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Comparative Evaluation of Different Surface Conditioning Techniques Following Immediate Dentin Sealing on Zirconia–Dentin Bond Strength: An In Vitro Study

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Abstract

Background The increasing use of monolithic zirconia restorations has significantly improved the mechanical performance and longevity of indirect restorations[4,17]. However, achieving a durable adhesive bond between zirconia and dentin remains a major clinical challenge because zirconia lacks a silica-rich glass phase and therefore cannot be conventionally acid etched[4,6]. Immediate dentin sealing (IDS) has emerged as an effective adhesive protocol that enhances bond durability, minimizes postoperative sensitivity, and protects freshly cut dentin during provisionalization[2]. Despite the growing acceptance of IDS, limited evidence exists regarding the influence of different post-IDS dentin surface conditioning methods on the bond strength of zirconia restorations.

Aim: To evaluate and compare the effect of pumice polishing, airborne-particle abrasion, and Er:YAG laser conditioning following immediate dentin sealing on the shear bond strength between zirconia and human dentin.

Materials and Methods: Forty-five extracted human premolars were selected according to predefined inclusion criteria and randomly allocated into three experimental groups (n = 15). Standardized dentin surfaces were prepared after decoronation, followed by immediate dentin sealing using Clearfil SE Bond. Zirconia blocks (3 × 4 × 5 mm) were fabricated from UPcera ST White zirconia using CAD/CAM technology and pretreated with airborne-particle abrasion and an

MDP-containing primer[8,12]. The dentin specimens were conditioned using pumice slurry (Group I), 50 µm aluminum oxide air abrasion (Group II), or Er:YAG laser irradiation (Group III). Zirconia specimens were cemented using RelyX™ U200 self-adhesive resin cement. Shear bond strength was evaluated using a universal testing machine. Data were analyzed using one-way ANOVA followed by Tukey's post hoc test with statistical significance set at $p < 0.05$.

Results: The Er:YAG laser group demonstrated the highest mean shear bond strength (10.83 ± 0.28 MPa), followed closely by the air abrasion group (10.79 ± 0.34 MPa), whereas the pumice group exhibited the lowest bond strength (8.92 ± 0.41 MPa). One-way ANOVA revealed a highly significant difference among the study groups ($p < 0.001$). Tukey's post hoc analysis demonstrated statistically significant differences between the pumice group and both air abrasion and laser groups, whereas no significant difference was observed between the air abrasion and laser groups.

Conclusion: Surface conditioning following immediate dentin sealing significantly influences zirconia–dentin bond strength. Air abrasion and Er:YAG laser conditioning produced significantly greater bond strength than pumice polishing. Both techniques may therefore be considered effective conditioning protocols for improving the adhesive performance of zirconia restorations following IDS.

Keywords Immediate Dentin Sealing, Zirconia, Shear Bond Strength, Air Abrasion, Er:YAG Laser, CAD/CAM Zirconia, Resin Cement, Adhesive Dentistry.

Introduction

Contemporary restorative dentistry has progressively shifted toward minimally invasive treatment philosophies that prioritize preservation of sound tooth structure while restoring esthetics, function, and longevity[14,15]. Advances in adhesive dentistry have substantially improved the clinical success of indirect restorations by enabling reliable bonding between restorative materials and dental substrates[3,16]. Among these restorative materials, zirconia has emerged as one of the most preferred ceramic systems because of its exceptional fracture toughness, high flexural strength, favorable biocompatibility, and excellent esthetic properties[4]. These characteristics have led to its widespread application in crowns, fixed partial dentures, implant-supported restorations, and full-mouth rehabilitations[17].

Although zirconia possesses superior mechanical properties, its polycrystalline structure presents a considerable challenge for adhesive cementation[6,13]. Unlike silica-based ceramics, zirconia lacks a glass phase, rendering conventional hydrofluoric acid etching ineffective[4,17]. Consequently, durable bonding depends largely on alternative mechanical and chemical surface treatment strategies, including airborne-particle abrasion and the application of functional phosphate monomers such as 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP). While these approaches improve zirconia surface characteristics, the quality of the dentin adhesive interface remains equally important for the long-term success of indirect restorations[9,11].

Preparation of teeth for indirect restorations inevitably exposes dentin by removing the protective enamel layer. Freshly cut dentin contains open dentinal tubules and an intact collagen matrix, making it susceptible to bacterial contamination, dentinal fluid movement, postoperative sensitivity, and degradation during the provisional phase[1]. Traditionally, dentin bonding agents have been applied during the final cementation appointment, a protocol known as delayed dentin sealing (DDS)[2]. However, during the interval between tooth preparation and final cementation, the exposed dentin remains vulnerable to contamination by saliva, provisional cements, and oral microorganisms, potentially compromising the quality of the adhesive interface[19].

Immediate dentin sealing (IDS), first introduced as an alternative adhesive strategy, involves sealing freshly prepared dentin immediately after tooth preparation using a dentin bonding agent before impression making[2]. This technique allows optimal polymerization of the adhesive under uncontaminated conditions and facilitates the formation of a stable hybrid layer[3]. Numerous laboratory and clinical investigations have demonstrated that IDS improves bond strength, reduces postoperative sensitivity, enhances marginal adaptation, and protects the dentin–pulp complex throughout provisionalization[2,19,20]. The preservation of the hybrid layer before definitive cementation is considered one of the primary reasons for the superior clinical performance associated with IDS[19].

Despite these advantages, contamination of the resin-coated dentin surface during laboratory procedures remains possible. Therefore, appropriate surface conditioning before definitive cementation becomes an important step to restore the bonding potential of the sealed dentin[2,20]. Various conditioning methods have been proposed for this purpose. Conventional pumice polishing is commonly used for surface cleaning but offers limited surface modification. Airborne-particle abrasion using aluminum oxide particles creates microretentive irregularities that increase surface roughness and surface energy, thereby enhancing micromechanical retention[7,18]. Alternatively, Er:YAG laser irradiation has gained increasing attention because of its ability to selectively ablate the smear layer, expose dentinal tubules, and generate a clean, microretentive surface with minimal thermal damage when used under appropriate parameters.

Although the individual benefits of immediate dentin sealing and zirconia surface treatment have been extensively documented[2,10,13] comparatively fewer studies have investigated how different post-IDS dentin conditioning protocols influence the adhesive performance of zirconia restorations[20]. Furthermore, direct comparisons between conventional pumice polishing, airborne-particle abrasion, and Er:YAG laser conditioning remain limited. Identifying the most effective conditioning protocol may contribute to improved clinical longevity and durability of bonded zirconia restorations.

Therefore, the present in vitro study was undertaken to comparatively evaluate the influence of three different dentin surface conditioning techniques—pumice polishing, airborne-particle abrasion, and Er:YAG laser conditioning—performed after immediate dentin sealing on the shear bond strength between zirconia and human dentin. The null hypothesis tested was that no significant difference would exist in shear bond strength among the three conditioning protocols.

Materials and Methodology

Study Design

This in vitro comparative experimental study was conducted in the Department of Conservative Dentistry and Endodontics, D.A. Pandu Memorial R.V. Dental College, Bengaluru, to evaluate the effect of different dentin surface conditioning techniques following immediate dentin sealing (IDS) on the shear bond strength of zirconia bonded to human dentin. Ethical approval was obtained from the Institutional Ethics Committee prior to commencement of the study.

Sample Size Estimation

Sample size estimation was performed using G*Power software (Version 3.1.9.7, Heinrich-Heine University, Düsseldorf, Germany). Considering an effect size of 0.48

obtained from previous literature, a significance level (α) of 5%, and a study power of 80%, the minimum required sample size was calculated to be 45 specimens, which were equally distributed into three experimental groups (n = 15).

Sample Selection

Forty-five freshly extracted human premolars extracted for orthodontic or periodontal reasons were collected from the Department of Oral and Maxillofacial Surgery. Following extraction, the teeth were cleaned of soft tissue remnants and stored in distilled water until use.

Inclusion Criteria

- Intact human premolars free from caries
- Teeth without restorations
- Teeth without cracks or fractures confirmed under ×10 stereomicroscopic examination

Exclusion Criteria

- Carious teeth
- Restored teeth
- Endodontically treated teeth
- Teeth exhibiting cracks, fractures, developmental defects, or severe attrition

Materials Used

The following materials were used during the study:

Material	Manufacturer
Clearfil SE Bond self-etch adhesive	Kuraray Noritake Dental Inc., Japan
RelyX™ U200 self-adhesive resin cement	3M ESPE, Germany
UPcera ST White zirconia blocks (3Y-TZP)	UPcera Dental Technology, China
Aluminum oxide particles (50 µm)	Rondoflex
Pumice powder	Commercial dental grade
Er:YAG laser (2940 nm)	LiteTouch, Syneron Dental Lasers
Universal Testing Machine (INSTRON UTM E-3000)	Instron Corporation
CAD/CAM milling system	Dental CAD/CAM System

Armamentarium required

Single rooted 45 premolars.

Specimen Preparation

The roots of all teeth were embedded vertically in self-cure acrylic resin blocks, leaving the coronal portion exposed. The crowns were sectioned horizontally at the cementoenamel junction using a water-cooled diamond disc to expose flat occlusal dentin surfaces. The dentin surfaces were subsequently polished using 1000-grit silicon carbide abrasive paper under running water to produce a standardized smear layer. The prepared specimens were thoroughly rinsed and gently air-dried before adhesive procedures.

Sectioning of samples at the level of CEJ using a diamond disk under water coolant

Sectioned sample

Decoronated 45 samples

Immediate Dentin Sealing Protocol

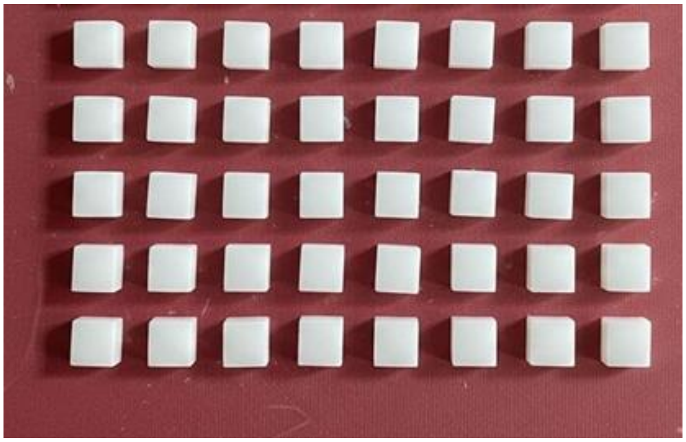
Immediate dentin sealing was performed on all specimens using a two-step self-etch adhesive system (Clearfil SE Bond). The primer was applied according to the manufacturer's recommendations, gently air dried, followed by application of the bonding resin. The adhesive layer was then light polymerized for 10 seconds using a LED curing unit. After completion of IDS, all specimens were stored in distilled water until surface conditioning procedures were performed.

Application of Primer

Application of Bonding agent and curing for 10sec

Zirconia Specimen Preparation

Rectangular zirconia blocks measuring 3 × 4 × 5 mm were fabricated from pre-sintered UPcera ST White zirconia using CAD/CAM milling technology4. The zirconia surfaces were airborne-particle abraded and subsequently treated with an MDP-containing primer to improve chemical adhesion with resin cement before cementation[8,12,18].



Zirconia blocks of dimension 3*4*5mm

Group Allocation

The specimens were randomly allocated into three experimental groups (n = 15).

Group I – Pumice Conditioning

Following IDS, the dentin surfaces were conditioned using a freshly prepared pumice slurry consisting of 5 g pumice powder mixed with 4 mL distilled water. The slurry was applied using a soft rotary bristle brush operated at approximately 1500–2000 rpm for 15 seconds under light pressure. The specimens were then rinsed thoroughly with water and gently air dried.

Group 1- Dentin sample conditioned with pumice

Group II – Air Abrasion

The dentin surfaces were conditioned using 50 µm aluminum oxide particles delivered through an airborne-particle abrasion unit[7,18]. The nozzle was positioned 10 mm from the dentin surface at an angle of 90° under a pressure of approximately 0.17 MPa (25 psi) for 5 seconds. Following abrasion, the specimens were ultrasonically cleaned in distilled water for five minutes and air dried.

Group III – Er:YAG Laser Conditioning

Dentin conditioning was performed using an Er:YAG laser operating at a wavelength of 2940 nm. Laser irradiation was delivered using a 1.3-mm tip positioned 2 mm from the dentin surface with the following parameters:

- Energy: 100 mJ/pulse
- Frequency: 10 Hz
- Exposure time: 60 seconds
- Water spray: Activated
- Total energy delivered: 60 J Following irradiation, the specimens were rinsed with distilled water and cleaned for five minutes before cementation.

Cementation Procedure

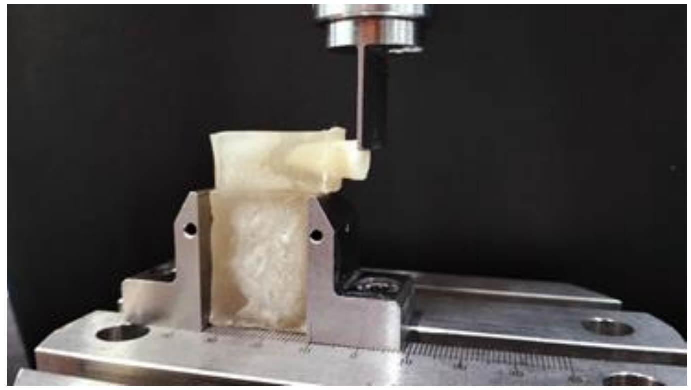
Each zirconia block was bonded to its corresponding dentin specimen using RelyX™ U200 self-adhesive resin cement according to the manufacturer's instructions[6,10]. Uniform seating pressure was applied during cementation, and excess cement was carefully removed. Polymerization was completed using an LED curing unit for 20 seconds. The cemented specimens were subsequently stored in distilled water until mechanical testing.

Zirconia blocks luted on to the dentin sample using resin cement (3M ESPE RelyXTM U200)

Shear Bond Strength Testing

Shear bond strength testing was carried out using a universal testing machine (INSTRON UTM E-3000). Each specimen was secured in the testing jig, and a chisel-shaped loading head was positioned parallel to the zirconia–dentin interface. Load was applied at a constant crosshead speed until adhesive failure occurred. The maximum load at failure (N) was recorded and converted into shear bond strength (MPa) using the following equation:

$$\text{Shear Bond Strength (MPa)} = \frac{\text{Maximum Failure Load (N)}}{\text{Bonding Area (mm}^2\text{)}}$$



Shear bond strength checked using universal testing machine (INSTRON UTM E-3000)

Statistical Analysis

The collected data were analyzed using Statistical Package for the Social Sciences (SPSS) Version 22.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics were expressed as mean ± standard deviation. Intergroup comparison of shear bond strength was performed using one-way analysis of variance (ANOVA). Pairwise comparisons were carried out using Tukey's post hoc test. Statistical significance was established at $p < 0.05$.

Results

A total of 45 specimens were evaluated, with 15 specimens assigned to each experimental group. The shear bond strength values (MPa) obtained after zirconia cementation were analyzed statistically using one-way ANOVA followed by Tukey's post hoc multiple comparison test.

Shear Bond Strength

Table 1: Comparison of mean shear bond strength among the study groups

Group	n	Mean (MPa)	Standard Deviation	Minimum	Maximum
Group I (Pumice)	15	8.92	0.41	8.28	9.50
Group II (Air abrasion)	15	10.79	0.34	10.23	11.32
Group III (Er:YAG laser)	15	10.83	0.28	10.28	11.17

The highest mean shear bond strength was observed in Group III (Er:YAG laser) (10.83 ± 0.28 MPa), followed closely by Group II (air abrasion) (10.79 ± 0.34 MPa). Group I (pumice) demonstrated the lowest bond strength (8.92 ± 0.41 MPa).

Intergroup Comparison Table 2. One-way ANOVA

Source	SS	df	MS	F	p-value
Between Groups	35.73	2	17.87	148.10	<0.001*
Within Groups	5.07	42	0.12		
Total	40.80	44			

*Statistically significant

One-way ANOVA demonstrated a highly significant difference in shear bond strength among the three experimental groups ($F = 148.10$, $p < 0.001$), indicating that the type of dentin surface conditioning significantly influenced zirconia–dentin bonding.

Pairwise Comparison

Table 3: Tukey's post hoc analysis

Comparison	Mean Difference (MPa)	p-value	Interpretation
Group I vs Group II	1.87	<0.001	Significant
Group I vs Group III	1.91	<0.001	Significant
Group II vs Group III	0.04	>0.05	Not Significant

Pairwise comparison revealed significantly higher bond strengths for both air abrasion and Er:YAG laser groups compared with pumice conditioning. No statistically significant difference was found between air abrasion and laser conditioning, indicating that both techniques performed similarly under the experimental conditions.

The present investigation demonstrated that dentin surface conditioning following immediate dentin sealing significantly influenced zirconia–dentin bond strength. Er:YAG laser conditioning produced the highest bond strength values, closely followed by airborne-particle abrasion. Although laser conditioning showed a numerically greater mean value, it did not differ significantly from air abrasion. Pumice conditioning yielded significantly lower bond strength than both experimental conditioning protocols.

Discussion

The longevity of adhesively luted zirconia restorations depends on the integrity of the resin–dentin interface as well as the durability of the adhesive bond[9,14]. Immediate dentin sealing has been advocated as a predictable strategy to preserve freshly prepared dentin by establishing an early hybrid layer before contamination occurs[2,19]. Nevertheless, contamination of the resin-coated surface during provisionalization and laboratory procedures necessitates additional surface conditioning before definitive cementation[19,20]. The present study therefore evaluated whether different conditioning methods applied after IDS influence zirconia–dentin bond strength.

The findings demonstrated that both air abrasion and Er:YAG laser conditioning significantly increased shear bond strength compared with pumice polishing. Consequently, the null hypothesis was rejected, as statistically significant differences were observed among the experimental groups.

The superior performance of the Er:YAG laser group may be attributed to its ability to modify the adhesive-coated dentin surface by selectively ablating superficial contaminants while preserving the underlying hybrid layer[19]. Er:YAG irradiation removes the smear layer, increases surface roughness, exposes micro-irregularities, and enhances wettability without generating excessive thermal injury when appropriate irradiation parameters are employed. These surface alterations facilitate improved resin cement adaptation and micromechanical interlocking, thereby increasing bond strength[7].

Although the laser group demonstrated the highest mean bond strength, the difference compared with air abrasion was not statistically significant. This suggests that both techniques effectively prepare the IDS surface for definitive adhesive cementation. Airborne-particle abrasion with 50 µm aluminum oxide particles likely enhances adhesion through micromechanical roughening of the resin-coated surface, increasing the available bonding area while simultaneously improving surface energy[7,18]. The roughened substrate may promote better penetration and adaptation of resin cement, resulting in enhanced bond durability[6,9].

The comparatively lower bond strength observed following pumice conditioning can be explained by the limited ability of pumice polishing to modify surface topography. Pumice primarily removes superficial contaminants but produces minimal micromechanical alterations capable of enhancing adhesive retention. Consequently, the resin cement depends largely on the original adhesive layer for retention, resulting in significantly lower bond strength compared with laser irradiation and airborne-particle abrasion.

These findings agree with Magne, who demonstrated that immediate dentin sealing creates a stable adhesive interface capable of improving the bonding performance of indirect restorations by protecting freshly cut dentin during provisionalization. Similarly, Van Meerbeek and colleagues emphasized that the quality and durability of the hybrid layer largely determine long-term adhesive success, particularly when self-etch adhesive systems are employed.

The present findings are also consistent with the observations of Kapoor et al., who reported that immediate dentin sealing significantly improves the adhesion of zirconia restorations compared with delayed dentin sealing by minimizing bacterial contamination and preserving hybrid layer integrity[20]. Likewise, Kern demonstrated that successful zirconia bonding depends not only on appropriate ceramic surface treatment but also on optimization of the adhesive interface at the tooth surface[5].

The improved performance observed after airborne-particle abrasion corresponds with previous reports indicating that controlled aluminum oxide abrasion increases surface roughness and surface energy, thereby improving resin infiltration and micromechanical retention[7,18]. These observations support the concept that appropriate substrate preparation remains essential even after immediate dentin sealing has been completed[19].

The findings concerning Er:YAG laser conditioning also corroborate previous investigations demonstrating that laser irradiation effectively modifies dentin morphology by eliminating the smear layer and creating an irregular microretentive surface favorable for adhesive bonding. When appropriate energy settings are selected, laser conditioning enhances resin penetration without causing excessive collagen denaturation or thermal damage. This may explain the consistently high bond strength values obtained in the present study.

An interesting finding of the present investigation was the absence of a statistically significant difference between laser conditioning and airborne-particle abrasion. Although Er:YAG laser produced slightly higher mean values, both conditioning methods achieved clinically comparable adhesive performance. From a clinical perspective, airborne-particle abrasion may remain the more accessible option because of its lower cost and widespread availability, whereas laser conditioning offers a minimally invasive alternative for clinicians with access to laser technology.

One limitation of the present investigation is it's in vitro design, which cannot fully reproduce the complex oral environment[9,14]. Factors such as cyclic occlusal loading, thermal fluctuations, pH variations, enzymatic degradation, and long-term water storage may influence adhesive durability differently under clinical conditions9. Furthermore, only one adhesive system, one resin cement, and one zirconia material were evaluated. Therefore, caution should be exercised when extrapolating these findings directly to clinical practice.

Future studies incorporating thermocycling, cyclic fatigue loading, artificial aging, and long-term water storage are recommended to evaluate the durability of the adhesive interface[9]. In addition, investigation of universal adhesives, self-adhesive resin cements, alternative laser parameters, and different zirconia generations would further strengthen the available evidence[10,13].

Clinical Significance

Immediate dentin sealing has become an integral component of adhesive dentistry for indirect restorations because it protects freshly prepared dentin and improves bond durability[2]. The present study demonstrated that conditioning the resin-coated dentin surface with either airborne-particle abrasion or Er:YAG laser before definitive cementation significantly enhances zirconia–dentin bond strength compared with conventional pumice polishing. These findings suggest that clinicians may achieve a more predictable and durable adhesive interface by incorporating appropriate post-IDS surface conditioning protocols, thereby potentially improving the longevity and clinical success of zirconia restorations[17,20].

Limitations of the Study

The present investigation has certain limitations that should be considered while interpreting the results:

- The study was conducted in vitro, which does not completely reproduce the complex oral environment.
- Thermocycling and long-term artificial aging were not performed.
- Only one zirconia material (UPcera ST White 3Y-TZP) was evaluated.
- A single adhesive system (Clearfil SE Bond) and one self-adhesive resin cement (RelyX™ U200) were used.
- Failure mode analysis using stereomicroscopy or scanning electron microscopy (SEM) was not performed.
- Fatigue loading and cyclic mechanical stresses that occur clinically were not simulated.

Future Recommendations

Future investigations should focus on:

- Long-term aging using thermocycling and prolonged water storage.
- Cyclic fatigue testing to simulate intraoral functional loading.
- Evaluation of newer universal adhesives containing functional phosphate monomers.
- Comparison among different generations of zirconia, including 4Y-TZP and 5Y-TZP.
- Scanning electron microscopic evaluation of conditioned dentin surfaces and fracture patterns.
- Clinical trials evaluating the long-term survival of zirconia restorations bonded after immediate dentin sealing.

Conclusion

Within the limitations of this in vitro study, the following conclusions can be drawn:

- Dentin surface conditioning following immediate dentin sealing significantly influenced the shear bond strength of zirconia bonded to human dentin.
- Er:YAG laser conditioning demonstrated the highest mean shear bond strength (10.83 ± 0.28 MPa), followed closely by airborne-particle abrasion (10.79 ± 0.34 MPa).
- Conventional pumice polishing resulted in significantly lower bond strength compared with both air abrasion and laser conditioning.
- No statistically significant difference was observed between Er:YAG laser and airborne-particle abrasion, indicating that both methods are equally effective for conditioning resin-coated dentin before zirconia cementation.
- Appropriate post-immediate dentin sealing surface conditioning appears to improve the quality of the adhesive interface and may contribute to enhanced longevity of zirconia restorations.

Ethical Approval

The study protocol was approved by the Institutional Ethics Committee of D.A. Pandu Memorial R.V. Dental College, Bengaluru. The study was conducted in accordance with institutional ethical guidelines for research involving extracted human teeth. IRB NO-DAPMRVDC/03-019/2024

Informed Consent

Extracted teeth were collected following institutional guidelines with informed consent obtained for their use in research.

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