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Effect of Sodium Hypochlorite–Induced Dentin Deproteinization on the Push-Out Bond Strength of a Self-Adhesive Resin Cement to Root Dentin: An In Vitro Study

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Abstract

Background

The success of fiber post restorations depends on effective bonding between resin cement and root dentin. Sodium hypochlorite (NaOCl) dentin deproteinization has been suggested as a method to improve resin–dentin interaction; however, the effects of concentration and application time remain unclear.

Objectives

This in vitro study investigated the effect of different NaOCl concentrations and application times on the push-out bond strength of a self-adhesive resin cement to root dentin.

Materials and Methods

Fifty extracted human single-rooted premolars were assigned to five groups (n = 10): control, 5% NaOCl for 2 minutes, 5% NaOCl for 10 minutes, 20% NaOCl for 2 minutes, and 20% NaOCl for 10 minutes. After root canal treatment and fiber post cementation with a dual-cure self-adhesive resin cement, push-out bond strength was evaluated. Data were analyzed using one-way ANOVA and Dunnett's post hoc test ($\alpha = 0.05$).

Results

NaOCl deproteinization significantly increased push-out bond strength compared with the control group ($P < 0.05$). Increasing NaOCl concentration resulted in higher bond strength, whereas extending the application time had a limited effect. The highest bond strength was observed in the 20% NaOCl groups.

Conclusion

Sodium hypochlorite-induced dentin deproteinization improved the bonding performance of self-adhesive resin cement to root dentin. NaOCl concentration may have a greater influence on bond strength than application time. Further studies are needed to confirm the clinical applicability of this approach.

Introduction

Endodontically treated teeth frequently present with considerable loss of coronal and radicular structure resulting from caries progression, previous restorative interventions, trauma, and the endodontic treatment process itself. This structural deterioration may compromise the biomechanical integrity of the remaining tooth substrate, increasing the risk of fracture and negatively affecting long-term clinical outcomes when an appropriate restorative approach is not selected.[1] Therefore, establishing a predictable restorative strategy is essential to restore function, preserve remaining tooth structure, and enhance the longevity of endodontically treated teeth.[2]

In cases where adequate residual coronal structure is available, direct adhesive restorations may provide acceptable clinical performance. However, severely weakened teeth often require the use of intracanal posts to improve core retention and provide adequate support for the final restoration.[2] Among the different post systems currently available, fiber-reinforced composite posts have gained widespread acceptance due to their favorable biomechanical behavior. Their elastic modulus is similar to that of dentin, allowing a more homogeneous transmission of occlusal stresses along the root structure and potentially reducing the occurrence of unfavorable root fractures.[3–4] Moreover, fiber posts offer additional clinical advantages, including superior esthetic outcomes, good biocompatibility, and compatibility with contemporary adhesive techniques, particularly when combined with ceramic restorations.[4]

Despite the favorable characteristics of fiber-reinforced posts, loss of adhesion at the post–cement–dentin interface remains a primary factor associated with restoration failure.[5] The long-term stability of fiber post restorations is largely dependent on the effectiveness and durability of the bond established between resin cement and intraradicular dentin. Consequently, strategies aimed at improving dentin bonding performance continue to represent an important area of investigation within adhesive and restorative dentistry.[5,6]

Conventional adhesive resin cements typically involve multiple clinical steps, including phosphoric acid etching, application of primers, and placement of adhesive systems. Although these procedures can provide effective bonding when properly performed, their clinical success is highly dependent on operator skill and strict adherence to the recommended protocols. Variations in dentin moisture control, incomplete infiltration of resin monomers into the demineralized collagen matrix, or excessive removal of dentinal water may negatively influence hybrid layer formation and ultimately compromise bond strength.[7]

To overcome some of the limitations associated with multi-step adhesive procedures, self-adhesive resin cements were developed as simplified luting materials that combine conditioning and cementation steps. These materials contain acidic functional monomers that are capable of partially demineralizing the dentin surface while simultaneously promoting resin infiltration, thereby eliminating the need for separate etching and bonding procedures.[8] Their simplified application protocol, reduced technique sensitivity, and clinical convenience have contributed to their increasing use in restorative dentistry.

Nevertheless, despite these advantages, the bonding effectiveness of self-adhesive resin cements to dentin remains a subject of debate. Several in vitro studies have reported that the interaction between these materials and dentin is relatively limited, characterized by insufficient smear layer dissolution, shallow demineralization, and restricted penetration into the dentinal substrate. As a result, lower bond strength values compared with conventional adhesive approaches have been reported in some investigations.[8] Conversely, other studies have demonstrated comparable bonding performance, suggesting that the clinical and laboratory behavior of self-adhesive resin cements may be influenced by multiple factors, including dentin characteristics, material composition, and surface treatment

protocols.[8,9] These inconsistent findings highlight the need for additional approaches to optimize the root dentin surface and enhance the adhesive performance of self-adhesive resin cements.

The smear layer represents one of the critical factors affecting resin–dentin adhesion. This amorphous layer produced during instrumentation may act as a physical barrier that limits resin penetration and neutralizes the acidic components of adhesive materials, thereby reducing their ability to interact effectively with the underlying dentin substrate.[10] Although phosphoric acid remains an effective agent for smear layer removal, excessive acid conditioning may result in extensive demineralization and exposure of unsupported collagen fibrils. Such alterations may interfere with adequate resin infiltration and negatively affect the mechanical stability of the adhesive interface.[10]

An alternative strategy for modifying the dentin substrate involves deproteinization using sodium hypochlorite. Dentin is primarily composed of a mineralized matrix containing a substantial organic component, mainly type I collagen. Selective removal of this collagenous phase may alter the characteristics of the dentin surface by reducing its hydrophilic nature, enhancing the interaction between resin materials and the inorganic substrate, and potentially improving resin penetration and micromechanical retention. In addition, the elimination of collagen fibrils may decrease the susceptibility of the adhesive interface to hydrolytic degradation, thereby contributing to improved long-term bond stability.[11] However, previous investigations evaluating the effect of sodium hypochlorite treatment on resin–dentin adhesion have yielded inconsistent outcomes, with reports describing both improvements and reductions in bond strength depending on factors such as sodium hypochlorite concentration, application duration, and adhesive system characteristics.[11]

Considering the ongoing challenges associated with achieving reliable adhesion to intraradicular dentin, further investigation into surface modification protocols that may enhance the performance of self-adhesive resin cements is warranted. In particular, determining the optimal concentration and application time of sodium hypochlorite treatment may provide valuable insights into improving the predictability of fiber post cementation procedures.

Therefore, the present in vitro study aimed to evaluate the effect of different sodium hypochlorite concentrations and application durations on the push-out bond strength of a self-adhesive resin cement to root dentin. The null hypothesis tested was that sodium hypochlorite concentration and application time would have no significant effect on the push-out bond strength of the self-adhesive resin cement.

Materials and Methods

Study design and ethical considerations

This in vitro experimental study was designed and conducted in accordance with the ethical principles outlined in the Declaration of Helsinki regarding research involving human-derived biological specimens. The study protocol was reviewed and approved by the Ethics Committee of AJA University of Medical Sciences (Approval No. IR.AJAUMS.REC.1399.94).

Sample size calculation

The sample size was estimated based on a power analysis using previously reported data from studies investigating the push-out bond strength of fiber posts luted with self-adhesive resin cements. Considering the expected differences among experimental groups and to ensure adequate statistical power, a total of 50 extracted human teeth were included in the present investigation.

Tooth selection and specimen storage

Fifty freshly extracted human single-rooted premolars with fully developed roots were obtained from the Department of Oral Surgery, Faculty of Dentistry. The teeth had been extracted for periodontal or orthodontic indications unrelated to the objectives of this study. Written informed consent was obtained from all participants prior to tooth collection.

Immediately after extraction, all specimens were carefully cleaned to remove residual periodontal tissues and calculus using hand scalers. The teeth were then disinfected in a 0.5% chloramine solution and stored in distilled water at 4°C for no longer than one month until further processing.

Teeth were selected according to the following inclusion criteria: single straight root canals, intact external root surfaces, complete apical development, absence of anatomical abnormalities, and a minimum root length of 14 mm. Teeth presenting with root caries, cracks or fractures, previous endodontic treatment, internal or external root resorption, calcified canals, or other structural abnormalities were excluded from the study.

Experimental grouping

The selected specimens were randomly assigned to five experimental groups (n = 10) according to the concentration and application time of sodium hypochlorite used for dentin deproteinization:

- **Group 1 (Control)**: No dentin deproteinization treatment.
- **Group 2**: Treatment with 5% sodium hypochlorite for 2 minutes.
- **Group 3**: Treatment with 5% sodium hypochlorite for 10 minutes.
- **Group 4**: Treatment with 20% sodium hypochlorite for 2 minutes.
- **Group 5**: Treatment with 20% sodium hypochlorite for 10 minutes.

Random allocation was performed using a computer-generated randomization sequence to ensure unbiased distribution of specimens among the experimental groups.

Root canal preparation and obturation

The crowns of all teeth were removed perpendicular to the long axis of the roots using a water-cooled diamond disc to obtain standardized root specimens with a length of 14 mm measured from the cementoenamel junction.

Endodontic access cavities were prepared using a #4 round carbide bur under continuous water irrigation. The working length was determined by inserting a #10 K-file into the canal until the file tip was visible at the apical foramen, followed by subtracting 1 mm from this measurement.

Root canal instrumentation was performed using the ProTaper rotary system (Dentsply Maillefer, Ballaigues, Switzerland) up to size F3, following the manufacturer's recommended protocol. During instrumentation, a standardized irrigation regimen was applied. The canals were irrigated with 5 mL of 5.25% sodium hypochlorite after each instrument, followed by application of 5 mL of 17% EDTA for 2 minutes to facilitate smear layer removal. A final irrigation with 5 mL of 5.25% sodium hypochlorite was subsequently performed.[12]

After completion of canal preparation, the root canals were dried using sterile paper points and obturated with gutta-percha and AH Plus resin-based sealer using the lateral condensation technique. The adequacy of the root fillings was confirmed by radiographic examination. Following complete polymerization of the sealer, standardized post spaces were prepared to a depth of 10 mm using the corresponding drill provided for the size 2 Whitepost FGM fiber post system (FGM, Joinville, SC, Brazil).[13]

Dentin deproteinization protocol

Following preparation of the post spaces, dentin deproteinization was performed according to the assigned experimental protocol. Sodium hypochlorite solutions at concentrations of 5% and 20% were introduced into the post spaces using an irrigation cannula and maintained for either 2 or 10 minutes, depending on the experimental group.

After the designated treatment period, the post spaces were thoroughly rinsed with distilled water for 10 seconds to remove residual sodium hypochlorite. The canals were subsequently dried using sterile paper points and gentle application of oil-free compressed air.[14]

Fiber post surface treatment and cementation

Prior to cementation, the fiber posts were cleaned with alcohol to remove any surface contaminants and subsequently treated with a silane coupling agent (RelyX Ceramic Primer, 3M ESPE, St. Paul, MN, USA) according to the manufacturer's instructions to enhance the chemical interaction between the post surface and resin cement.

A dual-cure self-adhesive resin cement was applied directly into the prepared post space using a Lentulo spiral to ensure adequate distribution of the cement and minimize the possibility of void formation within the canal. The size 2 Whitepost FGM fiber posts were then carefully inserted into the post spaces using

gentle finger pressure until the desired position was achieved. Excess resin cement was removed, and light activation was performed for 40 seconds using an LED curing unit with an irradiance of approximately 900 mW/cm².

Following fiber post cementation, all specimens were embedded in self-curing acrylic resin blocks using cylindrical molds to facilitate subsequent mechanical testing. The specimens were then stored at 37°C under 100% relative humidity conditions for 24 hours to allow complete setting of the resin cement before bond strength evaluation.

Specimen sectioning

Each root specimen was sectioned perpendicular to its long axis using a low-speed precision diamond saw under continuous water irrigation to prevent excessive heat generation during cutting. Two standardized slices, each approximately 4 mm in thickness, were obtained from each specimen, representing the coronal and apical regions of the post space.[15]

Push-out bond strength evaluation

The push-out bond strength of the fiber posts was assessed using a universal testing machine (Instron® 5965, Instron Corp., High Wycombe, UK). A compressive load was applied in an apical-to-coronal direction at a crosshead speed of 2.5 mm/min until debonding occurred.

The maximum load required to dislodge the post segment was automatically recorded by the testing software and expressed in Newtons (N). Bond strength values were subsequently calculated in megapascals (MPa) by dividing the recorded load by the bonded surface area of each specimen. The occurrence of bond failure was determined by a sudden reduction in the load–displacement curve obtained during mechanical testing.[16]

Statistical analysis

All statistical analyses were performed using SPSS software (version 23.0; IBM Corp., Armonk, NY, USA). The distribution of data was assessed for normality using both the Kolmogorov–Smirnov and Shapiro–Wilk tests. Descriptive data were presented as mean values with standard deviations (mean ± SD).

Differences in push-out bond strength values among the experimental groups were analyzed using one-way analysis of variance (ANOVA). When significant differences were detected, Dunnett's post hoc test was applied for multiple comparisons with the control group. The level of statistical significance was set at $P < 0.05$.

Results

A total of 50 root specimens were included in the study, with 10 specimens assigned to each experimental group.

Push-out bond strength of coronal root dentin

The mean push-out bond strength values of the self-adhesive resin cement to coronal root dentin are presented in Table 1. One-way ANOVA demonstrated a statistically significant difference among the five experimental groups ($P < 0.05$).

The control group showed the lowest mean bond strength value (9.00 ± 1.30 MPa). All sodium hypochlorite-treated groups exhibited higher bond strength values compared with the control group. The highest mean bond strength was recorded in specimens treated with 20% sodium hypochlorite for 10 minutes (14.20 ± 1.75 MPa), followed by the group treated with 20% sodium hypochlorite for 2 minutes (14.02 ± 1.36 MPa).

The groups treated with 5% sodium hypochlorite showed mean bond strength values of 12.30 ± 1.57 MPa and 12.16 ± 1.57 MPa after application times of 10 and 2 minutes, respectively.

The results indicated that increasing the sodium hypochlorite concentration from 5% to 20% was associated with higher push-out bond strength values in coronal dentin. However, extending the application time from 2 to 10 minutes resulted in only a slight increase in bond strength.

Table 1
Mean push-out bond strength (MPa) of the self-adhesive resin cement to coronal root dentin.

Group	n	Mean ± SD (MPa)
Control	10	9.00 ± 1.30
5% NaOCl – 2 min	10	12.16 ± 1.57
5% NaOCl – 10 min	10	12.30 ± 1.57
20% NaOCl – 2 min	10	14.02 ± 1.36
20% NaOCl – 10 min	10	14.20 ± 1.75

Push-out bond strength of apical root dentin

The mean push-out bond strength values obtained for apical root dentin are summarized in Table 2. Statistical analysis revealed significant differences among the five experimental groups ($P < 0.05$).

The control group demonstrated the lowest bond strength value (7.80 ± 1.30 MPa). All groups receiving sodium hypochlorite treatment showed higher bond strength values compared with the untreated control group. The highest mean value was observed in the 20% sodium hypochlorite treatment group applied for 10 minutes (12.76 ± 1.76 MPa), followed by the 20% sodium hypochlorite treatment for 2 minutes (12.42 ± 1.33 MPa).

For the 5% sodium hypochlorite groups, mean bond strength values were 10.95 ± 3.04 MPa and 10.56 ± 1.53 MPa after application times of 10 and 2 minutes, respectively.

Similar to the coronal dentin findings, higher sodium hypochlorite concentrations were associated with increased push-out bond strength values in apical dentin. In contrast, increasing the application time from 2 to 10 minutes resulted in only a limited change in bond strength.

Table 2
Mean push-out bond strength (MPa) of the self-adhesive resin cement to apical root dentin.

Group	n	Mean ± SD (MPa)
Control	10	7.80 ± 1.30
5% NaOCl – 2 min	10	10.56 ± 1.53
5% NaOCl – 10 min	10	10.95 ± 3.04
20% NaOCl – 2 min	10	12.42 ± 1.33
20% NaOCl – 10 min	10	12.76 ± 1.76

Discussion

Fiber-reinforced composite posts are currently considered a reliable restorative option for endodontically treated teeth because their mechanical properties are closely related to those of natural dentin. Their favorable elastic modulus allows a more homogeneous distribution of functional stresses along the root structure and may reduce the risk of unfavorable root fractures.[1–3] However, the long-term success of fiber post restorations depends not only on the mechanical properties of the post system but also on the stability of the adhesive interface formed between the fiber post, resin cement, and intraradicular dentin. Therefore, strategies aimed at improving dentin surface characteristics before cementation remain an important area of research in adhesive restorative dentistry.

The present study evaluated the effect of different sodium hypochlorite concentrations and application times on the push-out bond strength of a self-adhesive resin cement to root dentin. The findings demonstrated that dentin deproteinization with sodium hypochlorite resulted in higher push-out bond strength values in both coronal and apical dentin compared with untreated specimens. Moreover, increasing the NaOCl concentration from 5% to 20% produced a greater increase in bond strength than extending the application time from 2 to 10 minutes. These findings suggest that sodium hypochlorite concentration may have a more pronounced influence on bonding performance than application duration.

The enhanced bond strength observed after sodium hypochlorite treatment may be explained by the chemical modification of the dentin organic matrix. Sodium hypochlorite is widely used in endodontic procedures because of its antimicrobial activity and its ability to dissolve organic tissues.[9] In addition to

its disinfecting properties, NaOCl can interact with the organic components of dentin, particularly type I collagen, leading to partial degradation of the collagen network and alteration of the dentin surface characteristics.[4,5]

Dentin deproteinization may provide several potential advantages for resin bonding. The removal of exposed collagen fibrils can reduce the amount of water retained within the dentin substrate and create a more mineral-rich surface that may facilitate interaction between resin monomers and the underlying hydroxyapatite structure. Previous investigations have suggested that collagen removal may influence resin infiltration, hybrid layer formation, and the stability of the adhesive interface.[12–15]

In the present study, the positive effect of NaOCl treatment was observed for both coronal and apical root dentin. This finding may be related to the modification of the dentin substrate following deproteinization, which could facilitate improved adaptation of the self-adhesive resin cement to the root canal walls. However, the magnitude of this effect appeared to depend mainly on NaOCl concentration, as increasing the concentration from 5% to 20% produced a greater improvement in bond strength, whereas extending the application time resulted in only a limited additional effect.

The differences in bond strength between coronal and apical root dentin have been widely recognized as an important challenge in adhesive cementation procedures. In the present study, although sodium hypochlorite treatment increased bond strength values in both regions, significant differences between coronal and apical dentin were observed only under specific treatment conditions. This finding may be related to the inherent anatomical and structural differences between these two regions. Apical dentin generally exhibits fewer and narrower dentinal tubules, reduced tubular density, and greater structural variability compared with coronal dentin, which may limit resin penetration and reduce the effectiveness of adhesive procedures.[7,8]

The push-out bond strength test was selected in the present investigation because it provides a reliable method for evaluating the retention of fiber posts within root canals. Compared with conventional bond strength approaches, the push-out test produces a more uniform stress distribution along the post–cement–dentin interface and is considered more representative of the clinical behavior of intracanal post restorations.[10] Therefore, the use of this methodology allows meaningful comparison of bonding effectiveness among different surface treatment protocols and cementation strategies.

The influence of sodium hypochlorite on resin–dentin bonding remains controversial, and previous studies have reported inconsistent findings. These discrepancies may be related to variations in NaOCl concentration, exposure time, adhesive system composition, dentin substrate characteristics, and experimental methodology. Although sodium hypochlorite can enhance bonding by modifying the organic component of dentin, excessive exposure may negatively affect the adhesive interface through oxidative mechanisms.

Morris et al.[17] investigated the effect of sodium hypochlorite treatment on resin cement bonding to endodontically treated dentin and reported that NaOCl exposure could influence bond strength

depending on the treatment protocol. The authors suggested that residual oxidizing agents within the dentin substrate may interfere with resin polymerization by affecting free-radical reactions, potentially compromising the integrity of the adhesive interface.

Similarly, Nikaido et al.[18] reported that sodium hypochlorite treatment altered the bonding performance of resin materials to endodontically treated dentin. They proposed that the presence of residual oxygen-containing compounds after NaOCl application may reduce the effectiveness of adhesive polymerization, particularly when adequate neutralization or removal of residual oxidants is not achieved.

In contrast, other investigations have demonstrated beneficial effects of sodium hypochlorite pretreatment on dentin bonding. Lisboa et al.[19] reported that dentin deproteinization improved resin–dentin bond strength, attributing this effect to the removal of the collagen-rich organic layer and improved interaction between resin materials and the underlying mineralized dentin substrate. These findings are consistent with the results of the present study, in which NaOCl-treated specimens demonstrated higher push-out bond strength values than untreated controls.

Conversely, Adlson et al.[20] reported unfavorable effects of sodium hypochlorite treatment on fiber post retention, particularly when specific adhesive strategies were employed. Differences between their findings and the present results may be explained by variations in resin cement composition, adhesive approach, NaOCl application protocol, and testing methodology. Since bonding performance is influenced by multiple interacting factors, direct comparison among studies should be interpreted cautiously.

Overall, the conflicting evidence regarding sodium hypochlorite treatment indicates that its effect on dentin bonding is not solely determined by the chemical action of NaOCl itself. Instead, the final outcome appears to depend on achieving an appropriate balance between organic matrix modification and preservation of the chemical conditions required for effective resin polymerization.

The improvement in bond strength observed after sodium hypochlorite deproteinization may also be explained by the structural changes induced within the dentin substrate. Dentin is a complex biological tissue composed mainly of hydroxyapatite crystals embedded in an organic matrix, with type I collagen representing the major organic component. Although collagen plays an essential role in maintaining dentin structure, the exposed collagen network within the adhesive interface may increase water retention and contribute to progressive degradation of resin–dentin bonds over time.[21,22]

By selectively removing the exposed collagen fibrils, sodium hypochlorite treatment may alter the physicochemical characteristics of dentin and create a substrate that is more favorable for resin interaction. The reduction of the collagen-rich organic layer may enhance the accessibility of functional resin monomers to the mineralized dentin surface and promote improved micromechanical retention. In addition, decreasing the hydrophilic nature of dentin may reduce water-related degradation processes and contribute to greater stability of the adhesive interface.[21]

The present findings suggest that NaOCl concentration had a greater effect on bond strength than application time. The higher bond strength values observed in the 20% sodium hypochlorite groups may be attributed to more extensive modification of the organic dentin matrix and more effective removal of exposed collagen components. In contrast, prolonging the application period from 2 to 10 minutes resulted in only a limited increase in bond strength, suggesting that once sufficient deproteinization has occurred, additional exposure time may provide minimal additional benefit.

The long-term durability of resin–dentin bonding is influenced not only by initial bond strength but also by the stability of the hybrid layer and resistance to degradation. Previous studies have demonstrated that endogenous proteolytic enzymes within dentin, particularly matrix metalloproteinases (MMPs), may contribute to the breakdown of collagen fibrils within the hybrid layer and compromise adhesive durability over time.[22–24] By reducing the amount of exposed collagen available for enzymatic degradation, dentin deproteinization may theoretically contribute to preservation of the adhesive interface.

However, the potential benefits of sodium hypochlorite treatment should be interpreted together with its possible limitations. Excessive NaOCl concentration or prolonged exposure may increase oxidative effects and generate residual oxygen-containing compounds within dentin, which may interfere with resin polymerization. Therefore, the clinical application of highly concentrated sodium hypochlorite solutions requires careful consideration, and further studies are necessary to determine the optimal balance between effective deproteinization and preservation of adhesive polymerization.

From a clinical perspective, the findings of this study suggest that dentin deproteinization may represent a simple adjunctive approach for improving the retention of fiber posts luted with self-adhesive resin cement. The observation that increasing NaOCl concentration had a greater impact on bond strength than extending application time may be clinically relevant by allowing a more efficient surface treatment protocol. Nevertheless, these results should be interpreted cautiously because the present investigation was performed under laboratory conditions.

Several limitations should be acknowledged. First, the in vitro design does not completely reproduce the complex oral environment, where factors such as thermal fluctuations, cyclic masticatory loading, saliva exposure, and long-term aging may influence the stability of the adhesive interface. Second, only one fiber post system and one self-adhesive resin cement were evaluated; therefore, the findings may not be directly applicable to other restorative systems with different chemical compositions or bonding mechanisms.

Future studies should investigate the long-term effects of sodium hypochlorite deproteinization using artificial aging protocols, including thermocycling and mechanical fatigue testing. In addition, evaluation of different resin cements, fiber post systems, and adhesive strategies, combined with microscopic analyses such as scanning electron microscopy and confocal microscopy, may provide further insight into the relationship between dentin modification and adhesive interface quality.

Within the limitations of this in vitro study, sodium hypochlorite pretreatment increased the push-out bond strength of a self-adhesive resin cement to both coronal and apical root dentin. The concentration of sodium hypochlorite appeared to be a more influential factor than application time, with higher concentrations producing greater improvements in bond strength. Further investigations are required to confirm the long-term clinical relevance and biological safety of this approach before routine clinical implementation.

Declarations

Consent for Publication

Not applicable.

Availability of Data and Materials

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

ES contributed to the study conception, methodology, data analysis, interpretation of findings, and manuscript preparation. All authors contributed to reviewing and revising the manuscript and approved the final version for publication. All authors agree to be accountable for the integrity and accuracy of the work.

Clinical Trial Registration

Not applicable.

Use of Artificial Intelligence

Artificial intelligence-based tools were used during manuscript preparation only for language refinement and improvement of scientific writing clarity. These tools were not involved in study design, data acquisition, statistical analysis, interpretation of findings, or development of scientific conclusions. The authors remain fully responsible for the accuracy, originality, and integrity of the manuscript.

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