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Adhesion Science in Dentistry: A Comprehensive Review

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ABSTRACT:
Background: Adhesion plays a pivotal role in contemporary conservative and endodontic dentistry, facilitating minimally invasive procedures, enhanced aesthetics, and long-term restorative success.
Aim: This review highlights the fundamental principles of adhesion, challenges associated with bonding to dental substrates, and the clinical implications for durable and predictable outcomes.
Overview: Adhesion refers to the bonding interaction between restorative materials and tooth structures, particularly enamel and dentin. While enamel, composed mainly of hydroxyapatite, responds predictably to phosphoric acid etching, enabling micromechanical retention, dentin presents a more complex bonding environment due to its hydrated, heterogeneous nature and the presence of fluid-filled tubules. Root dentin further complicates adhesion due to anatomical variability and limited access for light curing. Factors such as polymerization shrinkage, mismatched thermal expansion, surface energy, and wetting dynamics significantly influence the quality and durability of the adhesive interface.
Conclusion: A comprehensive understanding of tooth substrate characteristics, adhesion mechanisms, and limitations of current adhesive systems is essential for improving clinical outcomes. Ongoing advancements in adhesive technology are critical to enhance the longevity and effectiveness of restorative procedures in conservative and endodontic practice.
Keywords: dental adhesion, enamel bonding, dentin bonding, resin composites, smear layer, hybrid layer, restorative dentistry

I. INTRODUCTION:

Adhesion in Dentistry refers to the process by which dental materials (such as composite resins, sealants, or cements) bond to tooth structures (enamel and dentin). It's a critical concept in modern restorative and preventive dentistry, allowing for minimally invasive techniques, better aesthetics, and long-lasting restorations.[1]

One major problem in restorative dentistry is the lack of proper union between the restorative material and the tooth surface. The gap at the tooth-restoration interface may create problems such as sensitivity and recurrent caries, etc. subsequently failure of the restoration. The processes of inventions over a period of time have led to the development of various techniques and modalities, which help in adhesion/bonding.[2]

Bonding or adhesion may be physical, mechanical or chemical and such restorations are known as bonded restorations or adhesive restorations. However, the continuous search to minimize the restoration – tooth interface has not been able to achieve complete success because of many inherent weaknesses of restorative materials like setting/polymerization expansion/contraction, different coefficients of thermal expansion and modulus of elasticity, etc.[2]

Bonding improves retention and stabilization of a restoration without excessive removal of sound tooth structure. Adhesive restorations are better able to transmit and distribute functional stresses across the bonding interface thereby reinforcing weakened tooth tissue. Bonding also facilitates repair and replacement of deteriorated fillings with little or no additional removal of tooth structure.[2]

Adhesive techniques have greatly expanded the horizon of aesthetic dentistry. Correction of shapes, positions, dimensions and shades of teeth is now possible with the adhesive restorative materials. Repair of fractured teeth can be carried out using the same fractured fragments thereby maintaining original aesthetics. Bonding successfully reduces the extent and amount of microleakage. Preventing the ingress of oral fluids and bacteria along the cavity-restoration interface reduces most clinical problems such as post-operative sensitivity, marginal staining and recurrent caries.[2]

Adhesion is the force or the intermolecular attraction that exists between molecules of two unlike substances when placed in intimate contact with each other. The substance added to produce the adhesion is known as the 'adhesive' and the material to which it applied is known as the 'adherend'.

An interface is present wherever adhesion exists. Adhesion can be seen between any two phases, e.g. solid, liquid or gas with the exception of two gases where an interface is not present. Most commonly, a solid is the adherend and liquid is the adhesive.[2]

II. HISTORY OF ADHESION:

After World War II, Dr. Oscar Hagger developed an acidic glycerophosphoric acid dimethacrylate that enabled resin adhesion to dentin (Hagger, 1951a, 1951b). This innovation led to the first clinically used adhesive product, Sevriton, marketed by the Amalgamated Dental Company.[3]

Buonocore's success with bonding resins to acid-etched enamel (1955) prompted attempts to apply the technique to dentin (Buonocore et al., 1956), but early efforts failed due to poor resin wettability and limited understanding of dentin as a bonding substrate. This led to the development of phosphate esters of methacrylic acid for dentin bonding, many of which were designed for application over the smear layer (e.g., Scotchbondby 3M).[4]

Bowen (1965) proposed that surface-active monomers could facilitate thebonding of resins to teeth.Asmussen and Munksgaard (1984–1988) developed a bonding system using 0.5 M EDTA to remove the smear layer, followed by application of Gluma—a primer containing 5% glutaraldehyde and 35% HEMA—to enhance dentin-resin adhesion.[5]

III. TYPES OF ADHESION:

Adhesion in dentistry is of three types and involves the following mechanisms:

A. Chemical adhesion: Is based on primary valence forces such as covalent, ionic or metallic bonds.

B. Physical adhesion: Relies on secondary valence forces. Such forces occur at molecular dipoles (van der Waals forces), the interaction of induced dipoles (dispersion forces) or electron clouds (hydrogen bonds).

C. Mechanical adhesion: Relies on penetration of one material into a different material at a microscopic level. The formation of hybridized dentin is regarded as a form of mechanical adhesion in the sense that resin polymers become entangled with collagen fibrils.[2]

For good adhesion, close contact must exist between the adhesive and the substrate. The surface tension of the adhesive must be lower than the surface energy of enamel and dentin.[5]

IV. FACTORS AFFECTING ADHESION:

The phenomenon of adhesion is dependent upon certain factors. The three factors, surface energy, wetting and contact angle are important determinants of adhesion. Not only do they individually control adhesion but are also closely interrelated.

A. Contact angle:

Contact angle is an important factor in controlling adhesion. It is a measure of wettability and is the angle formed by the adhesive with the adherend at the interface. Smaller the contact angle greater is the wettability of the adhesive.[2]

A low viscosity of the adhesive is imperative for better flow and bond formation. However, micro irregularities and crevices still remain a limiting factor in close bondformation because air may be entrapped at the base of the pockets and serve asdiscontinuities in the adhesive joint. Under continual thermal and mechanicalloading, stress concentration occurs around these sites and a break could beinitiated adjacent to the void, which could then propagate unhindered.[2]

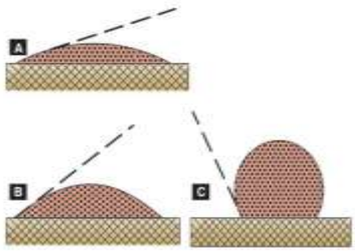

Figure 1: Degree of contact angle influences the wetting of surface; (A) when contact angle is small, wettability of the adhesive is better; (B) and (C) When contact angle is large, liquid does not wet the surface completely.

B. Wetting:

It is the ability of a liquid to spread and adhere to a solid surface. This can be seen when two dry glass slides don't stick due to microscopic surface irregularities, which limit actual contact. However, adding a thin film of water allows it to fill gaps and bond to both surfaces, making the slides difficult to separate. This increased adhesion occurs because the liquid wets the surface, creating a stronger interaction.[2]

The wetting ability of a liquid adhesive depends on the surface energy and cleanliness of the adherend. Higher surface energy improves wetting, which is why metals wet well. In contrast, materials like Teflon have very low surface energy and resist wetting. Surface contamination also reduces adhesive wetting.[2]

C. Surface Energy:

Atoms at a solid's surface have higher energy than those inside due to unequal atomic surroundings, leading to surface tension. This surface energy causes materials like gold, silver, and platinum to attract molecules such as oxygen. Gold binds oxygen via physical (secondary) forces, while silver forms chemical bonds (e.g., silver oxide).[2]

Adhesion can occur through physical or chemical forces. Physical forces act at larger distances, while chemical forces become effective as molecules get closer—typically within 3.0–4.0 nm. Hard solids have surface energies between 500–5000 ergs/cm²; the harder the surface, the greater the surface energy and adhesive potential.[2]

V. TYPES OF ADHESION:

A. Enamel Adhesion:

i. Composition of Enamel:

The inorganic content of mature enamel is 95% to 98% by weight (wt %) and 86% by volume (vol%), the primary component being hydroxyapatite. The remaining consists of water (4 wt% and 12 vol %) and organic material (1 to 2 wt% and 2 vol %).

The main inorganic component exists as submicron crystallites arranged in a three-dimensional, oriented pattern, forming microscopic structural units known as rods or prisms. The natural enamel surface is smooth, with rod ends exposed in a keyhole pattern. Operative procedures expose rods in various planes—tangential, oblique, or longitudinal. Enamel is structurally uniform, except for a surface layer of aprismatic enamel, where crystallites are parallel and perpendicular to the surface.[6]

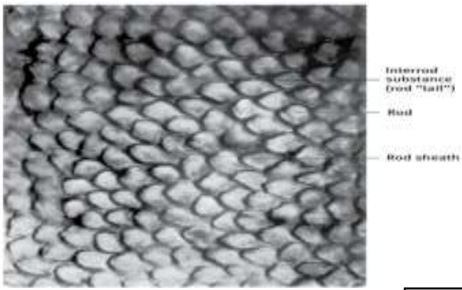

Figure 2: Decalcified section of enamel of human tooth germ. Rods cut transversely have appearance of fish scales.

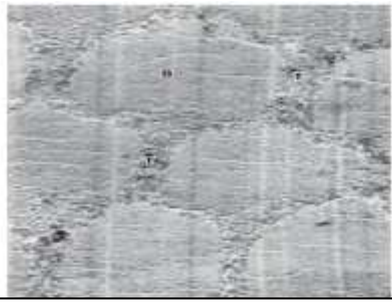

Figure 3: Electron micrograph of mature human enamel shows keyhole-shaped rods with differing crystal orientation in the body (B) and tail (T).

Inspired by the industrial use of 85% phosphoric acid to improve adhesion on metals, Buonocore introduced acid etching of enamel to seal pits and fissures. His technique sparked ongoing research into achieving strong, durable resin-to-tooth adhesion.[7]

Acid etching roughens the smooth enamel surface and increases its surface free energy. When a fluid resin is applied, it penetrates the irregularities through capillary action. As the monomers polymerize, the resin forms microscopic tags that interlock with the enamel. This micro-mechanical retention is the key to resin-enamel adhesion. [5]

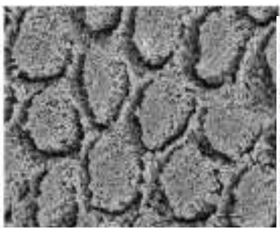

Figure 4: Scanning electron micrograph of enamel etched with 35% phosphoric acid for 15 seconds.

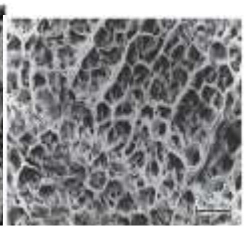

Figure 5: Replica of enamel etched with 35% phosphoric acid. Enamel wasdissolved completely in 6N hydrogen chloride for 24 hours.

Enamel etching results in three different micromorphologic patterns.

The Type I pattern involves the dissolution of prism cores without dissolution of prism peripheries.

The Type II etching pattern is the opposite of type I: The peripheral enamel is dissolved, but the cores are left intact.

Type III etching is less distinct than the other two patterns. It includes areas that resemble the other patterns and areas whose topography is not related to enamel prism morphology.[5]

Figure 6: SE micrograph of enamel etched with 35% phosphoric acid for 15 seconds, denoting a type I etching pattern in A. Type III etching pattern in B.

Following Buonocore's use of 85% phosphoric acid, researchers have tested various concentrations for enamel etching. Gwinnett and Buonocore recommended using lower concentrations to avoid precipitates that hinder adhesion. For example, 50% phosphoric acid used for 60 seconds forms a monocalcium phosphate monohydrate precipitate thatcan be rinsed off. However, acids below 27% may form dicalcium phosphate monohydrate, which is harder to remove and may impair bonding.[5]

Silverstone et al. found that 30–40% phosphoric acid produces optimal retentive etch patterns. Concentrations above 40% dissolve less calcium and yield less defined etch patterns. As a result, most modern phosphoric acid gels are formulated in the 30–40% range, though some lower concentrations have shown comparable adhesion.[5]

Enamel adhesion using phosphoric acid etching typically yields shear bond strengths over 20 MPa (ranging from 1–145 MPa), which is sufficient for retention and for preventing microleakage atenamel margins. In addition, adhesive restorations reinforce prepared teeth by supporting cusps, enamel, and dentin, reducing the risk of fracture.[5]

B. Dentin Adhesion:

I. Composition of Dentin:

Unlike enamel, dentin is heterogeneous and contains more water (12%) and organic material (18%), mainly type I collagen, with only 70% hydroxyapatite by weight. By volume, it consists of 50% inorganic, 25% organic, and 25% water. These components are unevenly distributed between intertubular and peritubular dentin, contributing to its complex structure.[6]

Dentin is a vital, dynamic, and highly permeable tissue due to the presence of numerous dentinal tubules that radiate from the pulp to the dentinoenamel junction (DEJ). These tubules contain odontoblastic processes and directly connect to the pulp.[6]

Tubule diameter decreases from 2.5 µm near the pulp to 0.8 µm at the DEJ, and density drops from 45,000/mm² to 20,000/mm², averaging around 30,000/mm² in mid-dentin—making tubule lumina a significant part of dentin volume.[6]

Each tubule is surrounded by hypermineralized peritubular dentin, while the surrounding intertubular dentin is less mineralized and richer in collagen fibrils. The tubules also contain dentinal fluid, a membrane called the lamina limitans, and intratubular collagen fibrils of uncertain origin and function.[6]

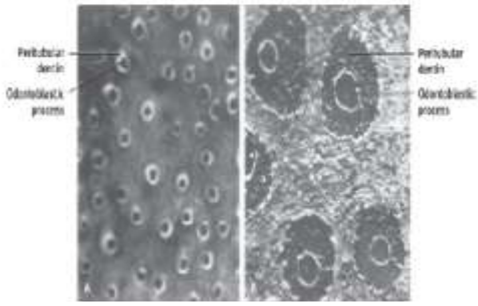

Figure 7: Microscopic appearance of peritubular dentin. (A) Under mineralized ground section showing increased mineral density in peritubular zone. (B) Electron micrograph of demineralized section of dentin showing loss of mineral in peritubular zone.

Acid conditioners are used to remove the smear layer and demineralized superficial dentin (about 3–6 µm) to expose a microporous collagen scaffold for resin infiltration. However, on intertubular dentin, acid exposure can cause denaturation and collapse of residual collagen within the smear layer. This "collagen smear layer" is acid-insoluble and may reduce resin permeability.At tubule orifices, peritubular dentin is often completely dissolved, creating a funnel-shaped structure that exposes collagen fibrils, which serve as additional retention sites.After conditioning, a moist dentin surface should be maintained (the wet bonding technique) to prevent collagen collapse and enhance resin wetting and penetration.[2]

Acid etching of dentin, followed by rinsing, results in the removal of the smear layer and exposure of collagen fibers, as first described by Nakabayashi et al(1982). In etch-and-rinse adhesives, orthophosphoric acid both removes the smear layer and demineralizes 3–5 µm of surface dentin, exposing a collagen mesh in the intertubular and peritubular dentin, which provides an ideal surface for micromechanical bonding.[8]

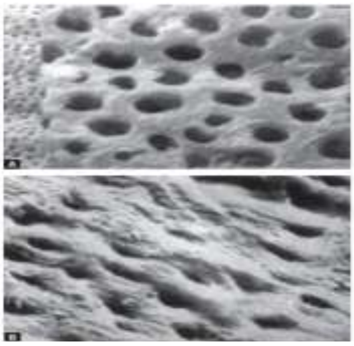

Figure 8: SEM images of etched dentin surface: (A) After phosphoric acid etching (B) After conditioning with a combination etchant of 10% citric acid and 20% calcium chloride.

Proper impregnation of the demineralized dentin is essential for achieving strong and durable resin bonds. Over-drying the etched cavity can cause collapse of the collagen network, reducing interfibrillar spaces and hindering adhesive infiltration. Effective penetration of the adhesive into exposed collagen fibers results in the formation of the hybrid layer or resin-infiltrated dentin (Nakabayashi et al., 1982).[8]

Ideally, the adhesive resin should fully infiltrate the demineralized dentin. Incomplete impregnation leads to a porous, less stable structure known as a 'hybridoid' layer. Studies show that the commonly used 35–37% orthophosphoric acid for 15 seconds is sufficient; prolonged etching increases demineralization without improving bond strength, resulting in a weak hybrid layer. Proper rinsing is critical to eliminate the gel and its silica content, which can interfere with bonding. Controlled drying—avoiding over-drying—is essential before applying the primer and bonding agent, either separately or as a combined solution.[8]

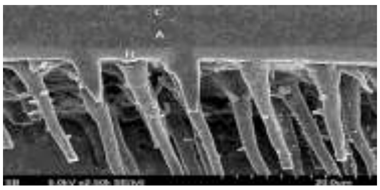

Figure 9: Hybrid layer

II. Challenges in dentin adhesion:
i. Substrate:

Bonding to enamel is a relatively simple process, without major technical requirements or difficulties. Bonding to dentin presents a much greater challenge. Several factors account for this difference between enamel and dentin bonding.[7]

Dentin is a naturally hydrated tissue containing numerous fluid-filled tubules that extend from the pulp to the dentino-enamel junction (DEJ), driven by constant pulpal pressure (25–30 mm Hg or 34–40 cm H_2O). These tubules house odontoblastic processes and structures like the lamina limitans, which narrow the tubule lumen. Tubule density and diameter vary with depth: near the pulp, there are approximately 45,000 tubules/mm² occupying 22% of the surface area, with diameters around 2.37 µm, while near the DEJ, density drops to about 20,000/mm², occupying just 1% of the surface with diameters around 0.63 µm.[7]

Whenever tooth structure is prepared with a bur or other instrument, residual organic and inorganic components form a "smear layer" of debris on the surface. The smear layer fills the orifices of dentinal tubules, forming "smear plugs", and decreases dentin permeability by 86%. The composition of the smear layer is basically hydroxyapatite and altered denatured collagen.[5] Submicron porosity of the smear layer still allows for diffusion of dentinal fluid. The removal of the smear layer and smear plugs with acidic solutions results in an increase of the fluid flow onto the exposed dentin surface. This fluid can interfere with adhesion because hydrophobic resins do not adhere to hydrophilic substrates even if resin tags are formed in the dentin tubules.[5]

Figure 10: SEM image of a smear plug (SP) blocking a dentinal tubule.

Dentin permeability is influenced by multiple factors, including pulpal pressure—which can be reduced by vasoconstrictors in local anesthetics—as well as tubule radius and length, dentin fluid viscosity, pressure gradients, molecular size of dissolved substances, and their clearance by pulpal blood flow. These variables make dentin a dynamic and challenging substrate for bonding.[7]

ii. Stresses at the Resin–Dentin Interface:

Composites shrink during polymerization, generating stresses within the material that depend on the restoration's configuration. When bonded to only one surface (e.g., a direct facial veneer), stresses can be relieved by flow from the unbonded surface. However, in a typical occlusal preparation where composite bonds to five surfaces—mesial, distal, buccal, lingual, and pulpal—only the occlusal surface remains free, resulting in a high configuration factor (C-factor) of 5.[7]This limits stress relief, leading to internal bond disruption and marginal gaps, which can increase microleakage and postoperative sensitivity. [7]

Besides the C-factor, polymerization shrinkage stress is influenced by factors such as the polymerization rate, degree of conversion, composite stiffness and its development during curing, filler type and volume, monomer composition, insertion technique, and composite opacity.[7]

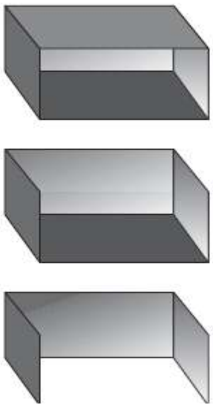

Fig 11: Schematic representation of the configuration (c) factor.

C. Root Dentin Adhesion:

Root dentin adhesion strategies include etch-and-rinse (ER) adhesives, which require phosphoric acid etching and rinsing, and self-etch (SE) adhesives. Due to limited light access in the middle and apical root thirds, dual-cure resin cements are typically preferred. Alternatively, self-adhesive resin cements can be used without a separate adhesive system.[9]

Although bonding protocols for root dentin generally follow the same steps as for coronal dentin, an in vitro study by Bouillaguet et al. (2003) found that bond strengths are lower when posts are cemented inside the root canal compared to flat radicular dentin surfaces. This highlights several clinical challenges in root canal bonding that require careful attention to reduce bonding failures.[9]

I. Challengesin Root Dentin Adhesion:

i. Intraradicular Anatomy:

Knowledge of root canal anatomy of the different teeth is essential in order to minimize the risk of complications such as loss of axial alignment or perforations when preparing the post space.[9]

ii. Root Anatomy:

The root canal of anterior maxillary teeth is typically oval-shaped in the cervical third and becomes more circular toward the apical third. In anterior mandibular teeth, about 40% have two canals, usually circular in cross-section. If only one canal is present, it tends to be round but broad buccolingually and narrow mesiodistally, increasing the risk of perforation. Therefore, post space preparation should be limited to cases with significant crown loss.[9]

Canines are usually single-rooted with a straight canal. Although there is a higher risk of perforation near the thin apical third during endodontic treatment, this does not affect post placement since the post space does not extend that far. [9]

The first maxillary premolar has two roots in about 62% of cases, typically with two canals, whereas the second maxillary premolar is usually single-rooted with one broad buccopalatal canal. Lower premolars are generally single-rooted with canals that are wide buccolingually. [9]

In molars requiring post placement, the post space should be prepared in the widest, straightest canal—typically the palatal canal in maxillary molars and the distal canal in mandibular molars.[9]

iii. The Dentin Substrate:

A common clinical question is whether intraradicular dentin differs in composition from coronal dentin. According to a literature review by Schwartz (2006), although few studies have explored this, available evidence suggests only minor differences between the two.[9,10]

Like coronal dentin, intraradicular dentin contains tubules extending from the pulp to the cementum, surrounded by peritubular and intertubular dentin. However, the number of tubules decreases significantly toward the apical region, causing notable variation in the ratio of peritubular to intertubular dentin from the coronal to the apical third (Ferrari et al., 2000; Mjör et al., 2001).[11,12]

In the apical third of the root, dentinal tubules are fewer (Ferrari et al., 2000; Mjör et al., 2001; Mannocci et al., 2004),[11,12,13] and the dentin may be irregular or even devoid of tubules. When tubules are present, they are often sclerotic and filled with mineral deposits similar to peritubular dentin, as seen in transparent dentin (Paqué et al., 2006).[14]Despite these variations, the minor differences between coronal and intraradicular dentin do not appear to hinder bonding to radicular dentin.[9]

iv. Incompatibility between Adhesives and Cements:

Currently, various adhesive systems are available, including full versions such as 3-step etch-and-rinse (ER) and 2-step self-etch (SE), as well as simplified versions like 2-step ER and 1-step SE. Simplified adhesives are favored in clinical practice due to their ease of use. However, studies have shown that these simplified systems are incompatible with chemically and dual-cured resin-based composites (Sanares et al., 2001; Tay et al., 2003a, 2004).[15,16]In contrast, full adhesive systems do not show such incompatibility, likely due to the presence of a separate hydrophobic resin layer.[9]

Two primary mechanisms explain this incompatibility: chemical and physical. Chemical incompatibility arises from adverse interactions between residual acidic monomers in the adhesive and tertiary amine catalysts in the composite, which can hinder polymerization (Sanares et al., 2001).[15]Though initially described for dual- or self-cure composites, this has also been noted with light-cure materials under delayed activation. Physical incompatibility stems from high water permeability and the presence of an oxygen-inhibited layer that draws moisture from dentin. This creates fluid-filled zones (or "water trees") within the adhesive layer, disrupting the bond interface (Tay et al., 2003a; Tay & Pashley, 2003).[9]

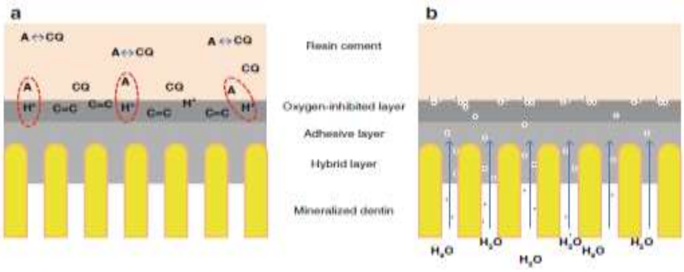

Figure 12: A schematic illustrates two main incompatibilities between acidic adhesives and resin cements: (a) chemical—in which protons from acidic monomers compete with camphorquinone (CQ) for interaction with tertiary amines, reducing free radical formation and hindering polymerization; and (b) physical—where water from underlying dentin passes through the permeable adhesive layer and accumulates at the interface, compromising the bond with the resin cement.

Additionally, light curing in root canals is compromised due to limited light penetration, especially in apical regions, reducing bond strength (Goracci et al., 2008; Wu et al., 2009).[17]Therefore, clinicians should avoid simplified adhesives with dual-cure materials or apply an additional hydrophobic layer to enhance bonding.[9]

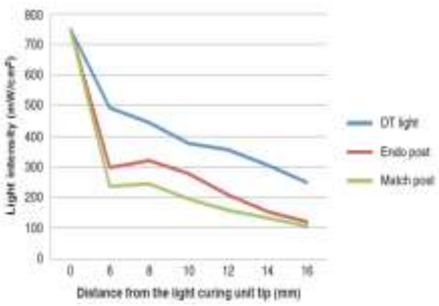

Figure 13: Light attenuation was evaluated in three fiberglass post systems, with light intensity at the incisal (0 mm) region set at 100%.

v. Operator Experience:

Bonding fiber posts in root canals is technically challenging and highly dependent on operator experience. Less experienced clinicians achieved lower bond strengths when using etch-and-rinse adhesives, whether full or simplified. However, operator influence was minimal when self-adhesive cements were used.[9]

Reduced bond strength with etch-and-rinse adhesives in less experienced clinicians likely results from improper technique and limited knowledge of root dentin bonding factors. Self-adhesive cements, requiring fewer steps and no moisture control, are less technique-sensitive. Simplifying bonding protocols can improve consistency and bond strength for less experienced operators. [9]

vi. Cavity Configuration (C-Factor):

During polymerization of methacrylate-based materials, resin monomers move closer together, reducing intermolecular spaces and causing shrinkage stress. This stress can cause debonding from root dentin, leading clinically to reduced post retention, gap formation, and increased risk of bacterial leakage at the adhesive interface. [9]

Post spaces have much higher C-factors (>200) than coronal restorations (1–5), increasing shrinkage stress risk. Reducing resin cement thickness in the root canal—using direct or indirect anatomic posts—helps minimize polymerization shrinkage, enhance bond strength, and decrease gap formation at the dentin-cement interface. [9]

Reducing resin cement volume is difficult because circular fiber posts often don't fit oval or over-instrumented canals. Relining prefabricated posts with composite resin improves adaptation to canal shape, minimizing bonding interface problems. [9]

VI. CONCLUSION:

Adhesion in dentistry is a critical factor for the long-term success of restorative and endodontic treatments. Effective bonding enhances the durability, retention, and seal of dental materials, preventing microleakage and secondary caries. However, achieving reliable adhesion requires careful consideration of material properties, technique sensitivity, and operator skill. Advances in adhesive systems and techniques continue to improve clinical outcomes by simplifying procedures and reducing technique-related errors. Continued research and proper clinical application are essential to optimize adhesion and ensure the longevity of dental restorations.

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