Review Article

Advances in Adhesive Systems and Universal Bonding Agents: A Review of Long-Term Clinical Outcomes and Failure Patterns

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ABSTRACT

Adhesive dentistry has progressed from multi-step etch-and-rinse protocols to simplified self-etch and universal bonding agents designed to bond reliably to enamel, dentin, ceramics, metals and composite substrates. This narrative review evaluates advances in contemporary adhesive systems, with emphasis on long-term clinical outcomes, degradation mechanisms and patterns of failure observed in resin-based restorations. Evidence from clinical trials, systematic reviews and mechanistic laboratory studies indicates that universal adhesives have improved procedural flexibility and reduced technique complexity, but their long-term success remains highly dependent on substrate condition, moisture control, enamel pretreatment and chemical stability of the adhesive interface. Five-year randomized clinical data generally support acceptable retention of non-carious cervical lesion restorations restored with universal adhesives; however, several studies show superior marginal adaptation and lower discoloration when selective enamel etching or an etch-and-rinse strategy is used. Failures are rarely attributable to a single factor. Instead, they reflect progressive hydrolytic degradation of hydrophilic resin, collagen breakdown within the hybrid layer, incomplete monomer infiltration, polymerization stress, occlusal loading, caries risk and operator-related variables. The 10-methacryloyloxydecyl dihydrogen phosphate monomer has strengthened chemical interaction with hydroxyapatite and zirconia, but this advantage can be compromised by water sorption, acidic monomer incompatibility and suboptimal application. Current evidence favors selective enamel etching, active adhesive application, adequate solvent evaporation and careful case selection. Future research should prioritize pragmatic long-term trials, standardized failure definitions, aging protocols that reflect oral conditions and development of bioactive, enzyme-inhibiting and less permeable adhesive interfaces.

Keywords

adhesive dentistry; universal adhesives; dental bonding agents; hybrid layer; clinical longevity; marginal adaptation; restoration failure

INTRODUCTION

Adhesive dentistry has transformed restorative practice by enabling conservative cavity preparation, reinforcement of remaining tooth structure and esthetic rehabilitation using resin-based materials. Earlier generations of dentin bonding agents required separate etching, priming and bonding steps, whereas simplified self-etch and one-bottle systems were introduced to reduce clinical time and procedural sensitivity. Universal or multimode adhesives represent the most recent phase of this evolution. They are marketed for use in etch-and-rinse, self-etch and selective enamel-etch modes and often contain functional monomers intended to bond not only to tooth structure but also to zirconia, silica-based ceramics, metals and resin composites [1].

The clinical appeal of universal bonding agents is clear: a single adhesive can theoretically accommodate direct restorations, indirect restoration luting, intraoral repairs and desensitization. However, simplification has not eliminated the biological and chemical complexity of bonding to dentin. Dentin is hydrated, tubular, collagen-rich and variable in mineral content. Its response to etching, smear layer modification and adhesive infiltration

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differs markedly from that of enamel. The durability of the resin-dentin interface depends on the quality of hybrid-layer formation, solvent removal, polymer conversion, resin hydrophobicity and preservation of collagen fibrils against endogenous proteolytic activity [2].

Universal adhesives have therefore generated debate. Some laboratory reviews suggest that they perform well when used with selective enamel etching and active application, while others warn that one-bottle hydrophilic formulations remain vulnerable to water sorption, phase separation and nanoleakage.Asystematic review of bond strength reported that application strategy influences performance, with selective enamel etching improving enamel bonding and differences on dentin depending on adhesive pH and composition [3]. These findings challenge the assumption that a single universal protocol is equally effective in all situations.

Long-term clinical outcomes are especially important because early bond strength does not always predict restoration survival. Failures may emerge as retention loss, marginal discoloration, marginal gap formation, postoperative sensitivity, secondary caries, bulk fracture or repair failure. Clinical studies in non-carious cervical lesions are useful because these lesions offer limited macromechanical retention and therefore test adhesive effectiveness under functional stress. Five-year data have generally shown acceptable retention for selected universal adhesives, but failure patterns vary by adhesive strategy and by whether phosphoric acid was applied to enamel [4].

This review aims to synthesize current evidence on advances in adhesive systems and universal bonding agents, with emphasis on long-term clinical performance and failure mechanisms. The objectives are to describe the evolution and chemistry of contemporary adhesives, analyze clinical outcome data, summarize interface degradation and failure patterns, identify evidence-based application strategies and highlight gaps requiring future research.

Evolution and Classification of Adhesive Systems

Dental adhesives can be broadly classified according to etching strategy and number of clinical steps. Etch-and-rinse adhesives remove the smear layer using phosphoric acid, expose collagen fibrils and require resin infiltration of a demineralized dentin zone. Three-step etch-and-rinse systems have historically been considered a benchmark for durable bonding because they separate etching, priming and application of a relatively hydrophobic adhesive resin. Two-step etch-and-rinse systems simplified this sequence but increased reliance on accurate wet bonding and solvent evaporation [5].

Self-etch adhesives incorporate acidic monomers that demineralize and infiltrate dentin simultaneously, reducing the risk of over-etching and incomplete resin infiltration. Their interaction with dentin is shallower than that of etch-and-rinse systems, and the smear layer is modified rather than completely removed. Mild self-etch adhesives preserve residual hydroxyapatite around collagen fibrils, creating potential sites for chemical bonding. However, their ability to etch aprismatic or highly mineralized enamel is weaker than phosphoric acid, explaining why selective enamel etching is widely recommended before using self-etch or universal adhesives at enamel margins [6].

Universal adhesives are an extension of the self-etch concept but include chemical components intended for multimode use. Most contain acidic functional monomers, water, organic solvents such as ethanol or acetone, hydrophilic monomers such as hydroxyethyl methacrylate, cross-linking dimethacrylates, silane in some products, initiators and fillers. The inclusion of 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP) has received particular attention because it can form calcium salts with hydroxyapatite and bond to zirconia and metal oxides. This chemistry distinguishes modern universal adhesives from earlier systems that relied more heavily on micromechanical retention alone [7].

Substrate Biology and Mechanisms of Bond Degradation

The adhesive interface is not a static structure. After polymerization, the hybrid layer and adhesive resin are exposed to water, enzymes, thermal changes, pH fluctuation, bacterial biofilms and cyclic loading. Resin-dentin degradation occurs through two major interrelated processes: hydrolysis of resin components and enzymatic degradation of exposed collagen. Hydrophilic adhesives absorb water more readily than hydrophobic resins, and this water sorption can plasticize the polymer, reduce mechanical properties and create nanoleakage channels [8].

Collagen degradation is partly mediated by matrix metalloproteinases and cysteine cathepsins trapped within dentin. Acid etching can expose and activate these enzymes, particularly when collagen fibrils are not completely encapsulated by adhesive resin. Incomplete infiltration leaves vulnerable zones at the base of the hybrid layer, which become preferential sites for breakdown. Laboratory and translational studies have therefore investigated chlorhexidine, benzalkonium chloride, carbodiimide cross-linkers, ethanol wet bonding, biomimetic remineralization and collagen-stabilizing agents as strategies to improve bond durability [9].

Universal adhesives attempt to reduce some of these problems by limiting aggressive demineralization when used in self-etch mode, preserving hydroxyapatite for chemical interaction and simplifying clinical steps. Nevertheless, the same one-bottle design that makes them convenient also creates compromises. Water is required to ionize acidic monomers, but residual water after solvent evaporation increases permeability. Low pH may interfere with chemical-curing or dual-curing resin cements unless a compatible activator is used. Silane incorporated into acidic aqueous adhesive bottles may also have limited shelf stability compared with separately applied ceramic primers [10].

Clinical Outcomes of Universal Bonding Agents

Clinical evidence has accumulated most consistently for non-carious cervical lesion restorations. These lesions are commonly used in adhesive trials because retention depends primarily on adhesion rather than cavity form. A 24-month randomized controlled clinical trial comparing universal adhesives with conventional adhesives found acceptable overall performance, but differences in marginal adaptation and discoloration were influenced by the adhesive and application mode [11]. Such findings suggest that universal adhesives are clinically viable, but material-specific behavior remains relevant.

Five-year follow-up studies provide more meaningful insight into durability. In a clinical evaluation of a universal adhesive used in different strategies, etch-and-rinse performance was superior to self-etch mode after 5 years, and selective enamel etching was recommended when a self-etch approach was selected [12]. Another five-year trial reported satisfactory performance of a universal adhesive regardless of strategy, although the numerical patterns of marginal adaptation and discoloration continued to favor enamel phosphoric-acid pretreatment in many comparisons [13]. The apparent difference between these conclusions reflects a broader issue in adhesive research: retention may remain acceptable even when marginal quality begins to decline.

Sixty-month evaluation of three universal adhesives also showed generally acceptable retention in cervical restorations, but not all adhesives behaved identically. Product composition, acidity, solvent type, filler content and application protocol contributed to clinical differences. Some materials performed better with selective enamel etching, whereas others showed stable outcomes across strategies [14]. These results support a nuanced interpretation: universal adhesives are not interchangeable, and the term universal describes intended versatility rather than guaranteed equivalence.

Posterior composite restorations introduce additional challenges. Unlike cervical lesions, posterior cavities involve high configuration factors, polymerization shrinkage stress, occlusal fatigue and greater difficulty in moisture control. Failure often manifests as marginal breakdown, postoperative sensitivity, bulk fracture or secondary caries rather than immediate debonding. Long-term posterior outcomes are influenced not only by adhesive type but also by cavity size, caries activity, operator skill, placement technique, restorative material and patient-level risk factors [15].

Failure Patterns in Adhesive Restorations

Failure in adhesive dentistry should be understood as a spectrum rather than a binary event. Early failure often relates to contamination, inadequate etching, insufficient adhesive rubbing, poor solvent evaporation, under-curing or incomplete adaptation of composite. Delayed failure more commonly reflects hydrolytic degradation, marginal leakage, fatigue and recurrent caries. In laboratory studies, failure modes are frequently categorized as adhesive, cohesive or mixed; clinically, the corresponding patterns appear as retention loss, marginal staining, marginal gap, fracture or biological failure.

Adhesive and mixed failures are common in aged resin-dentin specimens, especially after water storage or thermomechanical challenge. Studies comparing primary and permanent dentin have shown that primary dentin bonds may be more susceptible to long-term degradation, probably because of structural differences such as tubule density, mineralization and dentin thickness [16]. This observation is clinically relevant because pediatric restorative dentistry often relies on simplified adhesives in conditions where isolation and cooperation may be difficult.

Marginal discoloration deserves careful interpretation. It may indicate superficial staining at an intact margin, but it can also signal interfacial gaps, nanoleakage or microleakage. Retention rates alone may therefore overestimate clinical success. The FDI and modified USPHS criteria attempt to capture gradations in marginal quality, postoperative sensitivity and secondary caries, but trial heterogeneity in scoring systems complicates comparison across studies. Furthermore, many clinical adhesive trials are conducted by experienced operators under controlled conditions, which may not fully represent everyday practice.

Secondary caries is often listed as a restoration failure, yet its relationship to adhesive performance is indirect. Caries recurrence depends on marginal integrity, biofilm control, patient risk, fluoride exposure, diet and restoration contour. A degraded margin may facilitate plaque stagnation, but secondary caries should not automatically be attributed to adhesive failure alone. This distinction is important when interpreting long-term clinical studies because patient-related risk can dominate material-related differences over time.

Optimization of Clinical Protocols

The most consistent clinical recommendation for universal adhesives is selective enamel etching. Phosphoric acid produces deeper and more retentive enamel microporosities than mild self-etch adhesives, improving marginal sealing and reducing enamel-margin discoloration. Selective etching seeks to obtain this benefit while avoiding excessive dentin demineralization. When the etchant inadvertently contacts dentin, careful moisture control becomes necessary to prevent collagen collapse or over-wet bonding.

Active application is another important procedural variable. Rubbing the adhesive into dentin improves monomer infiltration, solvent displacement and interaction of functional monomers with hydroxyapatite. Adequate air thinning is equally important because residual solvent and water impair polymerization and create a permeable adhesive layer. Manufacturers often recommend specific rubbing and evaporation times, but these steps are frequently shortened in clinical practice. The convenience of universal adhesives should not be interpreted as permission to reduce application discipline.[17-19]

Light curing remains a critical determinant of adhesive performance. Inadequate irradiance, curing from excessive distance, incompatible curing lights or shortened exposure can reduce polymer conversion and compromise the oxygen-inhibited adhesive layer. For indirect restorations and deep preparations, compatibility with resin cements must be checked. Some acidic simplified adhesives are incompatible with self-cure or dual-cure composites unless a separate activator is used, potentially resulting in weak polymerization at the bonded interface.

Substrate-specific protocols are also necessary. Bonding to sclerotic dentin may require surface roughening or prolonged application because mineral occlusion of tubules and hypermineralized surfaces restrict infiltration. Caries-affected dentin is more porous and less mineralized than sound dentin, requiring conservative excavation and careful adhesive selection. For ceramics and zirconia, universal adhesives containing 10-MDP may provide useful chemical interaction, but separate silane application remains preferable for silica-based ceramics when durable bonding is required, particularly if the adhesive bottle contains hydrolyzed or unstable silane [17].

Preventive and Repair-Oriented Strategies

Modern adhesive dentistry increasingly emphasizes repair rather than replacement. Universal adhesives are attractive for intraoral repair because they may bond to composite, ceramic, metal and tooth substrates with fewer primers. Repair preserves tooth structure and reduces the restorative cycle that progressively enlarges cavities. In vitro studies show promising repair bond strength when surface conditioning is appropriate, but repair durability depends on substrate aging, surface roughness, contamination, silane stability and correct selection of primers or universal adhesive components [18].

Preventing adhesive failure begins before restoration placement. Caries risk assessment, plaque control, fluoride exposure, management of parafunction and control of erosive challenges all influence restoration longevity. Adhesive systems cannot compensate for poor isolation, high caries activity or unfavorable occlusion. Rubber dam isolation remains ideal where feasible, especially for posterior restorations and cervical lesions close to the gingival margin. When isolation is compromised, glass ionomer or resin-modified glass ionomer materials may be more appropriate than resin composite in selected cases.

Several future-oriented preventive approaches are under investigation. These include MMP-inhibiting primers, collagen cross-linkers, antibacterial monomers, remineralizing fillers, bioactive adhesives, nanofillers that reduce permeability and hydrophobic overcoats placed over universal adhesives. The rationale is to convert the adhesive interface from a passive micromechanical zone into a more biologically stable, enzyme-resistant and remineralizing structure. Although laboratory findings are encouraging, clinical validation remains limited.

Future Directions

Future research should move beyond short-term bond strength and retention outcomes. Pragmatic clinical trials in general practice settings, with longer follow-up and patient-level risk stratification, are required to determine whether differences among adhesive strategies translate into meaningful survival advantages. Standardized reporting of cavity type, isolation method, operator experience, adhesive application time, curing parameters and failure definitions would improve comparability across studies.

Digital dentistry and minimally invasive workflows will further expand the role of universal adhesives. As indirect restorations, CAD/CAM ceramics, hybrid ceramics and chairside repair become more common, clinicians need evidence-based protocols for bonding to diverse surfaces. The future universal adhesive may not be a single bottle for all tasks, but rather a clinically intelligent system that combines simplified use with optional substrate-specific enhancers.

DISCUSSION

The evidence reviewed indicates that universal bonding agents have matured into clinically useful materials, but their success depends on respecting adhesive principles rather than assuming that universal equals automatic. Long-term clinical studies generally support acceptable performance in non-carious cervical lesions, especially when enamel is selectively etched or when etch-and-rinse protocols are used. However, marginal staining and adaptation changes often appear before frank retention loss, suggesting that the earliest signs of degradation may be subtle and may require longer follow-up to determine their clinical relevance.

A major strength of the current evidence base is the availability of randomized clinical trials extending to 5 years. These studies provide more clinically relevant data than immediate bond-strength experiments. Their limitations include concentration on cervical lesions, use of selected operators, relatively small sample sizes after attrition and heterogeneity in adhesives and evaluation criteria. Posterior restorations and indirect restorations remain less well represented despite being common clinical indications for universal adhesives.

Mechanistic studies help explain why clinical failures occur. Hydrolysis, collagenolysis, nanoleakage, incomplete polymerization and functional fatigue interact over time. The addition of 10-MDP and other functional monomers has improved chemical bonding, but chemical affinity cannot fully overcome water-rich dentin, residual solvent, enzyme activity or poor clinical technique. The most rational approach is therefore layered: select an adhesive with favorable composition, etch enamel selectively, apply actively, evaporate solvent thoroughly, cure adequately and control patient-level risk factors.

Several controversies persist. One is whether etch-and-rinse or self-etch mode is superior for universal adhesives. The best answer appears substrate dependent: enamel generally benefits from phosphoric acid, while dentin may perform well with mild self-etching if the adhesive is actively applied and chemically stable. Another controversy is whether universal adhesives can replace separate ceramic primers. Evidence supports their convenience in some repair scenarios, but separate silane or dedicated primers may still be preferable when maximum durable bonding to indirect substrates is required.

Clinically, the implications are practical. Universal adhesives should be viewed as versatile tools requiring precise protocols, not as shortcuts. Dentists should record the adhesive used, its mode of application and lot-related instructions, because material-specific differences influence outcomes. For researchers, the priority is to link molecular and interfacial findings with patient-centered clinical endpoints such as restoration survival, repairability, sensitivity, recurrent caries and cost-effectiveness.

CONCLUSION

Universal bonding agents represent a major advance in adhesive dentistry by simplifying procedures and expanding bonding versatility across tooth and restorative substrates. Long-term clinical evidence supports their use, particularly in cervical restorations, but outcomes are strongly influenced by enamel pretreatment, adhesive composition and clinical technique. Failure patterns are multifactorial and include interfacial degradation, marginal discoloration, retention loss, secondary caries and fracture. Selective enamel etching, active application, thorough solvent evaporation, adequate curing and careful case selection remain essential. Future progress will depend on adhesives that combine simplified handling with improved resistance to hydrolysis, collagen degradation and biofilm-related challenges, supported by robust long-term clinical trials.

REFERENCES

1. Perdigão J, Swift EJ Jr. Universal adhesives. J Esthet Restor Dent. 2015;27(6):331-334. doi:10.1111/jerd.12185. PMID: 26573170.
2. Mokeem LS, Garcia IM, Melo MAS, et al. Degradation and failure phenomena at the dentin bonding interface. Dent J (Basel). 2023;11(5):125. doi:10.3390/dj11050125. PMID: 37238927.
3. da Rosa WLO, Piva E, da Silva AF. Bond strength of universal adhesives: a systematic review and meta-analysis. J Dent. 2015;43(7):765-776. doi:10.1016/j.jdent.2015.04.003. PMID: 25882585.
4. Ñaupari-Villasante R, Loguercio AD, Reis A, et al. Five-year clinical evaluation of universal adhesive applied in different bonding strategies. Oper Dent. 2023;48(4):381-392. doi:10.2341/22-107-C. PMID: 37147235.
5. Van Meerbeek B, De Munck J, Yoshida Y, et al. Buonocore memorial lecture. Adhesion to enamel and dentin: current status and future challenges. Oper Dent. 2003;28(3):215-235. PMID: 12760693.
6. Van Meerbeek B, Yoshihara K, Yoshida Y, Mine A, De Munck J, Van Landuyt KL. State of the art of self-etch adhesives. Dent Mater. 2011;27(1):17-28. doi:10.1016/j.dental.2010.10.023. PMID: 21109301.
7. Yoshida Y, Nagakane K, Fukuda R, et al. Comparative study on adhesive performance of functional monomers. J Dent Res. 2004;83(6):454-458. doi:10.1177/154405910408300604. PMID: 15153451.
8. Frassetto A, Breschi L, Turco G, et al. Mechanisms of degradation of the hybrid layer in adhesive dentistry and therapeutic agents to improve bond durability: a literature review. Dent Mater. 2016;32(2):e41-e53. doi:10.1016/j.dental.2015.11.007. PMID: 26749253.
9. Tjäderhane L, Nascimento FD, Breschi L, et al. Optimizing dentin bond durability: strategies to prevent hydrolytic degradation of the hybrid layer. Dent Mater. 2013;29(10):999-1011. doi:10.1016/j.dental.2013.07.016. PMID: 23953737.
10. Van Landuyt KL, Snauwaert J, De Munck J, et al. Systematic review of the chemical composition of contemporary dental adhesives. Biomaterials. 2007;28(26):3757-3785. doi:10.1016/j.biomaterials.2007.04.044. PMID: 17543382.
11. Oz FD, Kutuk ZB, Ozturk C, Soleimani R, Gurgan S. Twenty-four-month clinical performance of different universal adhesives in etch-and-rinse, selective enamel-etch and self-etch application modes. Oper Dent. 2019;44(6):E283-E295. doi:10.2341/18-144-C. PMID: 30994773.
12. de Paris Matos T, Perdigão J, de Paula E, et al. Five-year clinical evaluation of a universal adhesive: a randomized double-blind trial. Dent Mater. 2020;36(11):1474-1485. doi:10.1016/j.dental.2020.08.007. PMID: 32933775.
13. Fuentes MV, Perdigão J, Baracco B, Giráldez I, Ceballos L. Effect of an additional bonding resin on the 5-year performance of a universal adhesive: a randomized clinical trial. Clin Oral Investig. 2023;27(1):375-386. doi:10.1007/s00784-022-04613-8. PMID: 35821134.
14. Oz FD, Ergin E, Canatan S, et al. Sixty-month follow up of three different universal adhesives used in different application modes. Clin Oral Investig. 2022;26(5):4299-4310. doi:10.1007/s00784-022-04388-0. PMID: 35212840.

15. Mendonça TS, Reis A, Loguercio AD, et al. Clinical performance of posterior resin composite restorations: a systematic review. J Appl Oral Sci. 2025;33:e20240519. doi:10.1590/1678-7757-2024-0519. PMID: 41197541.

16. Soares FZM, Lenzi TL, Rocha RO. Degradation of resin-dentine bond of different adhesive systems to primary and permanent dentine. Eur Arch Paediatr Dent. 2017;18(2):113-118. doi:10.1007/s40368-017-0282-z. PMID: 28271448.

17. Cuevas-Suárez CE, Ramos TS, Rodrigues SB, et al. Bonding strength of universal adhesives to indirect substrates: a systematic review and meta-analysis. J Prosthodont. 2020;29(4):298-308. doi:10.1111/jopr.13147. PMID: 31994803.

18. Staxrud F, Dahl JE. Potential of universal bonding agents for composite repair. Biomater Investig Dent. 2022;9(1):41-48. doi:10.1080/26415275.2022.2050669. PMID: 35573020.

19. Alayyash A, Shqaidef A, Almaslamani MJ, Alam MK. Effect of various orthodontic adhesives on shear bond strength after thermal cycling. Bangladesh J Med Sci. 2025;24(10):73-77. doi:10.3329/bjms.v24i10.79159.

20. Raja Awang RA, Islam MS, Jamayet N, Ismail NH. Flexural strength and viscosity of dental luting composite reinforced with zirconia and alumina. Bangladesh J Med Sci. 2024;23(4):1048-1053. doi:10.3329/bjms.v23i4.76515.

21. Ahmed T, Fareen N, Alam MK. The effect of surface treatment and thermocycling on the shear bond strength of orthodontic brackets to Y-TZP zirconia ceramics: a systematic review. Dental Press J Orthod. 2021;26(5):e212118.

22. Alam MK, Dhasarathan V, Aly MH, Zaman MU, Ganji KK, Basri R, et al. Investigation on enamel and dentine of tooth through 1D photonic structure to identify the caries in human teeth. Bioengineering (Basel). 2022;9(12):788. doi:10.3390/bioengineering9120788.