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# Effect of Post-Endodontic Cleaning Protocols on Sealer Bond Strength and Tubule Penetration

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## Abstract

***Background:*** It was aimed to evaluate the effect of different cavity cleaning techniques on the bond strength and dentinal tubule penetration of an epoxy resin-based root canal sealer in sealer-contaminated cavities.

***Methods:*** Thirty-five extracted mandibular premolars were prepared and obturated with AH Plus sealer labeled with 0.1% rhodamine B. The teeth were randomly divided into 5 groups according to the post-obturation cleaning technique: (1) no cleaning, (2) dry cotton pellet, (3) 70% ethanol, (4) ethanol+air polishing with sodium bicarbonate, and (5) air abrasion with aluminum oxide. The coronal 1 mm sections of the roots were obtained to assess push-out bond strength and sealer penetration using confocal laser scanning microscopy.

***Results:*** No statistically significant difference was found among the groups in terms of bond strength ($P = .655$) and dentinal tubule penetration ($P = .122$). However, higher bond strength values were observed in the air polishing group.

***Conclusions:*** None of the evaluated cavity cleaning protocols demonstrated a statistically significant advantage over the others regarding dentinal tubule penetration and push-out bond strength. However, air polishing showed a trend toward higher bond strength values. The trend toward improved bond strength with air polishing suggests that this method may enhance sealer adhesion to dentin and contribute to a more durable coronal seal in clinical practice.

***Keywords:*** Access cavity cleaning, air abrasion, air polishing, CLSM, ethanol, push-out bond strength

### What is already known on this topic?

- *Mechanically assisted cleaning techniques such as air polishing and air abrasion have been shown to be effective for removing residual sealer from the access cavity in previous in vitro and recent clinical studies.*
- *These techniques are increasingly recommended in clinical practice for post-endodontic access cavity cleaning.*
- *Surface alterations induced by cleaning procedures may influence dentin characteristics and potentially affect sealer adhesion.*

### What does this study add on this topic?

- *This study is the first to evaluate the effect of clinically recommended post-endodontic cleaning protocols on both dentinal tubule penetration and push-out bond strength of a root canal sealer.*
- *The findings provide evidence on whether air polishing and air abrasion alter the dentin–sealer interface beyond access cavity cleanliness.*
- *The results contribute clinically relevant data regarding the potential impact of post-endodontic cleaning methods on the long-term sealing performance of root canal treatments.*

## INTRODUCTION

Long-term success of root canal treatment largely depends on the ability to prevent coronal and apical leakage, as insufficient sealing may facilitate bacterial penetration and sustain periapical pathology.[1] The integrity of the root filling may be compromised by voids or gaps between gutta-percha, sealer, and dentinal walls owing to anatomical complexities, insufficient instrumentation, or operator variability.[2] As gutta-percha itself does not chemically bond to dentin, the use of a root canal sealer is mandatory to achieve interfacial adaptation, with epoxy resin–based and bioceramic materials being widely used due to their favorable physicochemical properties.[3]

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During obturation, sealer contamination of the coronal dentin is common. The presence of residual sealer on coronal dentin surfaces may interfere with adhesive infiltration and polymerization processes, potentially compromising retention, marginal integrity, and the clinical performance of immediate post-endodontic restorations.[4-6] Effective decontamination of the access cavity is therefore critical before adhesive procedures. Various mechanical, chemical, and abrasive approaches have been proposed for cavity decontamination; however, the routine clinical use of chemical solvents remains controversial due to concerns related to biocompatibility and inconsistent cleaning effectiveness, particularly when ethanol is used alone.[7]

In restorative and prosthodontic workflows, air polishing and air abrasion have been used to modify surface topography and increase surface energy, thereby promoting improved adhesive interactions.[4,8] Air polishing systems function by combining pressurized air, abrasive particles, and liquid media to mechanically remove surface contaminants and deposits, a principle that has been extensively applied in periodontal maintenance.[9] Meanwhile, air abrasion using aluminum oxide ($Al_2O_3$) particles is commonly applied in indirect restoration workflows and intraoral repair of composite and ceramic restorations to improve micromechanical retention.[10] A contemporary device, AquaCare (Velopex, UK), has been developed to allow the application of both air abrasion and air polishing techniques, depending on specific clinical requirements. In addition to removal efficacy, it is important to evaluate how these protocols influence the sealer's penetration into dentinal tubules and its adhesion to dentin, as these factors are closely linked to sealing performance and clinical durability.[11,12] Because post-obturation cleaning procedures are applied primarily to the coronal portion of the access cavity, the effects of these techniques are expected to be most pronounced in this region. In contrast, the middle third of the root canal is often selected for bond strength testing to minimize the influence of the oval canal morphology commonly observed coronally and to avoid the thin dentin walls and sclerotic tubules frequently present in the apical third.[13] Anatomical variability across root thirds can therefore affect the interpretation of sealer–dentin interactions,[13] highlighting the relevance of examining the coronal area where cleaning procedures are actually performed. Evaluating the bond strength at the sealer–dentin interface provides a standardized measure to assess the quality of adhesion between sealer and dentin.[3]

Penetration of root canal sealers into dentinal tubules is clinically advantageous because it can entomb residual bacteria[14] and promote the intratubular precipitation of bioactive mineral phases.[15] While scanning electron microscopy (SEM) has long been used to examine interfacial adaptation, confocal laser scanning microscopy (CLSM) now provides non-destructive and high-resolution visualization of the sealer–dentin interface.[16] Labeling sealers with trace levels of rhodamine B (0.1%) does not alter their physicochemical properties yet markedly enhances fluorescence, facilitating precise measurement of penetration depth.[17] Using serial optical sections, CLSM enables detailed assessment of sealer distribution along the canal circumference and produces optical slices thinner than 1 µm, offering more accurate evaluation of sealer tags and penetration depth than conventional microscopy techniques.[18]

Accordingly, while mechanically assisted cleaning approaches, including air abrasion and air polishing, have demonstrated promising outcomes in previous investigations,[4,9] and recent clinical research has further demonstrated that these methods, particularly air abrasion and air polishing, are among the most reliable and effective strategies for removing residual sealer from the access cavity,[19] their effect on the dentin–sealer interface remains unclear. Although widely recommended in clinical practice, the influence of these procedures on sealer bond strength and dentinal tubule penetration remains insufficiently clarified, despite the likelihood that surface modifications may influence adhesion and sealing performance. Addressing this gap is clinically relevant, as compromised adhesion or reduced sealer penetration could jeopardize the long-term success of endodontic treatment.[4] Accordingly, this study aimed to comparatively evaluate the effects of different post-obturation cavity cleaning protocols on the push-out bond strength and dentinal tubule penetration of an epoxy resin–based root canal sealer. The null hypotheses tested were that (1) post-obturation cleaning protocols do not influence sealer bond strength and (2) dentinal tubule penetration is not affected by the cleaning method applied.

## MATERIAL AND METHODS

The present in vitro investigation was carried out at the Department of Endodontics, Faculty of Dentistry, Marmara University, following approval by the institutional ethics committee (Protocol No: 27.02.2025/43, Date: February 27, 2025). Human dental specimens were obtained after routine consent procedures, and the study complied with the principles outlined in the Declaration of Helsinki.

### Sample Size Calculation

The required sample size was determined using G*Power software (version 3.1.9.7; University of Düsseldorf, Germany). Calculations were performed assuming a moderate effect size ($f = 0.4$), an $\alpha$ level of 0.05, and a statistical power of 80%. Accordingly, a total of 35 specimens were deemed sufficient, and 7 teeth were assigned to each of the 5 experimental groups.

### Criteria for Specimen Selection

This study included 35 human mandibular premolars obtained following tooth extraction. Teeth presenting a single, straight root canal and fully developed apices were

considered eligible. All specimens had been extracted for orthodontic or periodontal reasons at the Department of Oral and Maxillofacial Surgery, Marmara University, and were obtained following routine informed patient consent. Following extraction, the specimens were carefully rinsed and kept in a 0.1% thymol solution prior to use. Prior to instrumentation, each specimen was examined under a dental operating microscope (Leica M320, Leica Microsystems, Wetzlar, Germany) to detect external cracks, fractures, or structural defects. Periapical radiographs were obtained to verify canal morphology and confirm the presence of a single root canal. Specimens presenting caries, prior root canal therapy, resorptive defects, or calcified canals were not included in the analysis. Specimens with pronounced oval-shaped canals were excluded to ensure reliable push-out bond strength testing. In addition, teeth exhibiting more than a 20% variation in coronal canal diameter relative to the group mean were excluded to maintain anatomical standardization.

**Root Canal Preparation and Obturation**

The teeth were decoronated at the level of the cementoenamel junction using a high-speed diamond bur under continuous water cooling and standardized to a root length of 14 mm. Following decoronation, the roots were embedded in acrylic resin blocks. Canal patency was verified using a size #10 K-file (Mani, Japan) prior to mechanical preparation. Root canal instrumentation was performed using the ProTaper Next system (Dentsply Maillefer, Ballaigues, Switzerland), with preparation completed to an X3 file (30/.07) as the final apical dimension. Throughout canal preparation, irrigation was performed with 2.5% sodium hypochlorite (NaOCl) following the use of each instrument. After completion of instrumentation, the canals were irrigated with 5 mL of 17% ethylenediaminetetraacetic acid for 1 minute to aid smear layer removal, followed by a final rinse with 5 mL of 2.5% NaOCl. A final rinse with distilled water was then performed to eliminate residual irrigants. Subsequently, the root canals were dried using sterile X3-compatible absorbent paper points.

Canals were obturated using the cold lateral condensation technique with gutta-percha cones and AH Plus sealer (Dentsply Sirona, Konstanz, Germany), to which 0.1% rhodamine B dye powder had been added for confocal microscopy analysis.

**Group Allocation and Cleaning Protocols**

After obturation, specimens were randomly assigned to 5 experimental groups (n = 7) based on the cavity cleaning protocol applied to the dentin surface:

Group 1: Control: No cleaning.

Group 2: Dry cotton pellet, mechanical cleaning of the cavity floor using a sterile dry cotton pellet applied for 10 seconds.

Group 3: 70% Ethanol: Cotton pellet soaked in 70% ethanol applied for 10 seconds.

Group 4: Ethanol+air polishing, sodium bicarbonate powder (Velopex) was applied for 10 seconds following ethanol application, using a 17.5% ethanol-based solution (AquaSol, Velopex).

Group 5: Air abrasion, $Al_2O_3$ particles (29 µm, Velopex) were applied for 10 seconds under the same operating conditions and using the same carrier solution.

For both air polishing and air abrasion procedures, the AquaCare Twin device (Velopex, UK) was used under standardized conditions, including a pressure of 2 bar, medium powder flow rate, and a working distance of approximately 5 mm from the dentin surface. During application, the nozzle was moved vertically in an up-and-down motion to ensure uniform surface treatment.[19]

All experimental procedures were performed by the same operator to ensure methodological standardization.

Following the application of the cleaning protocols, all specimens were stored in an incubator at 37°C and 100% relative humidity for 2 weeks to allow complete polymerization of the AH Plus sealer and to achieve adequate setting hardness before being subjected to the push-out test. Until further testing, all specimens were kept at room temperature in the incubator to preserve humidity, prevent dehydration, and maintain their integrity.[18] All roots were sectioned perpendicular to their long axis using a low-speed Isomet diamond saw (Buehler, Lake Bluff, IL, USA) under continuous water cooling at a rotational speed of 500 rpm. For confocal analysis, approximately 1-mm-thick sections were obtained from the coronal portion of each root at the level where gutta-percha filling terminated. The coronal-facing surfaces of the sections were polished for 10 seconds using a polishing machine with progressively finer silicon carbide abrasive papers.

**Confocal Laser Scanning Microscopy**

All procedures were performed under low-light conditions to prevent photobleaching of the fluorescent dye. The specimens were kept within a sealed container and examined using a CLSM (Leica Microsystems, Germany) at ×10 magnification. A dry objective lens (HCX PL FLUOTAR 5.0×/0.15; NA: 0.15; refractive index: 1.00) was used, with no immersion medium. Scanning parameters included a speed of 400 Hz, a pinhole diameter of 94.4 µm, and an acousto-optical tunable filter setting of 42%. Rhodamine B dye was excited at a wavelength of 543 nm and emitted fluorescence at 532 nm.

Digital images were analyzed using ImageJ software (NIH, Bethesda, MD, USA) to quantify sealer penetration into dentinal tubules. For each sample, the maximum penetration depth was measured at 4 points (buccal, mesial, distal, and lingual) (Figure 1), and the mean of these values was calculated.[11,20,21] All evaluations were performed by the same

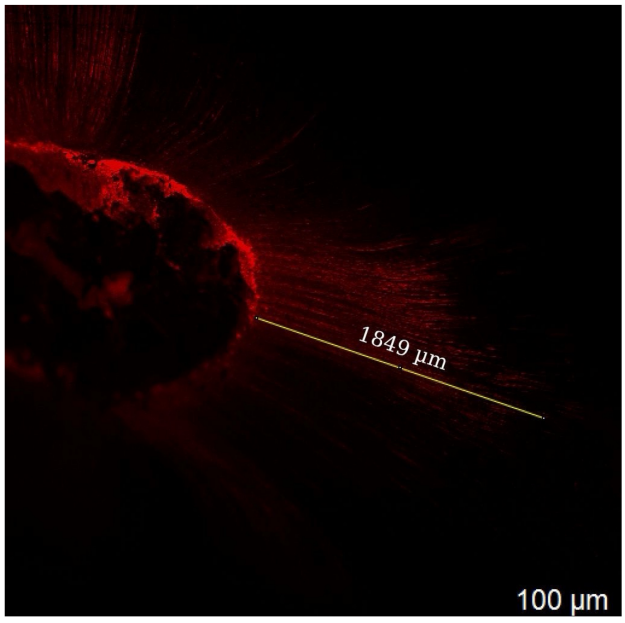


Figure 1. Representative image demonstrating maximum sealer penetration depth.

experienced operator and each measurement was repeated 3 times and averaged for statistical analysis.

Intraexaminer reliability was assessed by reevaluating 10% of the samples after a 10-day interval, with the examiner blinded to the previous measurements.[11]

### Push-Out Bond Strength Test

The same specimens used for CLSM were subsequently subjected to push-out bond strength testing. Each section was subjected to mechanical testing using a computerized materials testing system (Instron, Norwood, MA, USA) with a loading rate of 1 mm/min. A stainless steel plunger, selected to be slightly smaller than the diameter of the root canal lumen, was positioned to apply compressive loading from the apical toward the coronal direction until separation occurred. The maximum force at dislodgement (N) was recorded and converted to megapascals (MPa) by dividing the force by the bonded surface area of the sealer.

Table 1. Sealer Penetration Depth (µm)

| Group | Mean ± SD (µm) | Median (µm) | Maximum (µm) |
|---|---|---|---|
| Control (no cleaning) | 729.25 ± 353.78 | 746.89 | 1240.31 |
| Dry cotton pellet | 774.39 ± 453.92 | 790.10 | 1080.87 |
| Ethanol | 285.97 ± 246.33 | 240.61 | 782.16 |
| Ethanol + air polishing | 426.69 ± 381.61 | 416.53 | 558.15 |
| Air abrasion | 372.59 ± 265.18 | 368.14 | 715.48 |

*$P$ value obtained using the Kruskal–Wallis test. Significance level was set at $P < .05$.

### Statistical Analysis

Statistical analyses were conducted using SPSS software (version 22.0; IBM Corp., Armonk, NY, USA). Due to the small sample size and non-normal data distribution (confirmed via Shapiro–Wilk test), the Kruskal–Wallis test was used for group comparisons, followed by Dunn's post-hoc test where applicable. A significance level of $P < .05$ was set for all analyses.

## RESULTS

Maximum and mean dentinal tubule penetration depths (µm), together with push-out bond strength values (MPa), were assessed using identical specimens and analyzed among the 5 experimental groups.

### Dentinal Tubule Penetration (Confocal Microscopy)

There was no statistically significant difference among the groups regarding either mean or maximum sealer penetration depth ($P = .122$ and $P = .437$, respectively). However, the control and dry cotton groups showed relatively greater penetration, whereas the ethanol-only group exhibited the lowest values. Representative confocal microscopy images are shown in Figure 2, and detailed descriptive data are presented in Table 1.

### Push-Out Bond Strength

No statistically significant difference in push-out bond strength was observed among the groups ($P = .655$). Numerically, the air polishing group showed the highest

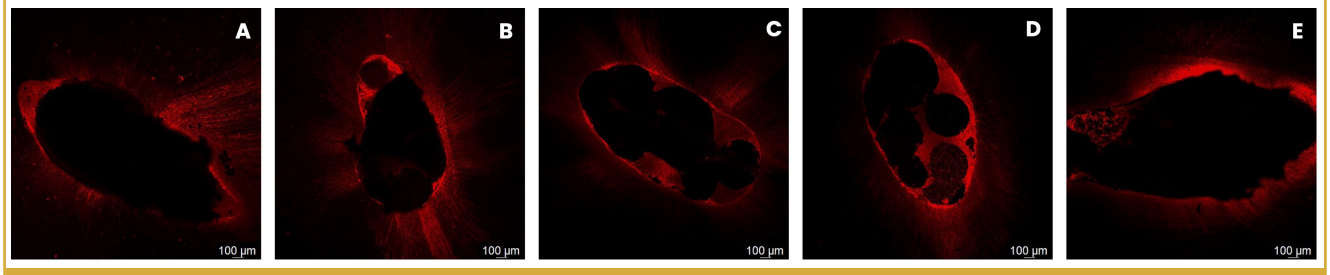


Figure 2. Confocal laser scanning microscopy images showing sealer distribution within the coronal dentinal tubules of each experimental group. (A) Control group (no cleaning), (B) dry cotton pellet, (C) ethanol saturated cotton pellet, (D) ethanol saturated cotton pellet + air polishing, and (E) air abrasion.

**Table 2. Push-Out Bond Strength (MPa)**

| Group | Mean ± SD (MPa) | Median (MPa) |
|---|---|---|
| Control (no cleaning) | 6.48 ± 2.81 | 6.14 |
| Dry cotton pellet | 11.48 ± 7.29 | 10.94 |
| Ethanol | 7.76 ± 4.22 | 6.34 |
| Ethanol+air polishing | 16.69 ± 16.94 | 10.78 |
| Air abrasion | 10.76 ± 6.43 | 9.96 |

*$P$ value obtained using the Kruskal–Wallis test. Significance level was set at $P < .05$.

mean bond strength, followed by air abrasion, while the control group had the lowest. Descriptive statistics are provided in Table 2.

## DISCUSSION

The null hypotheses, which stated that cleaning protocols would have no effect on dentinal tubule penetration and push-out bond strength, were accepted. Residual sealer present on dentin surfaces may adversely influence both the mechanical stability and the biological behavior of post-endodontic restorations. When cavity walls remain contaminated, adhesive interaction with dentin may be impaired, resulting in suboptimal bond strength and compromised marginal adaptation.[6,9] In particular, the presence of residual AH Plus on dentin surfaces has been associated with impaired bonding performance of both self-etch and etch-and-rinse adhesive systems.[7,22,23] In addition, these residues may disrupt stress distribution beneath the restoration, increasing the risk of interfacial failure. Micro-CT studies have also demonstrated that sealer contamination contributes to interfacial gaps between dentin and composite materials. Chemical interactions between unreacted sealer components and dentin, combined with moisture exposure, may further compromise adhesion. Consequently, thorough decontamination of the coronal cavity after obturation is considered a critical step for achieving durable adhesive bonding and favorable restorative outcomes.[1,24,25]

Dry and ethanol-saturated cotton pellets were selected in this study as they reflect routinely applied chairside approaches for the removal of sealer remnants from access cavities.[26] Air polishing using sodium bicarbonate and air abrasion with $Al_2O_3$ were chosen based on their reported effectiveness in removing epoxy resin residues and their capacity to modify dentin surface roughness, which may enhance micromechanical retention.[9] Both abrasive protocols were applied using the AquaCare device (Velopex, UK), which allows delivery of different cleaning modes through a single handpiece under standardized clinical parameters. These cleaning strategies were evaluated against AH Plus, a widely used epoxy resin–based sealer known for its strong adhesion to dentin, hydrophobic composition, and high physicochemical stability.[4,7] Due to these properties, conventional air/water spray has proven largely ineffective for removing set AH Plus.[27]

In this study, CLSM was employed to assess the distribution of the sealer and its adaptation along the dentin–sealer junction. This method offers high-resolution imaging and enables accurate, non-destructive analysis of fluorescently labeled sealers within the dentinal tubules.[28] Its ability to visualize the sealer–dentin interface in detail makes it a reliable technique for evaluating the performance of different cleaning protocols.

In this study, rhodamine B dye was used as a fluorescent marker to assess sealer adaptation and penetration depth, consistent with previous reports.[29] The application of fluorescent dyes in CLSM enhances image contrast, enabling clearer visualization and more accurate analysis of the sealer–dentin interface and intratubular penetration.[16] Using rhodamine B at a concentration of 0.1% has been shown not to alter the physical properties of the sealer.[17] Confocal laser scanning microscopy imaging also allows examination of sealer distribution at various depths and along the full canal circumference.[18] In comparative evaluations, CLSM has demonstrated superior performance to SEM in assessing both the depth of penetration and the quality of sealer tag formation within radicular dentin.[30]

The push-out bond strength test is commonly employed as a mechanical method to assess the resistance of the sealer–dentin interface to dislodgement forces.[31] This method reflects the mechanical interlocking that enhances sealer adhesion,[12] and a systematic review highlighted that methodological inconsistencies in push-out bond testing such as variations in plunger diameter, section thickness, and loading speed may significantly influence the reported bond strength outcomes.[32] A previous study reported that a statistically significant difference in push-out bond strength between bioceramic sealers and AH Plus was found only in the middle third of the root canal, suggesting that this region may be the most reliable for comparing sealer adhesion.[13] In contrast, the present study focused on the coronal third, as the primary aim was to assess whether sealer contamination and subsequent cleaning protocols influence adhesion in this specific area. Given that the coronal dentin is directly exposed during restoration and more likely to be affected by cleaning procedures, this region was considered clinically relevant for evaluating the effectiveness of post-endodontic cleaning techniques. Another study standardized specimens by selecting slices with closely matched canal diameters in the middle third of the root. Following a similar rationale, coronal canal circumference was measured at baseline, and teeth exhibiting more than a 20% variation were excluded to ensure methodological consistency.[33]

Despite the absence of statistical significance, the numerically higher bond strength values observed in the air polishing group may still carry clinical relevance. From a clinical perspective, even modest improvements in sealer bond strength may contribute to a more stable sealer–dentin

interface and potentially enhance the durability of the coronal seal.[10] Although the differences observed in the present study did not reach statistical significance, the trend toward higher bond strength values in the air polishing group may indicate that this cleaning approach creates a more favorable dentin surface for adhesive interaction. Similar findings have been reported in restorative dentistry, where air polishing and air abrasion procedures have been shown to increase surface energy and micromechanical retention, thereby improving bonding performance.[8] The highest mean bond strength was achieved in the air polishing group, which may be attributed to improved surface roughness and removal of superficial contaminants. Sodium bicarbonate particles can mechanically cleanse the dentin and increase surface energy, facilitating better adhesive resin infiltration.[7] This observation partially aligns with earlier reports demonstrating the beneficial effects of air abrasion and air polishing on bonding performance in CAD/CAM and composite repair applications. The short-duration abrasive action of sodium bicarbonate, together with the ethanol-containing cleaning solution, likely produced a cleaner[19] and more reactive dentin surface without causing excessive structural alteration. This surface condition may support better interaction with adhesive systems during coronal restoration, potentially enhancing interfacial integrity and long-term sealing performance.[17] Moreover, by improving the quality of the sealer–dentin interface, this approach may also contribute to the long-term success of the root canal filling itself. Clinically, these findings suggest that incorporating a brief air polishing step after obturation could create a more favorable bonding environment both for subsequent adhesive restorations and for maintaining durable sealer adhesion within the root canal. Therefore, the use of air polishing in endodontic workflows may be encouraged, and further studies are warranted to confirm its potential benefits under clinical conditions.

Interestingly, the dry cotton and control groups showed the highest median tubule penetration of the sealer, which may suggest that minimal disruption of the dentin surface allows the residual sealer to infiltrate more deeply into the tubules. However, higher sealer penetration does not necessarily translate to improved adhesion. On the contrary, residual sealer can hinder hybrid layer formation, compromise bonding, and result in interface degradation over time.[5,33] Application of 70% ethanol as a standalone cleaning approach resulted in limited dentinal tubule penetration and moderate bond strength values. The moderate bond strength may be attributed to insufficient surface cleaning, which could have reduced bonding effectiveness in the presence of epoxy resin-based sealers such as AH Plus.[7] Additionally, as an organic solvent, ethanol may have interfered with the sealer's flow characteristics or altered the surface conditions in a way that restricted tubule penetration. Despite its theoretical potential to enhance micromechanical retention, air abrasion did not produce superior outcomes in terms of either bond strength or dentinal tubule penetration in the present study. This may be due to irregular or overly aggressive abrasion that alters the dentin surface morphology in a way that inhibits uniform adhesive contact.[8] Moreover, $Al_2O_3$ particles may not effectively remove hydrophobic resin films that obstruct resin-dentin interaction.

In contrast, the group treated with sodium bicarbonate air polishing demonstrated the highest mean push-out bond strength. This result may be attributed to the gentle abrasive effect of sodium bicarbonate particles, which may have effectively removed superficial sealer contamination and simultaneously increased surface energy and microroughness conditions favorable for sealer penetration and adhesion. Although this group did not show the highest tubule penetration, its bond strength was notably improved, suggesting a more favorable dentin surface for mechanical interlocking.

Confocal microscopy proved to be an essential tool in visualizing sealer distribution and assessing dentinal tubule penetration. The combination of fluorescence labeling with rhodamine B and CLSM allowed accurate, non-destructive measurement of depth and spread. The variability in penetration depths observed across groups emphasizes the role of cleaning protocol in shaping the dentin surface microenvironment. Previous studies also reported that differences in the mean depth and area of sealer penetration were not statistically significant, possibly influenced by confounding variables such as sealer composition, tip design, or activation parameters.[34]

Certain methodological constraints must be considered during the interpretation of the findings. First, the present investigation was conducted under in vitro conditions, which cannot fully replicate the complex biological and mechanical environment of the oral cavity. Second, only 1 epoxy resin–based sealer was evaluated in this study, which may limit the generalizability of the findings to other types of sealers with different chemical compositions and bonding mechanisms. Additionally, natural dentin variability among specimens might have influenced the outcomes despite careful standardization. The relatively limited sample size may have reduced the statistical power of the analysis and should be acknowledged as a limitation, as it may limit the generalizability of the present findings. Future studies involving larger sample sizes and more advanced surface analysis methods are recommended to verify these findings and may help to further elucidate the relationship between cleaning effectiveness and sealer adhesion. Considering the methodological constraints of this study, none of the assessed cleaning protocols produced statistically significant differences in push-out bond strength or dentinal tubule penetration. However, the air polishing group yielded the highest bond strength values, while the dry cotton group maintained the greatest tubule penetration. These findings suggest that protocols involving minimal mechanical cleaning may allow deeper

sealer diffusion, whereas more effective surface conditioning techniques may promote stronger sealer–dentin bonding.

## CONCLUSION

Within the limitations of this in vitro study, none of the evaluated post-obturation cleaning protocols showed a statistically significant difference in dentinal tubule penetration or push-out bond strength. Although all specimens exhibited similar sealer penetration patterns under confocal microscopy, the groups without alcohol demonstrated greater dentinal tubule penetration. Among the tested techniques, air polishing produced consistently higher bond strength values, suggesting a potential advantage in improving dentin–sealer adhesion and, consequently, the long-term success of root canal treatment. The use of air polishing in endodontic workflows may therefore be encouraged, and further studies are warranted to confirm its potential benefits under clinical conditions.

**Data Availability Statement:** The data that support the findings of this study are available on request from the corresponding author.

**Artificial Intelligence Usage Statement:** The authors declared that no artificial intelligence tool was used in the preparation of the manuscript.

**Ethics Committee Approval:** Ethical committee approval was received from the Marmara University Faculty of Dentistry Clinical Research Ethics Committee (Approval No: 27.02.2025/43, Date: February 27, 2025).

**Informed Consent:** Written informed consent was obtained for the use of biological materials for research purposes.

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