
54. Delgado AJ, Ritter AV, Donovan TE, Ziemiecki T, Heymann HO. Effect of finishing techniques on the marginal integrity of resin-based composite and resin-modified glass ionomer restoration. J Esthet Restor Dent. 2015;27(4):184-93. https://doi.org/10.1111/jerd.12140
55. Szczesio-Wlodarczyk A, Sokolowski J, Kleczewska J, Bociong K. Ageing of dental composites based on methacrylate resins—A critical review of the causes and method of assessment. Polymers. 2020;12(4):882. https://doi.org/10.3390/polym12040882
56. Bin-Shuwaish MS, AlHussaini AA, AlHudaithy LH, AlDukhiel SA, Al-Jamhan AS. An in vitro evaluation of microleakage of resin based composites bonded to chlorhexidine-pretreated dentin by different protocols of a universal adhesive system. Saudi Dent J. 2021;33(7):503-10. https://doi.org/10.1016/j.sdentj.2020.09.006
57. de Almeida JB, Platt JA, Oshida Y, Moore BK, Cochran MA, Eckert GJ. Three different methods to evaluate microleakage of packable composites in Class II restorations. Oper Dent. 2003;28(4):453-60.
58. Çelik Ç, Bayraktar Y, Özdemir BE. Effect of Saliva Contamination on Microleakage of Open Sandwich Restorations. Acta Stomatol Croat. 2020;54(3):273-82. https://doi.org/10.15644/asc54/3/5
59. Carrilho E, Abrantes M, Paula A, Casalta-Lopes J, Botelho M, Ferreira M. Microleakage study of a restorative material via radioisotope methods. Revista Portuguesa de Estomatologia, Medicina Dentária e Cirurgia Maxilofacial. 2014;55(3):129-34. https://doi.org/10.1016/j.rpemd.2014.08.005
60. McCurdy CR Jr, Swartz ML, Phillips RW, Rhodes BF. A comparison of in vivo and in vitro microleakage of dental restorations. J Am Dent Assoc. 1974;88(3):592-602. https://doi.org/10.14219/jada.archive.1974.0107
61. Costa JF, Siqueira WL, Loguercio AD, Reis A, Oliveira Ed, Alves CM, Bauer JR, Grande RH. Characterization of aqueous silver nitrate solutions for leakage tests. J Appl Oral Sci. 2011;19(3):254-9. https://doi.org/10.1590/S1678-77572011000300014
62. Moradi S, Lomee M, Gharechahi M. Comparison of fluid filtration and bacterial leakage techniques for evaluation of microleakage in endodontics. Dent Res J. 2015;12(2):109-14.
63. Taylor MJ, Lynch E. Microleakage. J Dent. 1992;20(1):3-10. https://doi.org/10.1016/0300-5712(92)90002-T
64. Akhavan ZV, Moravej SE, Valian A. Effect of Thermocycling and type of restorative material on microleakage of Class II Restorations. J Dent School. 2016; 34(4): 202-13.
65. Rossomando KJ, Wendt SL Jr. Thermocycling and dwell times in microleakage evaluation for bonded restorations. Dent Mater. 1995;11(1):47-51. https://doi.org/10.1016/0109-5641(95)80008-5
66. Ozel E, Tuna EB, Firatli E. The effects of cavity-filling techniques on microleakage in class II resin restorations prepared with Er:YAG laser and diamond bur: A scanning electron microscopy study. Scanning. 2016;38(5):389-95. https://doi.org/10.1002/sca.21282
67. Zanatta RF, Wiegand A, Dullin C, Borges AB, Torres CR, Rizk M. Comparison of micro-CT and conventional dye penetration for microleakage assessment after different aging conditions. Int J Adhesion Adhesives. 2019;89:161-7. https://doi.org/10.1016/j.ijadhadh.2019.01.008
68. Carrera CA, Lan C, Escobar-Sanabria D, Li Y, Rudney J, Aparicio C, Fok A. The use of micro-CT with image segmentation to quantify leakage in dental restorations. Dent Mater. 2015;31(4):382-90. https://doi.org/10.1016/j.dental.2015.01.002
69. Pioch T, Stotz S, Staehle HJ, Duschner H. Applications of confocal laser scanning microscopy to dental bonding. Adv Dent Res. 1997;11(4):453-61. https://doi.org/10.1177/08959374970110041201
70. Ferracane JL. Resin composite—State of the art. Dent Mater. 2011;27(1):29-38. https://doi.org/10.1016/j.dental.2010.10.020
71. Cramer NB, Stansbury JW, Bowman CN. Recent advances and developments in composite dental restorative materials. J Dent Res. 2011;90(4):402-16. https://doi.org/10.1177/0022034510381263
72. Van Meerbeek B, Yoshihara K, Yoshida Y, Mine AJ, De Munck J, Van Landuyt KL. State of the art of self-etch adhesives. Dent Mater. 2011;27(1):17-28.

https://doi.org/10.1016/j.dental.2010.10.023

73. Ilie N, Hickel R. Resin composite restorative materials. Aust Dent J. 2011;56:59-66. https://doi.org/10.1111/j.1834-7819.2010.01296.x
74. Mitra SB, Wu D, Holmes BN. An application of nanotechnology in advanced dental materials. J Am Dent Assoc. 2003;134(10):1382-90. https://doi.org/10.14219/jada.archive.2003.0054
75. Rexhepi I, Santilli M, D'Addazio G, Tafuri G, Manciocchi E, Caputi S, Sinjari B. Clinical Applications and Mechanical Properties of CAD-CAM Materials in Restorative and Prosthetic Dentistry: A Systematic Review. J Funct Biomater. 2023;14(8):431. https://doi.org/10.3390/jfb14080431
76. Schwendicke F, Göstemeyer G, Blunck U, Paris S, Hsu LY, Tu YK. Directly placed restorative materials: review and network meta-analysis. J Dent Res. 2016;95(6):613-22. https://doi.org/10.1177/0022034516631285.