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REVIEW ARTICLE

Adhesive dentistry: Current concepts and clinical considerations

Jorge Perdigão DMD, MS, PhD, Professor[1] |
Edson Araujo DDS, MS, PhD, Associate Professor[2] |
Renato Q. Ramos DDS, MS, Graduate Student[3] |
George Gomes DDS, MSD, Private Practice[4] |
Lucas Pizzolotto DDS, MS, Graduate Student[5]

[1]Department of Restorative Sciences, Division of Operative Dentistry, University of Minnesota, Minneapolis, Minnesota, USA

[2]Department of Comprehensive Care, School of Dentistry, Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil

[3]Department of Operative Dentistry, School of Dentistry, Federal University of Santa Catarina, Florianópolis, Santa Catarina, Brazil

[4]George Gomes Dental Center, Oeiras, Lisbon, Portugal

[5]Department of Dental Materials, Faculty of Dental Sciences, Federal University of Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil

Correspondence
*Jorge Perdigão, School of Dentistry, University of Minnesota, 515 SE Delaware Street, 8-450 Moos Tower Minneapolis, MN, USA.
Email: perdi001@umn.edu

Abstract

Objectives: To address contemporary concepts in adhesive dental materials with emphasis on the evidence behind their clinical use.

Overview: Adhesive dentistry has undergone major transformations within the last 20 years. New dental adhesives and composite resins have been launched with special focus on their user-friendliness by reducing the number of components and/or clinical steps. The latest examples are universal adhesives and universal composite resins. While clinicians prefer multipurpose materials with shorter application times, the simplification of clinical procedures does not always result in the best clinical outcomes. This review summarizes the current evidence on adhesive restorative materials with focus on universal adhesives and universal composite resins.

Conclusions: (a) Although the clinical behavior of universal adhesives has exceeded expectations, dentists still need to etch enamel to achieve durable restorations; (b) there is no clinical evidence to back some of the popular adjunct techniques used with dental adhesives, including glutaraldehyde-based desensitizers and matrix metalloproteinase inhibitors; and (c) the color adaptation potential of new universal composite resins has simplified their clinical application by combining multiple shades without using different translucencies of the same shade.

Clinical Significance: New adhesive restorative materials are easier to use than their predecessors, while providing excellent clinical outcomes without compromising the esthetic quality of the restorations.

KEYWORDS
dental adhesion, dental bonding, dental materials, universal adhesives, universal composite resins

1 | INTRODUCTION

Establishing durable adhesion to dentin with resin monomer solutions has been an arduous task since the pioneering work of several research teams in the 1950s using the phosphate monomer glycerol phosphoric acid dimethacrylate (GPDM). This monomer, patented by Oskar Hagger in 1951, was included in the composition of Sevitron Cavity Seal (Amalgamated Dental Trade Distribution, Ltd., London, UK).[1-4]

Dental adhesives have gone through substantial transformations in their chemistry and number of components within the last 40 years as a result of the challenging pledge to create durable bonding to dentin using resin monomers. Adhesion to enamel, on the other hand, has remained consistently simple and reliable since the introduction of the acid-etch technique in 1955 by Michael Buonocore.[5] Etching enamel with phosphoric acid (Figure 1) has changed the course of restorative dentistry for years to come. Dr. Buonocore was well aware that he had just established the foundation for adhesive and preventive dentistry. He wrote "we foresee that the formation of good bonds, of the sort we have demonstrated, to enamel surfaces open the possibility of successfully sealing pits and fissures for purposes of caries prevention. In addition, good bonding at the enamel cavity margins would protect against secondary or marginal decay."[5]

The formation of resin interdigitations into the enamel microporosities created by the dissolution of hydroxyapatite with phosphoric acid is still the crucial mechanism for mechanical bonding of resin-based adhesives to etched enamel. For dentin, a similar micromechanical interlocking between resins and dentin has been theorized in spite of the intrinsic humid substrate.[6-9] This assumption was based on the abundant resin tags formed by dental adhesives into the dentinal tubules when dentin was etched with phosphoric acid. More recently, however, adhesives have been shown to provide reliable and durable adhesion to dentin clinically without the need to etch dentin with phosphoric acid.[10-12] Hence, the micromechanical mechanism for dentin adhesion has gradually lost relevance within the last 10 years, while chemical/ionic bonding gas gained prominence.

A few years after Dr. Buonocore described the enamel acid-etch technique, Dr. Bowen's team introduced the bisphenol A-glycidyl methacrylate (Bis-GMA) molecule in the early 1960s.[13,14] This work led to the first commercial composite resin, Addent (3M, St. Paul, MN), which was launched in 1964. This chemically- cured macrofilled composite resin enjoyed moderate success for several years until Adaptic (Johnson & Johnson Dental Products, East Windsor, NJ) was launched in 1968 as a paste-paste composite resin to challenge Addent's popularity, which was eventually improved and rebranded as Concise (3M). With the advances in inorganic filler technology and the introduction of light initiation of resin monomers, new composite resins with enhanced physical properties and clinical behavior gradually replaced those rudimentary macrofilled composite resins.

Many new dental adhesives and composite resins have been developed within the last few decades. The most recent innovations in adhesive restorative materials are universal adhesives and universal composite resins, which were designed to streamline the clinical procedure involving direct and indirect adhesive restorations.

The objective of this article is to review the recent advances in adhesive restorative materials, discuss their clinical application, and analyze the evidence behind some of the concepts currently advocated by non-peer-reviewed sources that are not supported by the existing clinical evidence.

2 | DENTAL ADHESIVES: TO REMOVE OR TO INTEGRATE THE SMEAR LAYER?

Dental adhesives are currently classified by generation or by the way they interact with the smear layer. The former is a classification commonly used by the industry and by opinion leaders. Types of adhesives are ordered chronologically by the order they were introduced into the dental market. This classification carries with it the misleading concept that the latest generation (highest number) incorporates the newest technology, therefore the best performing dental adhesives. Unfortunately, this is rarely the case.

Adhesives that remove the smear layer and its appended smear plugs (Figure 2) are known as etch-and-rinse (E&R) adhesives (Table 1). They rely on phosphoric acid etching of enamel and dentin. Besides removing the smear layer, the acid also decalcifies the most superficial 1–5 μm of dentin to remove hydroxyapatite and leave

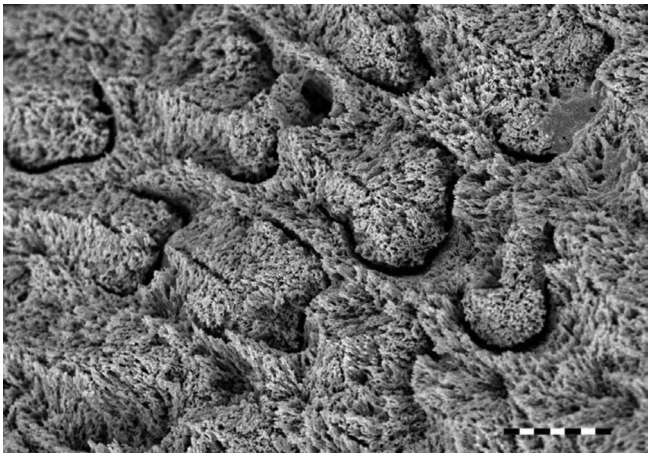

FIGURE 1 Micrograph of beveled human enamel etched with 35% phosphoric acid gel (Vococid Etching Gel, VOCO, Cuxhaven, Germany) for 15 s. Micron bar = 4 μm; Original magnification = X5000

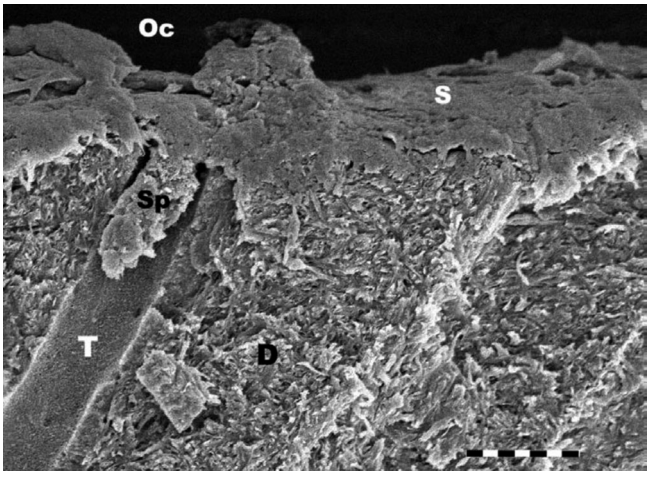

FIGURE 2 (A) Micrograph of smear layer created with a diamond but in high-speed with water refrigeration. Oc, occlusal surface; D, normal dentin; T, dentinal tubule; S, smear layer; Sp, smear plug. Micron bar = 2 μm; Original magnification = X10,000

behind a filigree of collagen fibers soaked in water left from rinsing the acid (Figure 3).

There are two types of E&R adhesives, two-step and three-step E&R adhesives (Table 1). While two-step E&R adhesives include an etchant and a hydrophilic solution that serves simultaneously as primer and bonding resin, three-step E&R adhesives have a separate primer and a separate hydrophobic bonding resin. Optibond FL (Kerr Corp., Orange, CA), a three-step E&R adhesive, is still the reference for all other E&R adhesives. It has resulted in excellent clinical retention at 13 years in noncarious cervical lesions (NCCLs).[15]

Adhesives that do not use a separate etching step are known as self-etch (SE) adhesives (Table 1). Their nonrinsing acidic primer does not remove the smear layer. Instead, it integrates the smear layer residues into the adhesive interface while slightly decalcifying superficial hydroxyapatite in dentin (Figure 4(A)) and enamel (Figure 4(B)). This depth of decalcification depends on the acidity of the primer: ultra-mild (pH ≥2.5), mild (pH ≈ 2), intermediately strong (pH between 1 and 2) and strong (pH <1).[10]

There are two types of SE adhesives, one-step and two-step SE adhesives. The latter include a separate hydrophobic bonding resin. Clearfil SE Bond (Kuraray Noritake Dental, Inc, Tokyo, Japan), first used in the late 1990s as Mega Bond in Japan, is a mild (pH ≈ 2) two-step SE adhesive that partially decalcifies dentin to a depth < 1 μm (Figure 4(A)), leaving behind hydroxyapatite crystals and smear layer remnants within the resulting sub-micron hybrid layer. Clearfil SE Bond has resulted in excellent 13-year clinical outcomes in NCCLs.[12] The retention rate was 93% when enamel was selectively etched. When the adhesive was applied to enamel and dentin in SE mode the retention rate was 86%. Our clinical recommendation for two-step SE adhesives is to use selective enamel etching to improve enamel bonding and marginal sealing (Figure 5).

TABLE 1 Current dental adhesion strategies

Etch-and-rinse 	3-step A ⟹ P ⟹ **Br**
	2-step A ⟹ (P/Br)
Self-etch 	2-step *Ac*P ⟹ **Br**
	1-step (*Ac*P/Br)

A = Phosphoric acid; P = Primer; *Ac*P =Acidic primer; Br = Solvent-free hydrophobic bonding

Abbreviations: A, phosphoric acid; *Ac*P, acidic primer; Br, solvent-free hydrophobic bonding; P, primer.

3 | ARE SIMPLIFIED ADHESIVES BETTER THAN MULTIBOTTLE ADHESIVES?

Simplified adhesives, that is, one-step SE and two-step E&R adhesives, do not include a separate hydrophobic bonding resin as the last step of the clinical procedure (Table 1). Based on the available clinical evidence, classical dental adhesives that include a hydrophobic bonding resin step, that is, three-step E&R adhesives and two-step SE adhesives, are more stable and result in more durable restorations than their simplified counterparts.[11] Despite their inferior clinical performance, simplified adhesives have become very popular as dentists tend to select materials that are easier to use. However, clinical and laboratory research has demonstrated that there is a trade-off between simplification of dental adhesives and respective outcomes.[11,16-20]

The acidity of simplified adhesives also determines their clinical behavior. Mild/ultra-mild one-step SE adhesives result in a significantly lower annual failure rate (3.6%) than strong one-step SE adhesives (5.4%).[11] In addition, adhesives with lower pH (more acidic) are incompatible with composite resins that have a chemical-curing mechanism, such as dual-cure buildup materials.[21,22] The setting mechanism of self-curing composite resins is based on a traditional redox reaction of benzoyl peroxide (catalyst paste) with aromatic tertiary amines (base paste). The oxygen-inhibited layer in

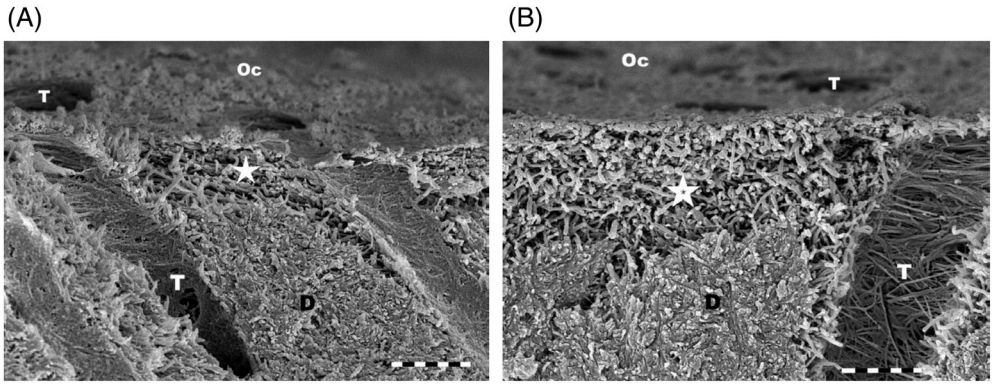

FIGURE 3 (A) Micrograph of dentin etched with low-viscosity 32% phosphoric acid gel (Scotchbond Universal Etchant, 3M Oral Care) for 15 s. (B) Micrograph of dentin etched with high-viscosity 34% phosphoric acid gel (Caulk Tooth Conditioner Gel, Dentsply Sirona) for 15 s. Oc, occlusal surface; D, normal dentin; T, dentinal tubule; asterisk denotes network of collagen fibers in dentin decalcified by the etchant. Micron bar = 2 μm; Original magnification = X10,000

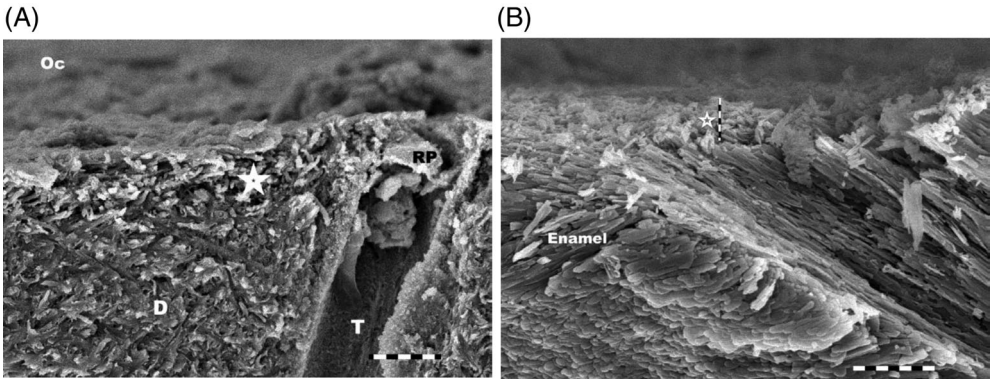

FIGURE 4 (A) Micrograph of human dentin treated with Clearfil SE Primer (Kuraray Noritake Dental, Inc.) for 20 s. The primer was partially removed with acetone. The asterisk denotes the area of partial dentin decalcification by the acidic Clearfil SE Primer (Kuraray Noritake Dental, Inc.). The collagen fibers are still surrounded by residual hydroxyapatite crystals and smear layer remnants. Micron bar = 1 μm; Original magnification = X15,000. Oc, occlusal surface; D, normal dentin; T, dentinal tubule; RP, resin-impregnated smear plug. (B) Micrograph of human enamel treated with Clearfil SE Primer (Kuraray Noritake Dental, Inc.) for 20 s. The asterisk with the vertical line denotes the depth of enamel decalcification by the acidic Clearfil SE Primer (Kuraray Noritake Dental, Inc.). Micron bar = 1 μm; Original magnification = X20,000

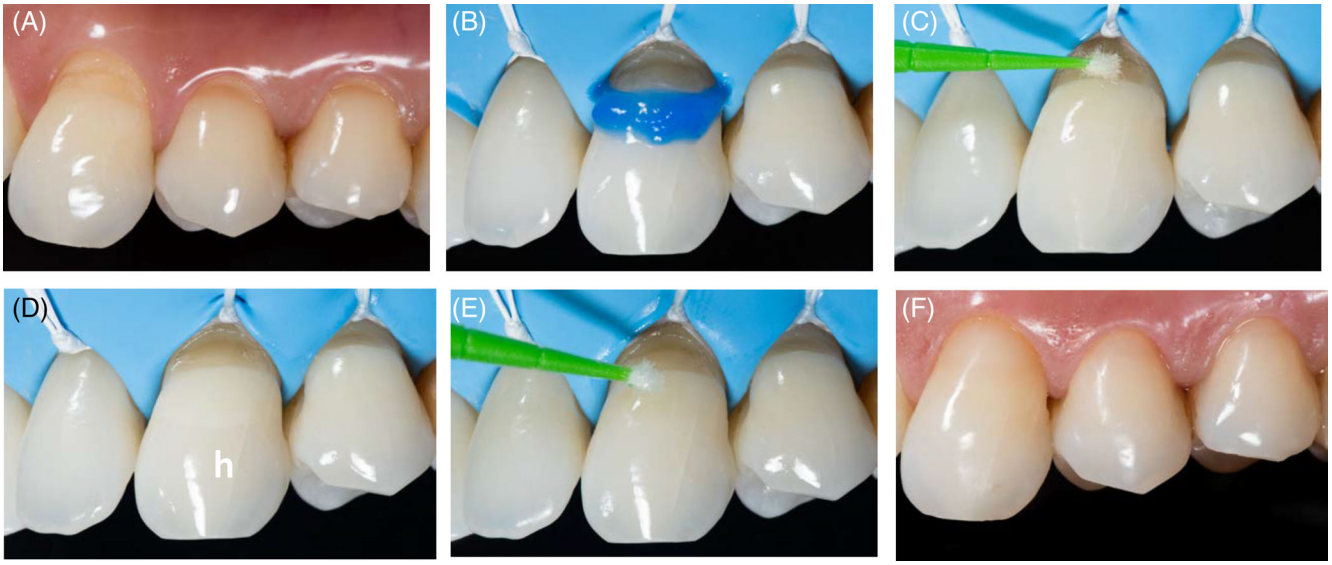

FIGURE 5 Clinical application of the two-step SE adhesive Clearfil SE Bond (Kuraray Noritake Dental, Inc.). (A) Preoperative view of NCCLs on the maxillary left canine and premolars; (B) Selective enamel etching of NCCL in the maxillary left canine; (C) Primer was applied, left undisturbed for 20 s, and gently air dried; (D) Preparation denoting a uniform coating of the primer on the dentin surface; (E) Bond was applied and gently air-dried. (F) Post-operative view. Clearfil SE Bond (Kuraray Noritake Dental, Inc.) was used for all three restorations

simplified adhesives is acidic. This acidity causes the deactivation of the aromatic amine initiators of chemically cured composite resins, making them incompatible with simplified adhesives. The corresponding bond strengths are much lower and water blisters form at the adhesive interface.[21,23] The oxygen-inhibited layer of simplified adhesives is also hypertonic, which leads to osmotic fluid transport through the semi-permeable adhesive layer causing degradation of the interface.[23]

Simplified adhesives have several other shortcomings, including poor clinical outcomes in NCCLs and posterior composite restorations.[11,16] These clinical shortcomings may be caused by the behavior of simplified adhesives as semi-permeable membranes on enamel and dentin.[19,23,24]

4 | UNIVERSAL ADHESIVES

Universal adhesives are one-step SE adhesives that are also recommended by the respective manufacturers as two-step E&R adhesives when phosphoric acid is used to etch enamel and dentin.[25] Clinicians may also use these adhesives with the *selective enamel etching* technique, in which only enamel is etched with phosphoric acid. The major difference between universal adhesives and traditional one-step SE adhesives is the presence of functional phosphate and/or carboxylate monomers in universal adhesives (Table 2). Some of these functional monomers are able to trigger chemical bonding to calcium in hydroxyapatite.[26,27]

Another characteristic of universal adhesives is that they are recommended for a multitude of clinical applications, including direct restorations, indirect restorations, core buildups, zirconia primer, and dentin desensitizer.

4.1 | What we know

4.1.1 | The role of chemical bonding

Chemical bonding to tooth structure is not a recent concept. Zinc polycarboxylate cement was developed in 1966[28] as the first self-adhesive material in Dentistry. In 1969 another dental material with self-adhesive properties was developed, the glass-ionomer cement (GIC).[29] Both materials shared polyacrylic acid as the liquid component.

More recently, the adhesion-decalcification concept[26,30] has shed some light upon the mechanism of chemical bonding to dentin. When carboxylic acids, such as polyacrylic acid in the composition of GIC, are applied on hydroxyapatite they form stable ionic bonds to calcium, which explains the excellent performance of glass-ionomer-based restoratives in cervical areas.[11] Polyacrylic acid stays attached to calcium on the hydroxyapatite surface resulting in minor decalcification.[31] Stronger acids, such as phosphoric acid, trigger a significant decalcification of hydroxyapatite with minimal or no chemical attachment. The dissolution rate of the respective calcium salts in the acid solution determines the pathway of chemical adhesion versus decalcification for each acid.[26,30] For example, the phosphate monomer phenyl-P, which has been used in the composition of SE adhesives, results in strong decalcification of hydroxyapatite.[32] The monomer 10-MDP (MDP, 10-methacryloyloxydecyl dihydrogen phosphate), on the other hand, adheres to calcium without causing strong enamel and dentin decalcification. But it still causes a very slight decalcification of hydroxyapatite that leads to calcium release and subsequent formation of stable self-assembled MDP-Ca salts in the form of nanolayering,[32-34] providing simultaneously *chemical* and *micromechanical* adhesion.

The MDP molecule includes a methacrylate polymerizable end, a long hydrophobic 10-carbon chain, and a short hydrophilic phosphate component that is able to ionize and interact with hydroxyapatite (Figure 6). The length of the long hydrophobic 10-carbon chain (or spacer) has also been reported to contribute to its bonding ability.[27] Longer spacer chains in monomers such as MDP are more hydrophobic, which may enhance the chemical interaction with calcium and reduce their degradation.[35]

The long-term clinical success of the two-step SE adhesive Clearfil SE Bond[12] may stem from the inclusion of MDP in its

TABLE 2 Current universal adhesives

	Functional monomer(s)	Solvents	pH[a]	Silane	Separate DC activator[b]
All-Bond Universal (Bisco, Inc.)	MDP	Ethanol, water	3.2	No	No
Adhese Universal (Ivoclar Vivadent)	MDP, MCAP	Ethanol, water	2.8	No	No
Clearfil Universal Bond (Kuraray Noritake Dental, Inc.)	MDP	Ethanol, water	2.3	Yes	Yes
Futurabond U (VOCO)	MDP	Ethanol, water	2.3	No	No[c]
G-Premio Bond (GC America Inc.)	MDP, 4-MET, MDTP	Acetone, water	1.5	No	Yes
One Coat 7 Universal (Coltene)	MDP	Ethanol, water	2.8	No	Yes
OptiBond Universal (Kerr Corp.)	GPDM	Water, acetone, ethanol	2.5	No	No
Prime & Bond Active or Prime & Bond Universal (Dentsply Sirona)	MDP, PENTA	Water, isopropyl alcohol	2.5	No	Yes
Scotchbond Universal Adhesive or Single Bond Universal Adhesive (3M Oral Care)	MDP, PAC	Ethanol, water	2.7	Yes	Yes
Scotchbond Universal Adhesive Plus (3M Oral Care)	MDP, PAC	Ethanol, water	2.7	Yes[d]	No
Universal Bond (Tokuyama Dental America, Inc.)	MOEP, MTU-6	Water, acetone, isopropyl alcohol	2.2	Yes	No[e]

Abbreviations: GPDM: glycero-phosphate dimethacrylate; MCAP: methacrylated carboxylic acid polymer; MDP: 10-methacryloyloxydecyl dihydrogen phosphate; MDTP: methacryloyloxydecyl dihydrogen thiophosphate; 4-MET: 4-methacryloyloxyethyl trimellitic acid; MOEP: 2-hydroxyethyl methacrylate phosphate (methacryloylethyl phosphate); MTU-6: 6-methacryloyloxyhexyl 2-thiouracil- 5-carboxylate; PAC: polyalkenoic acid copolymer; PENTA: dipentaerythritol penta acrylate monophosphate.

[a]More acidic universal adhesives (lower pH) are more likely to need a DC activator when used with dual- or self-cured composite resin materials that contain aromatic tertiary amines in their initiator system.

[b]The dual-cured activator is mixed with the universal adhesive for use with dual- or self-cured composite resin materials that contain aromatic tertiary amines in their initiator system. All universal adhesives can be used without DC activator when combined with newer dual-cured resin cements that do not contain aromatic tertiary amines.

[c]Dual-cured adhesive.

[d]Contains two silanes: 3-(aminopropyl) triethoxysilane (APTES); and γ-methacryloxypropyltriethoxysilane (γMPTES).

[e]Self-cured adhesive.

composition, providing the potential for chemical bonding to calcium in enamel and dentin.[32-34] In fact, the 13-year clinical study mentioned above[12] observed that restorations without previous enamel etching were still retained in spite of marginal discrepancies. These restorations were likely solely retained as a result of chemical bonding between calcium on the surface of NCCLs and MDP, in addition to the minimal etching capability of MDP that results in micromechanical retention.[32]

The adhesive Clearfil New Bond (Kuraray) included for the first time the molecule MDP in the early 1980s.[36,37] When the MDP patent expired in 2011 other manufacturers started adding this phosphate monomer to their new one-bottle dental adhesives.[38] This was the outset of a new family of dental adhesives known as multimode or universal adhesives. Scotchbond Universal Adhesive (SBU, 3M Oral Care, St. Paul, MN), which contains MDP, was the first commercial universal adhesive. For this reason, SBU is the universal adhesive that has been studied more often in vitro and clinically. While the dentin interfaces formed with universal adhesives are fairly stable after artificial aging in laboratory studies when dentin is not etched with phosphoric acid,[39-41] the clinical behavior of universal adhesives depends on enamel etching with phosphoric acid.[41-45] Thus, *selective enamel etching* (Figure 7(A)) may provide micro-mechanical retention and marginal sealing of etched enamel, in addition to potential chemical bonding between the functional monomer MDP and calcium in dentin hydroxyapatite.

4.1.2 | Do we need to leave dentin moist with universal adhesives?

As dentin is intrinsically humid, it is practically impossible to dry dentin during a clinical procedure. For this reason, dental adhesives, including universal adhesives, contain hydrophilic monomers to enhance the wettability to dentin[46] in addition to hydrophobic groups to copolymerize with the restorative material.

Moist dentin has been considered the ideal substrate for E&R adhesives to prevent the collapse of dentin collagen fibrils that are left upon rinsing the etchant. Dry etched dentin, on the other hand, has been shown to result in low bond strengths and incomplete saturation of the hybrid layer by the adhesive in vitro.[47,48] In spite of the poor in vitro results with dry dentin, clinical studies have failed to demonstrate the need for leaving dentin moist prior to applying E&R adhesives. This apparent paradox may be a result of in vitro tests being carried out in extracted teeth in which dentin does not resemble dentin found in clinical situations.[49] In fact, the clinical retention rates of E&R adhesives applied to moist dentin are not inferior to those of the same adhesives applied to dry dentin (Figure 7(B)).[15,50] Likewise, the 5-year clinical performance of SBU in E&R mode applied on dry dentin[42] did not result in worse retention than when the adhesive was applied on moist dentin. The successful clinical behavior of SBU on dry dentin may be a result of the respective manufacturer's instructions, which recommend rubbing the adhesive in for 20 s.[51] Clinical and in vitro evidence suggests that vigorous application of the adhesive may lead to a more complete penetration of the adhesive solution into the etched dentin collagen network[52-54] (Figure 8). Active application of universal adhesives is also recommended on enamel, especially when universal adhesives are applied in SE mode.[55]

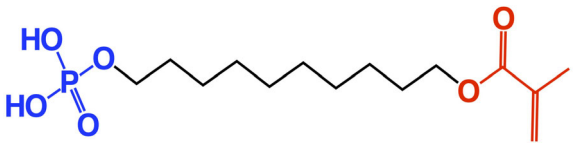

FIGURE 6 The 10-MDP molecule. The methacrylate polymerizable end is shown in red. The short hydrophilic phosphate component is shown in blue; long hydrophobic 10-carbon chain or spacer is depicted in black

4.1.3 | Clinical studies with universal adhesives

Several clinical studies, including a 5-year randomized clinical trial in NCCLs using both the USPHS and the FDI criteria, demonstrated that the clinical behavior of SBU makes this adhesive the current gold standard for universal adhesives.[42,56,57] The 5-year retention rate in NCCLs was 93% when the adhesive was applied in E&R mode independent of the degree of dentin moisture (dry or moist).[42] When SBU was applied in SE mode, the retention rate was 81.4% and the marginal adaptation and marginal discoloration were significantly worse.[42]

Another study with SBU reported excellent clinical outcomes at 36 months with an overall retention rate of 98.1%.[56] No statistical difference was found for different adhesion strategies. However, SBU resulted in more marginal staining and marginal deterioration in SE mode when compared with E&R and selective enamel etch modes.[56]

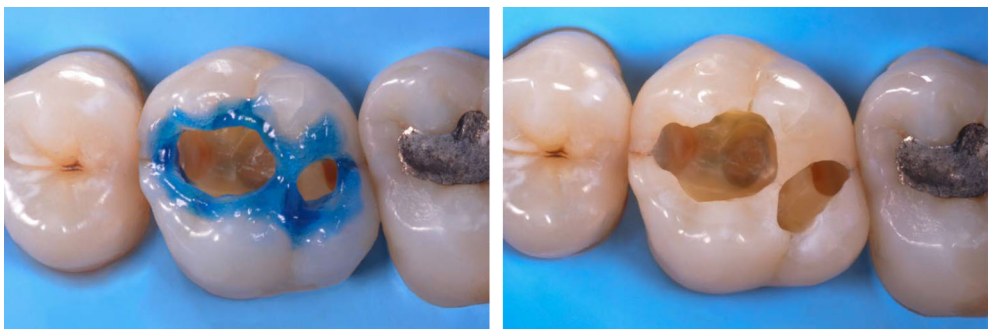

FIGURE 7 (A) Selective enamel etching technique of preparation on maxillary right first molar prior to restoring a posterior tooth with Scotchbond Universal Plus Adhesive and Filtek Universal (3M Oral Care). (B) After rinsing of the etchant for 10–15 s, the preparation was gently air-dried to remove excess water without desiccating dentin

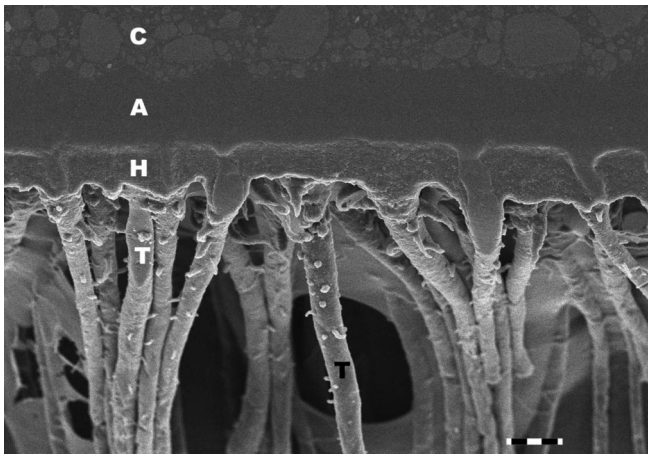

FIGURE 8 Micrograph of the interface between Scotchbond Universal Plus Adhesive (3M Oral Care) and dentin. The universal adhesive was applied actively on **dry** dentin as an E&R adhesive. The interface was challenged with 6 N HCl for 30 s and 1.0% NaOCl for 10 min. The hybrid layer (H) remained intact after this challenge. Micron bar = 6 μm; Original magnification = 2500X. C, Filtek Supreme Ultra Flowable Restorative (3M Oral Care); A, Scotchbond Universal Plus Adhesive (3M Oral Care); H, hybrid layer; T, resin tag

The 2-year effectiveness of SBU in both SE and E&R modes was also compared with those of a two-step E&R adhesive (Adper Single Bond Plus, 3M Oral Care) and a two-step SE adhesive (Clearfil SE Bond, Kuraray Noritake Dental, Inc.). SBU behaved similarly to the other two adhesives at 2 years regardless of the adhesion strategy.[58]

The E&R and the selective enamel etching strategies provided better clinical outcomes with All-Bond Universal (Bisco, Inc., Schaumburg, IL) and Gluma Universal (Kulzer North America, South Bend, IN) at 2 years.[43] Adhese Universal (ADU, Ivoclar Vivadent, Amherst, NY) resulted in very good in vitro and clinical results after up to 3 years.[55,59-61] The E&R strategy showed less marginal discoloration and better marginal adaptation than the SE approach. In addition, the retention rate of ADU in NCCLs was not affected by dentin roughness created with a diamond but regardless of the adhesion strategy.[62]

In spite of the clinical success of universal adhesives in NCCLs, a recent universal adhesive was not effective in a short-term clinical trial. The clinical outcomes of Xeno Select (Dentsply Sirona, Konstanz, Germany), also known as Prime & Bond One, were not acceptable as the overall retention rate in NCCLs was only 88% at 6 months.[63] This adhesive is no longer available.

Among other clinical shortcomings associated with universal adhesives that warrant further research, intense marginal discoloration and marginal discrepancies have been reported in several clinical studies.[44,56,62,64]

4.1.4 | Use of silane-containing universal adhesives with glass-matrix ceramics

Glass-matrix ceramics, such as lithium disilicate, are more resistant to fracture if etched with hydrofluoric acid (HF) and cemented with an adhesive protocol.[65,66] After rinsing off HF profusely with water and drying thoroughly with air, a silane primer solution is applied to the intaglio surface to provide additional chemical bonding, followed by a dental adhesive. The bifunctional silane molecule forms a siloxane network at the etched glass–ceramic surface and copolymerizes with methacrylate groups of the dental adhesive or the resin cement.[67,68] The most common silane monomer used in Dentistry is 3-methacryloxypropyltrimethoxysilane (MPS or γMPTS)[68] in a concentration ranging from 1 to 10% in an organic solvent.

Some universal adhesives, such as SBU, Clearfil Universal Bond (Kuraray Noritake Dental, Inc.) and Universal Bond (Tokuyama Dental America, Inc., Encinitas, CA) contain a silane in their composition with the goal of shortening the luting clinical procedure by combining adhesive and silane into one application. However, silanes become deactivated in acidic solutions that also contain water, such as universal adhesives.[69,70] For this reason, the application of a separate silane solution, or a silane freshly mixed with the adhesive, is still recommended.[71,72]

Recent developments in universal adhesives may have solved this incompatibility. A novel universal adhesive, Scotchbond Universal Plus Adhesive (3M Oral Care), now includes two silane molecules into the adhesive solution.[73,74] The bonding performance of the combined 3-(aminopropyl)triethoxysilane (APTES)/γ-methacryloxypropyltriethoxysilane (γMPTES) silane-containing Scotchbond Universal Plus Adhesive to glass-matrix ceramics has substantially improved compared to its predecessor, which contains γ-methacryloxypropyltrimethoxysilane (γMPTS).[74]

4.2 | Further studies needed

4.2.1 | The definitive role of MDP

The role of MDP in chemical bonding to hydroxyapatite is well-documented in vitro. Nevertheless, a few in vitro studies have questioned the potential for MDP to promote chemical bonding of universal adhesives to dentin and enamel. For example, when HEMA (2-hydroxyethyl methacrylate) and MDP are present in the same solution, a partial inhibitory effect of HEMA may affect the formation of nanolayering of MDP salts on dentin.[75] Other authors have demonstrated that nanolayering does not occur in resin-dentin interfaces of commercial universal adhesives that contain MDP in their composition.[76]

4.2.2 | Solvent evaporation time

There has been some discussion regarding the duration of the solvent evaporation time for universal adhesives. In addition to hydrophilic monomers, universal adhesives may contain up to 20% water in their composition. This water is required to ionize the phosphate monomers and trigger a slight decalcification of enamel and dentin by the phosphate group when the adhesive is used in SE mode.[25] For that reason, a solvent evaporation time of 5 s recommended by most

manufacturers may not be sufficient to remove water from the interface with enamel and dentin. Consequently, universal adhesives may need an extended solvent evaporation time to ensure removal of the residual water from the interface.[77] The water evaporation helps preventing the hydrolytical degradation of the hybrid layer and preserving the physical properties of the resin monomers upon polymerization.[77-79] Extending the solvent evaporation time to 15 s with a gentle stream of air to evaporate the excess water results in higher dentin bond strengths and less nanoleakage.[77] This recommendation may also apply to other adhesives. In fact, a recent systematic review based on in vitro studies reported that the adhesive solvent drying time of 5–10 s may be insufficient to achieve durable bonding to dentin. Instead, the solvent evaporation time should be extended to 15–30 s.[80] This information needs to be validated with clinical studies.

4.2.3 | Is an extra hydrophobic bonding resin needed with universal adhesives?

The application of an extra hydrophobic bonding layer is extremely important to improve the clinical performance of one-step SE adhesives.[17] For universal adhesives, the in vitro data also suggest that an extra hydrophobic bonding layer is important for stable adhesion.[81-83] However, the current clinical evidence does not corroborate the in vitro findings.[84] More clinical studies are definitely needed to clarify this apparent paradox.

4.2.4 | Enamel etching with low-viscosity etching gels

A few phosphoric acid gels that are recommended for use with universal adhesives are less viscous than their classical counterparts. Manufacturers add polyvinyl alcohol while others add silicone glycol to change the rheological properties of their phosphoric acid gels, making them easier do dispense and spread on the tooth surface. In spite of being easier do dispense from the respective syringe, the application of low-viscosity etchants is more difficult to control when used for the selective enamel etching technique.

Low-viscosity gels are less aggressive on dentin than their predecessors,[85] (Figure 3(A,B)) which does not influence dentin bond strengths or clinical behavior of the respective adhesives. However, the effect of these gels on enamel bonding has not been fully elucidated. Our ultra-morphological analysis under the Field-Emission SEM demonstrates that low-viscosity etching gels are unable to etch intact enamel to the same depth achieved with more viscous gels of similar concentration (Figure 9).

One detail that is often overlooked is the use of aggressive phosphoric acid gels with universal adhesives, in spite of not being recommended by the manufacturer of the respective universal adhesive.[86,87] For example, the etchant included with both SBU and SBU Plus decalcifies intertubular dentin to a depth of 1.6 μm,[85] while a more aggressive commercial gel may decalcify dentin to a depth of 4.0–5.0 μm. Thus, a confounding variable is introduced in the study design when a more aggressive etchant is used. This detail is particularly important because the depth of dentin decalcification may influence nanoleakage and the durability of the bonding. For this reason, universal adhesives should always be used with the etchant recommended by the respective manufacturer.

4.2.5 | Use of universal adhesives as zirconia primers

MDP can also adhere to zirconia via ionic and hydrogen bonding.[88] The application of MDP-based universal adhesives improves the immediate bond strength to zirconia but results in a significant drop in bond strengths after 6 months of water storage.[89] Another study reported that the additional use of an MDP-containing universal adhesive did not result in a significant effect for bonding to zirconia.[90] Furthermore, it is unclear what happens to the light-cured resin monomers of universal adhesives left uncured, as light does not reach the intaglio surface when the zirconia restoration is cemented.

In addition to MDP-containing universal adhesives, MDP- and silane-based ethanol solutions are also recommended as zirconia primers.[91] Because they contain a silane in addition to MDP, these primers can be used simultaneously as primers for zirconia and as silane coupling agents for glass-matrix ceramics, which is extremely convenient for clinicians.[92] There are several of these primers available, including Monobond Plus (Ivoclar Vivadent), Clearfil Ceramic Primer (Kuraray Noritake Dental, Inc.), and GC Ceramic Primer II (GC America Inc., Alsip, IL). MDP-based primers increase the in vitro durability of the bonds compared to MDP-containing universal adhesives.[90-92] MDP-based primers are also effective for translucent or cubic zirconia.[93]

5 | MYTHS AND FACTS IN DENTAL ADHESION

5.1 | Are matrix metalloproteinase inhibitors needed in dental adhesion?

Matrix metalloproteinases (MMPs) are proteolytic enzymes that can trigger the degradation of extracellular matrix proteins in different human tissues. The first report of MMP activity was observed in 1962 as collagenolytic disintegration of collagen fibers during metamorphosis in tadpoles.[94] MMPs are secreted as proenzymes (zymogens) that are activated by proteinases, chemical agents, and acidic environments. These proenzymes are also found in odontoblasts and human dentin.[95] Once activated, MMPs can activate the enzymatic degradation of dentin collagen matrix with subsequent breakdown of resin-dentin bonds in vitro[96,97] and in situ.[98] These enzymes are also capable of inducing the in vitro degradation of the dentin collagen

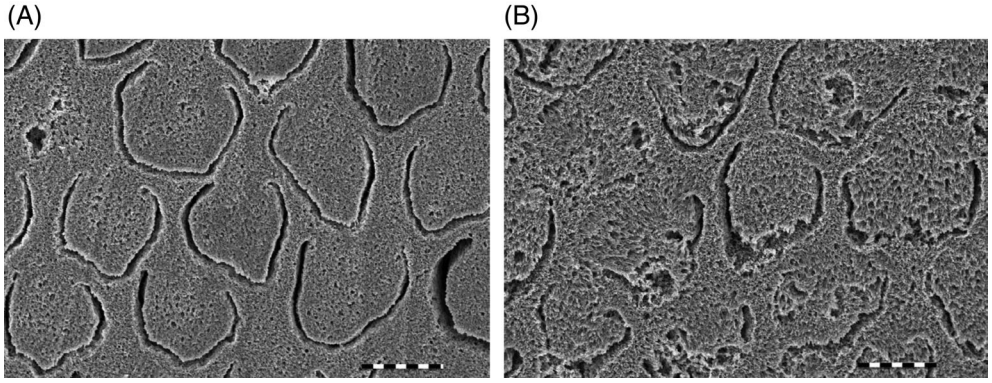

FIGURE 9 Micrograph of etched unbeveled human enamel of a maxillary central incisor. Half of the buccal surface (Figure 9(A)) was etched with a low-viscosity 35% phosphoric acid etching gel (Ultra-Etch, Ultradent, South Jordan, UT). The other half (Figure 9(B)) was etched with a high-viscosity 35% phosphoric acid gel (Scotchbond Etchant, 3M Oral Care). Note the more pronounced etching pattern and deeper decalcification with the high-viscosity gel in Figure 9(B). Micron bar = 4 μm; Original magnification = 5000X

within hybrid layers that are incompletely infiltrated with adhesive, potentially reducing the longevity of adhesive restorations.[95,99]

Dentin MMPs are also activated by dental adhesives in vitro.[97,99] The use of MMP inhibitors during adhesive restorative procedures, including chlorhexidine and proanthocyanidins, has been advocated to prevent the degradation of dentin bonds and improve the durability of restorations.[94,99-103] This topic has become ubiquitous in the dental adhesion literature within the last 15 years. Most publications seem to validate the advantages of including MMP inhibitors in adhesive procedures that are carried out in vitro. Nevertheless, only a few clinical trials have been published.[104-108] All clinical trials have failed to provide evidence to back the use of MMP inhibitors in clinical adhesive dentistry. A meta-analysis also reported that there is scarce evidence to recommend or negate the usefulness of MMP inhibitors applied prior to inserting adhesive restorations.[109]

5.2 | Postoperative sensitivity associated with adhesive restorations

There is a substantial number of testimonials and non-peer-reviewed articles supporting the perception that SE adhesives result in lower incidence of postoperative sensitivity in posterior composite restorations compared to E&R adhesives. However, the current evidence from clinical trials clearly shows that the adhesion strategy does not influence the development of postoperative sensitivity after the insertion of posterior composite restorations.[110-119] A systematic review and meta-analysis[120] also determined that postoperative sensitivity is not determined by the adhesion strategy.

Glutaraldehyde-based dentin desensitizers have been shown to be effective in reducing dentin hypersensitivity in areas of dentin exposed to the oral environment.[121,122] However, manufacturers and opinion leaders have also recommended their use underneath direct and indirect restorations to prevent postoperative sensitivity.[123-127] Unfortunately, this recommendation is not supported by clinical evidence. To our knowledge, only two peer-reviewed clinical trials have studied this subject. They did not find any association between the use of glutaraldehyde-based desensitizers and reduction of postoperative sensitivity underneath adhesive restorations.[128,129]

5.3 | Immediate dentin sealing

The immediate dentin sealing technique, or IDS, advocates the use of a dentin adhesive to protect or seal exposed dentin tubules after tooth preparation for an indirect restoration and prior to luting the provisional restoration.[130] This technique has been very popular among clinicians and has resulted in favorable in vitro results and case reports.[131-133] However, there is no strong clinical evidence to recommend the use of the IDS technique. The authors of a systematic review published in 2015 were unable to find any clinical studies with IDS.[134] Two randomized clinical trials published after 2015 with indirect posterior restorations did not observe any difference in success rate or post-luting sensitivity at 3 years when they compared the IDS technique with the conventional luting technique.[135,136] The 11-year results of a clinical trial with porcelain veneers on anterior teeth at 11 years found an increase in success rate from 81.8% to 96.4% using the IDS technique when the area of exposed dentin was above 50%.[137]

6 | UNIVERSAL COMPOSITE RESINS

Due to their considerable particle size, classical macrofilled composite resins did not polish well.[138] In fact, some of them were sold with an extra glazing to coat the surfaces of the completed restoration to give the patient the gratification of a temporary polish. In addition, they underwent occlusal wear and discoloration very quickly.[139-142]

The need for better composite resin materials led to the first significant development in filler technology in 1975 when Kulzer and Ivoclar filed patents in Germany for composite materials containing "microfine fillers with particle sizes of the order of 0.07 um," which

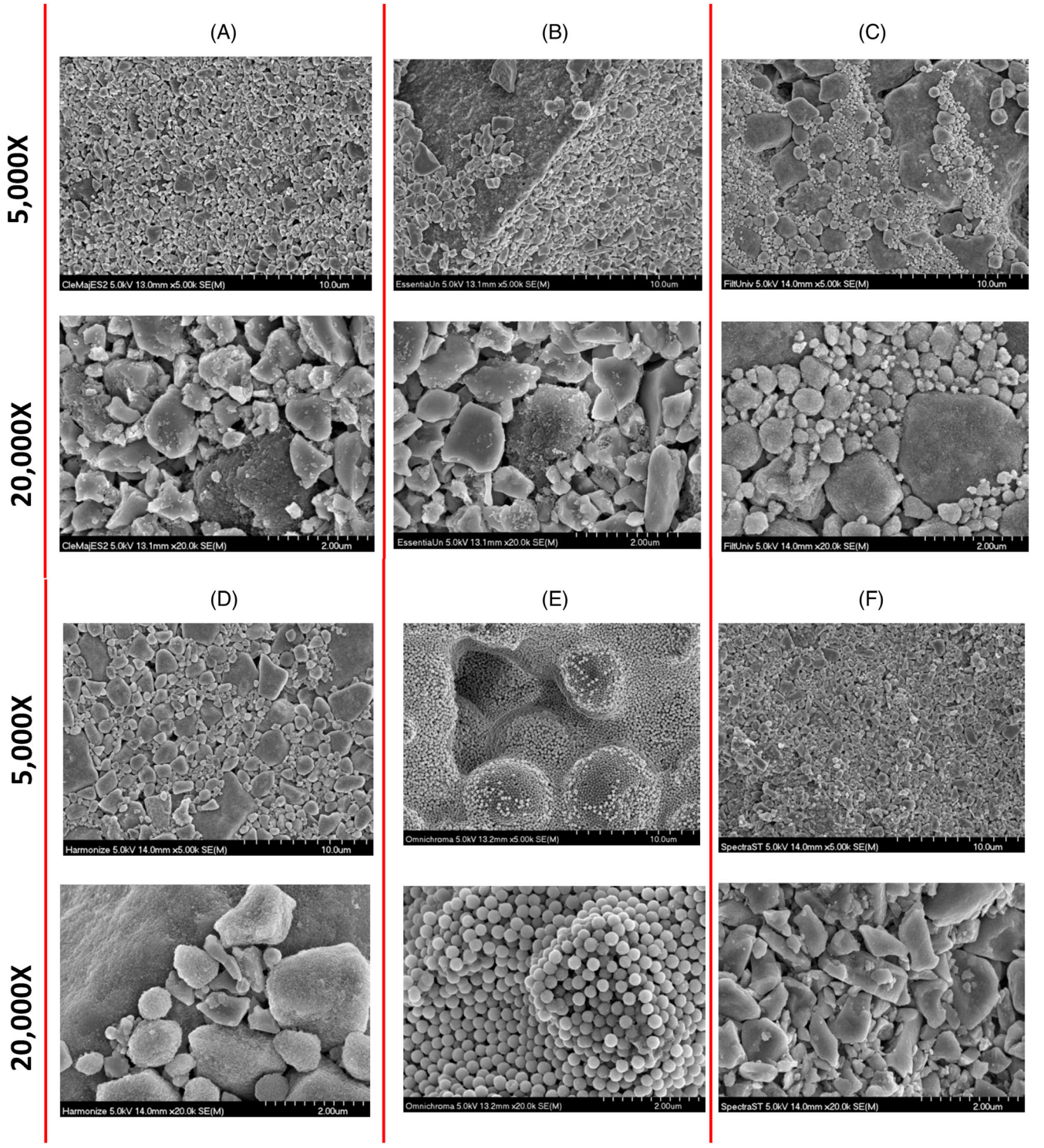

FIGURE 10 Ultra-morphological characterization of universal composite resins. The resin matrix was removed chemically to facilitate the analysis of the filler. (A) Clearfil Majesty ES-2 Premium (Kuraray Noritake Dental, Inc.); (B) Essential Universal (GC Europe); (C) Filtek Universal (3M Oral Care); (D) Harmonize (Kerr Corp.); (E) Omnichroma (Tokuyama Dental America, Inc.); (F) TPH Spectra ST (Dentsply Sirona)

would later become microfilled composite resins.[143] These materials contained 35–50% filler by weight with 0.04 μm silica filler particles and prepolymerized resin fillers to compensate for their low filler content. In spite of their excellent handling and final gloss, their physical properties were not ideal for extensive anterior restorations due to their intrinsic low fracture strength.[144] In the late 1970s, early 1980s, microfillers (0.04 μm wide particles of pyrogenic silica) were blended with conventional macrofillers to reinforce the organic matrix, improve the physical properties, provide better control of the viscosity, and improve wear.[144] However, the handling and final gloss of

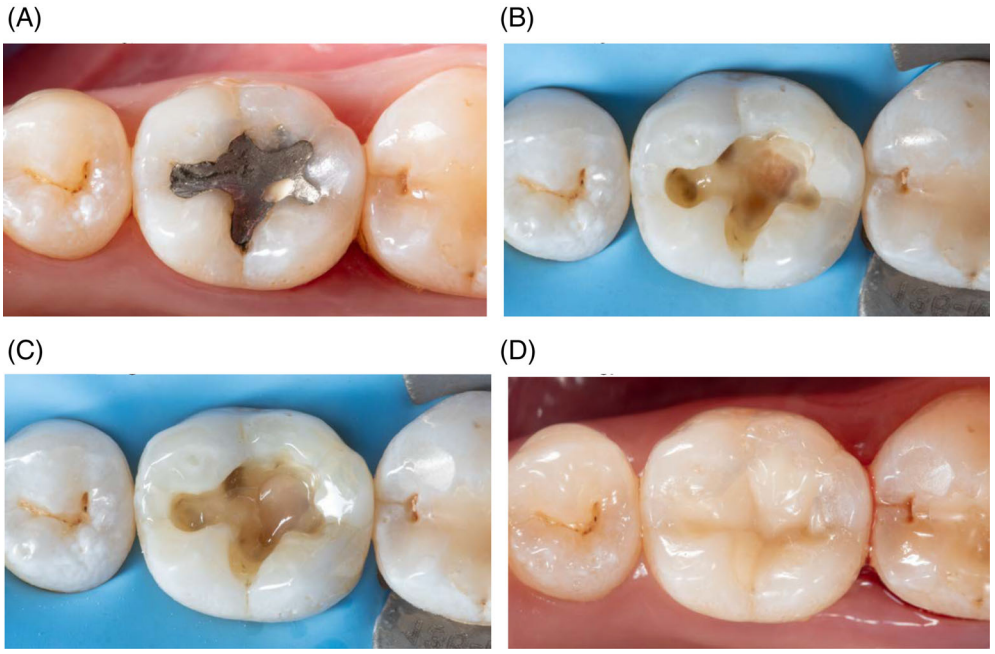

FIGURE 11 (A) Defective amalgam restoration on mandibular left first molar (B) Removal of the restoration and carious dentin (C) Enamel was etched with 35% phosphoric acid for 15 s, the two-step SE Clearfil SE Bond (Kuraray Noritake Dental, Inc.) adhesive was applied and light-cured, followed by an increment of Omichroma Blocker (Tokuyama Dental America, Inc.) to mask the dentin discoloration of the pulpal floor, followed by light curing. Three increments of the single shade Omnichroma composite resin were inserted and light cured individually. (D) Final restoration with Omnichroma (Tokuyama Dental America, Inc.)

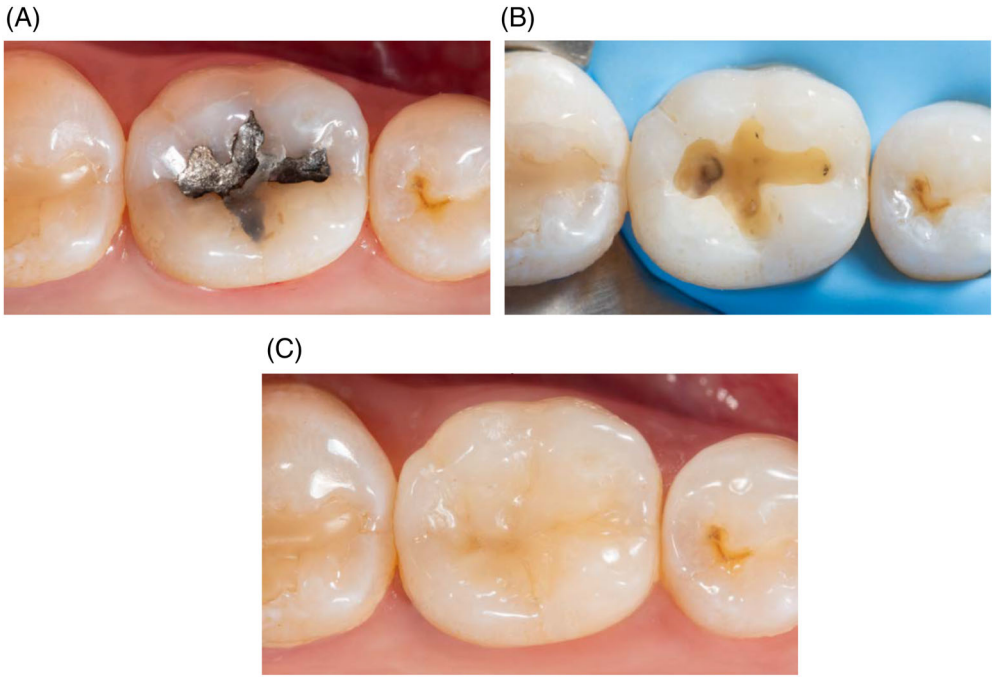

FIGURE 12 (A) Defective amalgam restoration on mandibular right first molar. (B) Removal of the restoration and carious dentin; (C) Enamel was etched with 35% phosphoric acid, the adhesive was applied and light-cured, followed by Essentia Universal (GC Europe) in three increments that were cured individually

these hybrid composites were not as good as those of microfilled composites.

A nanotechnology-based composite resin with individual particle size of 20 nm was launched in 2002.[145] The current version is Filtek Supreme Ultra (3M Oral Care) (also Filtek Supreme XTE, Filtek Ultimate, and Filtek Z350 XT in other regions). In spite of the advanced technology associated with nanofilled composite resins, their clinical outcomes are comparable to those of hybrid composites.[146,147]

The term "nanohybrid" has been used to refer to hybrid composite resins that contain a mixture of nanofiller particles and conventional filler particles. Looking at classical hybrid composites available in the early 1990s, such as Herculite XRV (Kerr Corp.), these materials already included a blend of nanosized particles (40 nm) and conventional macrofillers. Therefore, materials currently known as "nanohybrids" are hybrid composite resins.[148] Some publications have avoided the term "nanohybrid" and used instead terms such as nanofill, submicron composites, and traditional microhybrid composites.[149] Other publications, however, have grouped the terms nanofilled and "nanohybrid" composites in the same category.[147,150] There is no evidence that these so-called "nanohybrid" composite resins have better physical properties than the classical microhybrid materials.[151,152]

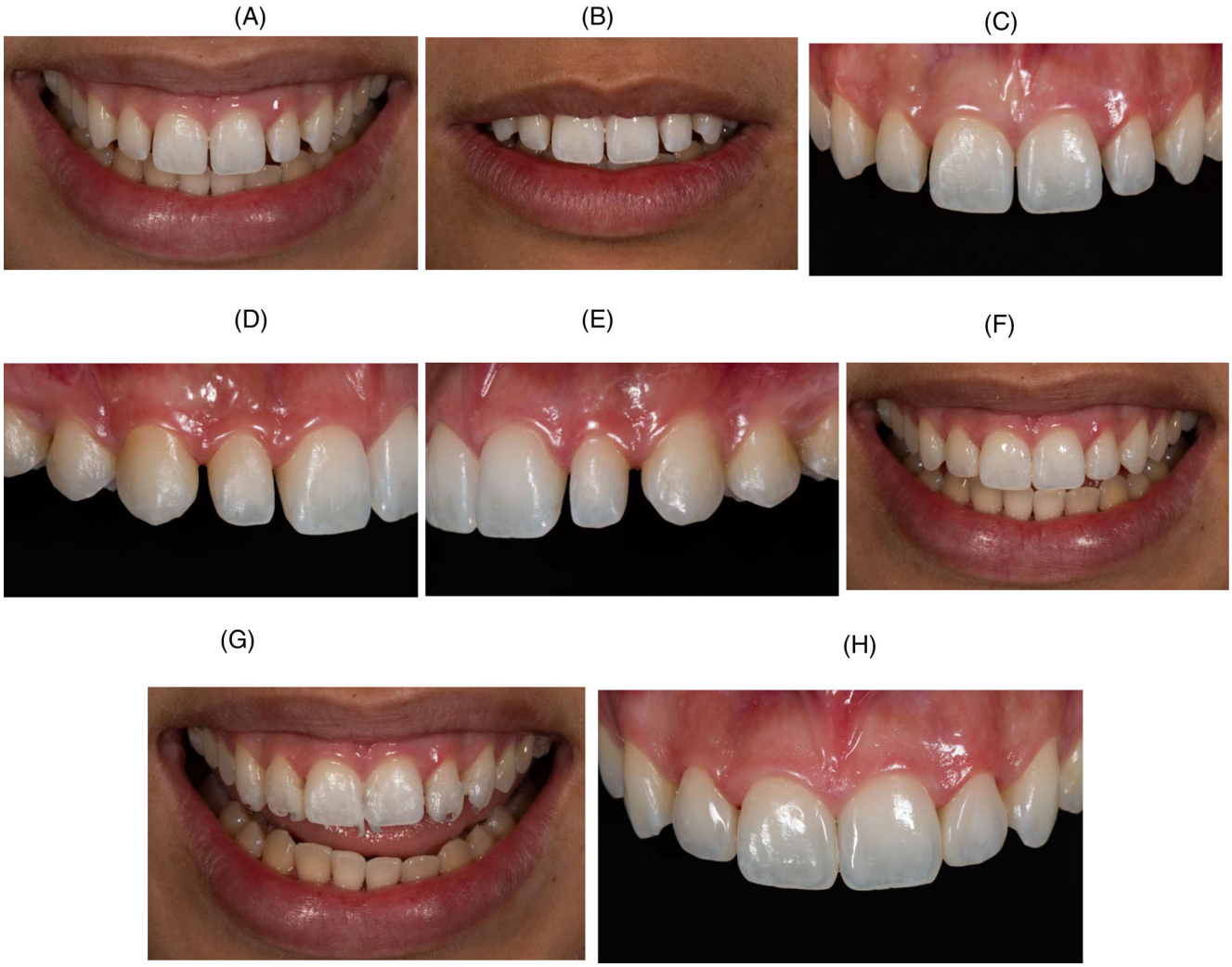

FIGURE 13 Multiple diastema closure in a 29-year-old female patient. (A) Preoperative smile line; (B) Lip at rest position; (C) Retracted view of maxillary anterior teeth; (D) Retracted right view; (E) Retracted left view; (F) Mockup with Omnichroma (Tokuyama Dental America, Inc.) applied on right central incisor and Essentia Universal (GC Europe) applied on left central incisor. We decided to restore the teeth with Omnichroma (G) Removal of mockup; (H) Post-operative view of Omnichroma restorations

The recent evolution in composite resin technology includes novel materials known as universal composite resins. Current materials include Clearfil Majesty ES-2 Premium (Kuraray Noritake Dental, Inc.), Essential Universal (GC Europe, Leuven, Belgium), Filtek Universal (3M Oral Care), Omnichroma (Tokuyama Dental America, Inc.), TPH Spectra ST (Dentsply Sirona, York, PA), among others (Figure 10). Some of these materials contain nanofiller clusters, which are depicted at X20,000 magnification in Figure 10.

Universal composite resins carry fewer shades, (either single- or group-shaded materials) than previous composite resins due to improved "blending in" effect with the tooth structure[153,154] also known as color adjustment potential (CAP).[155] Composite resins with pronounced color adjustment are able to interact with surrounding enamel and dentin, resulting in reduced color differences. This reduction in the number of shades simplifies the creation of almost imperceptible restorations using fewer shades,[156] as shown in Figures 11 and 12. Essentia Universal is available in one shade; Filtek Universal is available in eight regular shades, a pink opaquer and an extra white shade; Omnichroma only has one regular shade and one opaquer; SimpliShade Universal Composite (Kerr Corp.) is available in three regular shades, a bleach white and an universal opaque; and TPH Spectra ST has five regular shades and one bleach shade.

Regarding composite translucency, Essentia Universal (GC Europe), Filtek Universal (3M Oral Care), Omnichroma (Tokuyama Dental America, Inc.), SimpliShade Universal Composite (Kerr Corp.), and TPH Spectra ST (Dentsply Sirona) are available in one translucency rather than multiple enamel, dentin and body shades that have been used to mimic the optical properties of different areas of the tooth. This feature makes universal composites user-friendlier compared to other composites that rely on the multilayer technique for extensive anterior restorations, which has been used for over 20 years.[157,158] Other universal composites still carry different composite resin translucencies. Clearfil Majesty ES-2 Premium is available in five enamel shades, five dentin shades, four bleached shades and

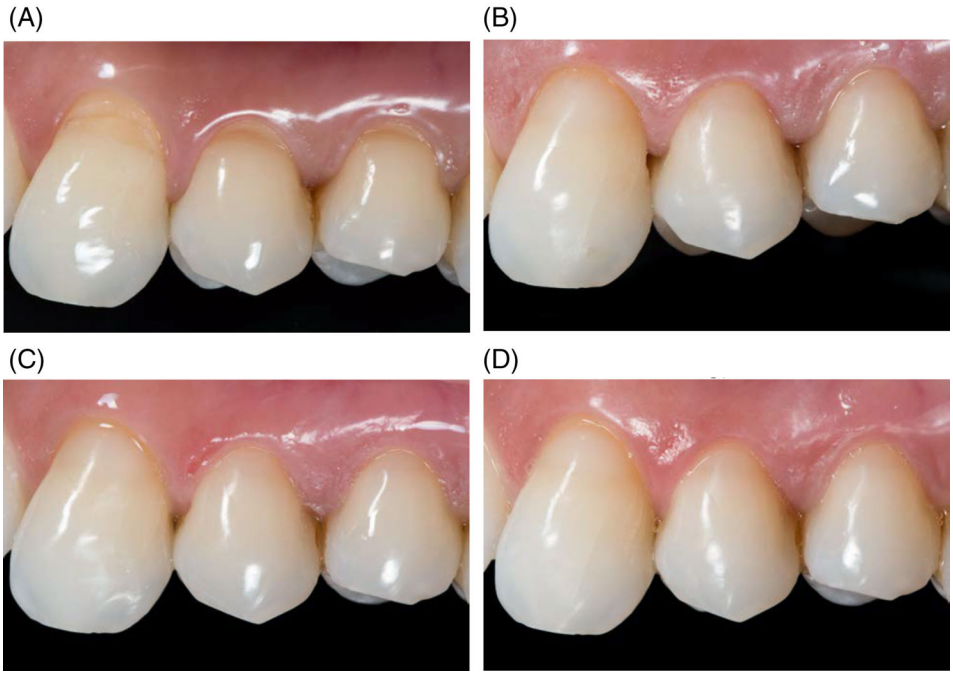

FIGURE 14 (A) Preoperative view of NCCLs on the maxillary left canine and premolars (restorative steps shown in Figure 5). The following universal composite resins were used: Omnichroma (Tokuyama Dental America, Inc.) for the maxillary left canine; Filtek Universal (3M Oral Care) for the maxillary left first premolar; and Essentia Universal (GC Europe) for the maxillary left second premolar (B) One-week postoperative view. The patient inquired if she could bleach her teeth (C). After 3 weeks of at-home whitening with a custom-made tray (D). Two weeks after finishing the bleaching regimen. All restorations blended in very well with the bleached tooth structure

four translucent shades. Harmonize is "the least" universal of the current universal composite resins, as it is available in 30 shades, including three different translucencies.

Omnichroma (Tokuyama Dental America, Inc.) was the first genuine universal composite resin. It is a single-shaded material that is indicated to match all 16 Vita Classical shades (VITA North America, Yorba Linda, CA). It also includes an opaque shade known as Blocker to use as dentin shade in translucent areas such as class IV restorations. The composition of Omnichroma consists of a blend of an identical 200 nm spherical particles (Figure 10(E)) of silicon dioxide (SiO_2) and zirconium dioxide (ZrO_2), 75%–80% filler by weight. It may be considered a microfilled composite resin, which makes it less radiopaque than other universal composite resins.[159] The particles are very similar to those of Estelite Quick and Estelite Sigma Quik (Tokuyama Dental America, Inc.), which we have also observed under the Field-Emission SEM (not shown). The ultra-morphological evaluation of Omnichroma disclosed clusters of prepolymerized particles ranging from 4 μm to 20 μm (Figure 10(E)).

Although the color adaptation coefficient of Omnichroma has been shown to be improved compared to composite resins of previous generations,[155] another study reported opposite results. Single-shaded materials such as Omnichroma may be unpredictable because they undergo a decrease in value and increase in chroma.[154] Overall, single- and group-shaded composite resins displayed worse shade matching ability than that of a conventional multishade composite material (Tetric Evo-Ceram, Ivoclar Vivadent), which may limit the use of single- and group-shaded composite resins to anterior teeth. Because the single-shade Omnichroma matches high-value shades better (Figure 13), a multishade composite resin may be better suited for esthetically challenging cases and teeth with low value, such as VITA C and D shades.[154] The better shade adaptation of Omnichroma in high-value cases was confirmed in another study, which showed that the shade difference between Omnichroma and the tooth structure decreased as the tooth becomes brighter. This composite resin demonstrated the ability to change shade as the surrounding tooth structure became brighter.[160] From our clinical experience with universal composites, the color adjustment properties of the materials are also noticeable even after bleaching the restored teeth (Figure 14).

The universal composites that we have used clinically are very easy to finish. Their polish retention seems to be excellent.[159] However, it has been reported that the color stability of a few of the current universal composite resins is not ideal.[161]

Another characteristic of a few universal composite resins is the exclusion of Bis-GMA from the respective organic matrix. Since the introduction of the first composite resin, the composition of the organic matrix of composite resins has not changed considerably. The first relevant exception was a silorane-based composite resin. However, its clinical behavior did not surpass that of proven Bis-GMA-based composite resins such as Filtek Z250 (3M Oral Care).[162,163] Recent developments stemming from the public opinion of BPA (bisphenol-A) toxicity have triggered changes in the composition of dental adhesives and composite resins by adding alternative resin monomers. According to the respective manufacturers' SDS documentation, the resin matrix formulations of Filtek Universal and Omnichroma do not contain Bis-GMA or bisphenol A ethoxylate dimethacrylate (Bis-EMA). Filtek Universal contains 1,12-dodecanediol dimethacrylate (DDDMA), urethane dimethacrylate (UDMA), an aromatic urethane dimethacrylate (AUDMA), and an addition-fragmentation monomer,[164] whereas Omnichroma contains triethylene glycol dimethacrylate (TEGDMA) and UDMA.

7 | CONCLUSION

Many new adhesive dental materials and clinical techniques introduced in Dentistry are supported by claims of novelty in addition to

greatly improved physical and clinical properties, without enough sound evidence. Concurrently, research on dental adhesive materials has aimed at making the clinical procedure more user-friendly by reducing the number of clinical steps. Although clinicians unquestionably prefer less complex and more versatile dental adhesives and composite resins, there must be a compromise between oversimplification of dental adhesive procedures and potential clinical outcomes.

1. Etching enamel with phosphoric acid is still the most reliable method to achieve durable and sealed restorations.
2. It is clear from the available independent in vitro and clinical data that simplified adhesives are subpar compared to adhesives that include an extra hydrophobic resin, that is, two-step SE and three-step E&R adhesives.
3. Universal adhesives are recommended by the respective manufacturers as E&R and SE adhesives in addition to selective enamel etching. The clinical evidence clearly indicates that the E&R and selective enamel etching are the two the recommended adhesion strategies that result in excellent clinical behavior.
4. Universal adhesives have the potential for chemical bonding to hydroxyapatite as long as dentin is not etched.
5. While leaving dentin moist is not recommended with universal adhesives, a vigorous application of at least 15–20 s and extended solvent evaporations times may optimize the behavior of these adhesives.
6. The use of universal adhesives as zirconia primers may need to be further investigated.
7. There is no definite clinical evidence to back popular adhesive techniques including the use of glutaraldehyde-based desensitizers and MMP inhibitors underneath adhesive restorations; and the use of a dentin adhesive to temporarily seal dentin prepared for indirect restorations.
8. Universal composite resins are easier to use than conventional composite resins, while being easy to handle and providing excellent esthetics. More clinical studies are needed to document their long-term use.

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The authors do not have any financial interest in the companies whose materials are included in this article

DATA AVAILABILITY STATEMENT

Author elects to not share data

ORCID

Jorge Perdigão https://orcid.org/0000-0003-1841-6365
Renato Q. Ramos https://orcid.org/0000-0002-2281-3462
Lucas Pizzolotto https://orcid.org/0000-0002-5217-1990

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