

## RESEARCH ARTICLE OPEN ACCESS

# Eight-Year Clinical Performance of Cantilevered Zirconia Resin-Bonded Fixed Dental Prostheses: A Randomized Controlled Trial Evaluating the Effect of Nanostructured Alumina Coating

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## ABSTRACT

**Objective:** To evaluate the clinical performance of cantilevered zirconia resin-bonded fixed dental prostheses (RBFDPs) pretreated with nanostructured alumina coating (NAC) as a non-invasive surface modification alternative to airborne-particle abrasion (APA).

**Materials and Methods:** In this prospective, randomized, controlled clinical trial, 57 patients requiring replacement of a maxillary or mandibular incisor received 64 zirconia RBFDPs, randomly assigned to APA ( $n = 32$ ) or NAC ( $n = 32$ ) groups. APA surfaces were air-abraded with 50- $\mu\text{m}$  alumina, whereas NAC surfaces were coated with NAC. Restorations were further classified by pontic position. Retention and survival rates were analyzed using Kaplan–Meier and log-rank tests; patient-specific factors were assessed with Mann–Whitney U and Fisher's exact tests ( $\alpha = 0.05$ ). Debonded surfaces were examined under scanning electron microscopy.

**Results:** Over a mean observation period of  $61.4 \pm 22.1$  months (range, 8.3–97.4 months), six debondings occurred, corresponding to an overall survival rate of 100% and retention rates of 88.4% for NAC and 89.1% for APA ( $p = 0.99$ ), with no significant differences among pontic groups ( $p = 0.18$ ). Failures were predominantly adhesive, characterized by partial coating delamination at the NAC–zirconia interface.

**Conclusions:** NAC-pretreated zirconia RBFDPs achieved mid- to long-term retention comparable to APA and represent a minimally invasive, clinically reliable pretreatment alternative.

**Clinical Significance:** NAC provides a minimally invasive zirconia pretreatment, particularly for RBFDPs fabricated from damage-prone translucent zirconia, mitigating mechanical failures while maintaining long-term retention comparable to APA.

## 1 | Introduction

Cantilevered zirconia resin-bonded fixed dental prostheses (RBFDPs) are increasingly utilized for single anterior tooth replacement, providing favorable biological, esthetic, and

mechanical outcomes [1]. Among fixed restorative options, RBFDP preparation requires the least tooth reduction [2], yet its design offers no mechanical retention and provides only a limited bonding surface. Therefore, the long-term success of this treatment modality depends almost entirely on the adhesion [3–8].

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While bonding to enamel is predictable, the chemical inertness of zirconia limits the zirconia-resin interface, resulting in lower bond durability compared with conventional glass ceramics [9].

Airborne-particle abrasion (APA) combined with phosphate monomer-based adhesive monomers, such as 10-Methacryloyloxydecyl dihydrogen phosphate (MDP), is a clinically established protocol for promoting adequate micromechanical and chemical bonding to zirconia [9, 10]. Most clinical studies evaluating APA-treated zirconia RBFDPs are limited by small sample sizes and predominantly short- to mid-term follow-up periods [3, 4, 7, 11–13]. Survival rates for zirconia RBFDPs remain consistently high [3], however, long-term retention declines over time, with reported values of approximately 80% for observation periods exceeding 10 years [11, 12]. Further, APA may induce surface flaws and plastic deformation, potentially compromising zirconia strength and increasing the risk of premature failure [14–18]. Concerns have primarily been raised regarding its effects on the mechanical integrity of newer translucent zirconia restorations [19, 20]. These materials have not yet been extensively evaluated in clinical RBFDP studies, leaving the fracture risk of thin retainer wings and connectors uncertain.

In light of these limitations, alternative pretreatment strategies have been investigated [21–27]. Among these, nanostructured alumina coating (NAC) has emerged as a promising approach [28, 29]. Unlike several subtractive methods, NAC is an additive surface modification that produces a nanolamellar surface morphology, increasing the effective bonding area up to sevenfold while preserving zirconia's strength and translucency [30]. It has been shown *in vitro* that NAC-coated zirconia RBFDPs exhibit significantly higher bond strength and fatigue resistance, and fewer retainer wing fractures compared to APA-treated counterparts [31].

Early clinical reports indicate that NAC-treated RBFDPs demonstrate favorable short-term retention and survival outcomes [32]. To the best of the authors' knowledge, NAC remains the only clinically tested alternative pretreatment method for zirconia RBFDPs in a randomized controlled clinical trial, yielding promising clinical results [32]. However, these findings are limited by a small sample size and a short follow-up period, and are unable to draw firm conclusions regarding the long-term efficiency of NAC and differences compared to APA-pretreated RBFDPs. Hence, a randomized controlled trial with a sufficient sample size and a more extended observation period is essential to validate the reported initial results and support the clinical adoption of NAC-pretreated RBFDPs.

Therefore, this randomized controlled clinical trial aimed to evaluate the mid- to long-term clinical performance of NAC-coated zirconia RBFDPs using a larger sample size. The null hypothesis was that there would be no significant difference in the survival and retention rates between APA- and NAC-treated zirconia RBFDPs.

## 2 | Materials and Methods

### 2.1 | Study Design, Ethics, and Patient Selection

This prospective, randomized, controlled, double-blind clinical trial was designed and reported in accordance with the CONSORT guidelines [33]. It was conducted at an academic

clinical center between December 2017 and August 2025. The study protocol was approved by an appropriate institutional ethics committee, and written informed consent was obtained from all participants or their legal guardians prior to inclusion in the study. The trial was registered in a publicly accessible clinical trials registry.

The number of restorations included in this ongoing study was guided by previously published preliminary results and post hoc analysis, which indicated a sample size enlargement for detecting relevant differences between groups [32]. Following CONSORT standards, participants were consecutively evaluated for eligibility during the study period. Six individuals were excluded due to ineligibility or refusal to participate, resulting in 57 participants being included. A total of 57 healthy patients (28 women and 29 men; age range, 13–71 years; mean  $\pm$  SD, 27.2  $\pm$  16.0 years) requiring replacement of a missing maxillary or mandibular central or lateral incisor were screened and deemed eligible by two calibrated investigators (T.M., P.J.). The inclusion criteria were: no signs of bruxism, abutment tooth without the active periodontal or periapical disease, adequate enamel bonding surface of at least 30 mm, adequate interocclusal space for a 0.7 mm retainer wing and a proximal connector of at least 2 mm in width and 3 mm in height, incisor-canine guidance without pontic guidance, and adequate edentulous space for the pontic [11].

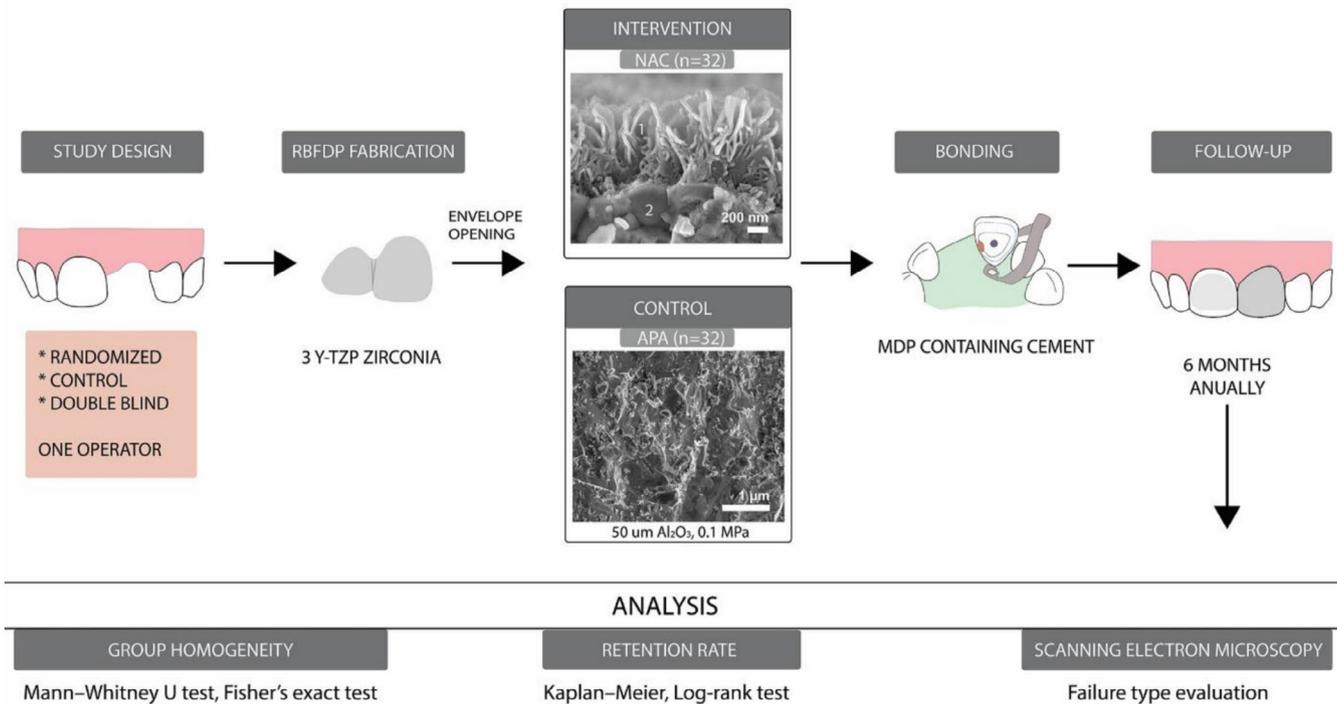
Overall, 64 cantilevered zirconia RBFDPs were delivered. The first group ( $n = 32$ ), in which the bonding surface was airborne-particle-abraded (APA), served as the control. In the second group ( $n = 32$ ), the restorations were pretreated with NAC. In participants ( $n = 6$ ) who received two restorations, the second restoration was allocated to the opposite study group using a split-mouth study design.

### 2.2 | Prosthetic and Bonding Procedures

The study design and workflow are summarized in Figure 1. Prosthetic procedures were performed by a single operator (T.M.). Tooth preparation was confined to the enamel and followed contemporary recommendations (Figure 2a) [34]. The incisal finish line was placed beneath the occlusal contact to ensure sufficient clearance while minimizing unnecessary enamel removal. Cervical chamfer was prepared equi- or supra-gingivally, and a pinhole on the cingulum was prepared. Impressions were obtained using a 2-step putty-wash technique with polyvinyl siloxane material of light- and heavy-body viscosity (Examix, GC Europe, Leuven, Belgium). Stone casts were poured, digitized, and used to design the RBFDP framework via computer-aided design and manufacturing (CAD/CAM) software (exocad, exocad, Darmstadt, Germany). Frameworks were milled from 3 mol% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP) blocks (Ceramill Zolid, Amann Girschbach AG, Koblach, Austria) and veneered with feldspathic porcelain (VITAVM9, VITA Zahnfabrik, Bad Säckingen, Germany).

In the APA group, surfaces were airborne-particle abraded after final try-in, directly prior to the bonding procedure, with 50- $\mu$ m alumina (0.1 MPa, 10 mm distance) and ultrasonically cleaned in

## CLINICAL PROCEDURE



**FIGURE 1** | Study protocol. Note that the coating deposition in the intervention (NAC) group was verified. NAC, nanostructured alumina coating (1) deposited on zirconia surface (2); APA, airborne-particle abrasion; 3Y-TZP, 3 mol% yttria-stabilized tetragonal zirconia; MDP, 10-methacryloyloxydecyl dihydrogen phosphate.

96% ethanol for 3 min, eliminating the need for contamination-cleaning steps [3].

In the NAC group, RBFDP frameworks were immersed in the NAC precursor solution (VALLBOND, Vall-cer, Ljubljana, Slovenia) and calcination fired at 900°C for 30 min before veneering, following established protocols [28]. The coating deposition was verified for each specimen by scanning electron microscopy (SEM). After try-in, bonding surfaces were conditioned with 37% phosphoric acid, according to established evidence [35].

The bonding surfaces of the RBFDP retainer wings were prepared by a dental technician after final try-in to ensure a double blind study protocol. Bonding of all RBFDPs was performed under rubber dam isolation with a resin cement containing MDP monomer (Panavia 21 TC, Kuraray, Tokyo, Japan) (Figure 2). Patients were recalled at 2 weeks, 6 months, and then annually, during which treatment outcomes were assessed. The primary outcome was RBFDP retention, defined as the restoration remaining functional without debonding. Survival as a secondary outcome was defined as restorations remaining functional throughout the follow-up period.

### 2.3 | Statistical Analysis

Mann-Whitney U test for continuous outcomes and the Fisher exact test for categorical data were used to assess

patient-specific differences between study groups (age, sex, the position of the restoration, bonding surface area). Furthermore, all RBFDPs were additionally classified according to pontic position into three groups to evaluate the influence of the pontic position on the retention rate: Group 1, maxillary central incisors; Group 2, maxillary lateral incisors; and Group 3, mandibular incisors.

Retention rates, considering only debonding as an event, and survival rates were calculated for all RBFDPs, APA group, NAC group, and Groups 1–3 using Kaplan–Meier analysis. Group differences were assessed with the log-rank test at a significance level of  $\alpha = 0.05$ . Biological and technical complications, as well as censoring events, were recorded. Statistical analyses were conducted in IBM SPSS Statistics v20.0 (IBM Corp). Retainer wing surfaces of debonded RBFDPs were inspected with SEM. The RBFDPs' bonding surface area for each restoration was calculated using a 3D mesh processing package (MeshLab, ISTI-CNR, Pisa, Italy). Debonded abutment surfaces were inspected under  $\times 3.5$  magnification, and retainer wing surfaces were examined using SEM.

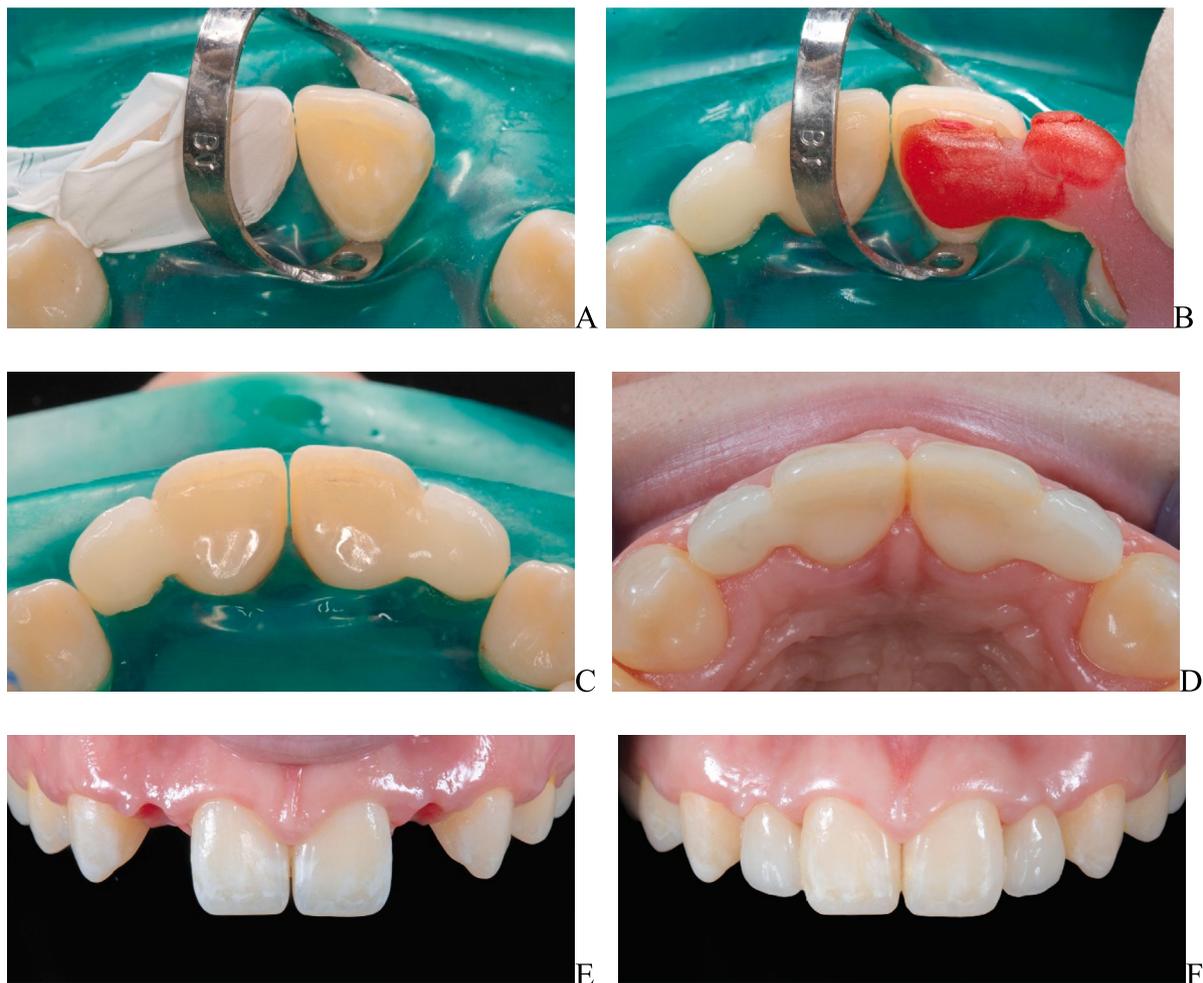
### 3 | Results

Within a mean  $\pm$  standard deviation observation period of  $61.4 \pm 22.1$  months with a minimum of 8.3 and a maximum of 97.4 months, 57 healthy participants with 64 cantilevered RBFDPs were examined with a drop-out rate of 0%. There were

no patient-specific differences among the two study groups ( $p > 0.05$ ) (Table 1). The cumulative survival rate for both groups was 100%.

Six debondings, one chipping, and three biological complications occurred. Two biological complications were observed 12 months after the insertion. They were represented by gingivitis under a maxillary central incisor pontic and a slight rotation

of a maxillary canine abutment, which was corrected with a removable orthodontic appliance. One case of occlusal trauma was identified 6 months after insertion, caused by a premature contact on the pontic and accompanied by increased tooth mobility. The condition resolved following occlusal adjustment. A minor technical complication, involving chipping of the incisal portion of the pontic, was observed in one restoration at the 4-year follow-up (Figure 3). The restoration remained functional

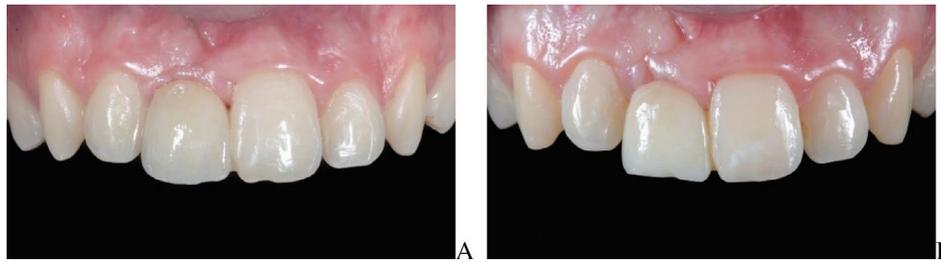


**FIGURE 2** | Replacement of the maxillary lateral incisors. (A) Tooth preparation confined to the enamel. (B) Positioning of the RBFDP with an acrylic splint. (C, D) Both RBFDPs after bonding. (E) Restorations before bonding. (F) One-year follow-up. RBFDP, resin-bonded fixed dental prosthesis.

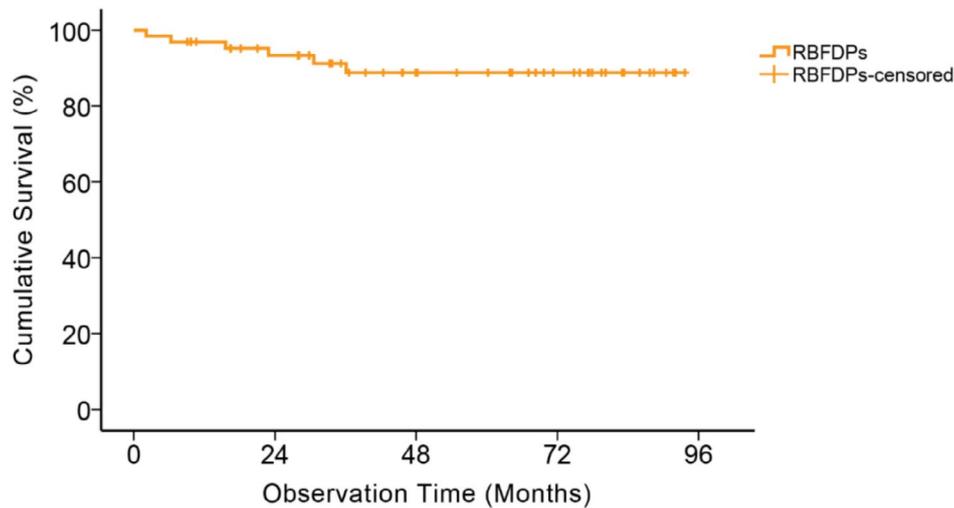
**TABLE 1** | Patient-specific differences between study groups (age, sex, position of the restoration, bonding surface area).

Characteristic	Outcomes	APA	NAC	<i>p</i>
Mean age (years)		30.3 (SD 2.9)	32.2 (SD 2.9)	0.34
Sex	Male	15	16	1
	Female	17	16	
Position of the restoration	Maxillary central incisor	13	8	0.45
	Maxillary lateral incisor	13	16	
	Mandibular incisor	6	8	
Bonding surface area (mm <sup>2</sup> )		50.8 (SD 2.9)	54.1 (SD 4.2)	0.99

Abbreviations: APA, airborne-particle abrasion; NAC, nanostructured alumina coating; SD, standard deviation.



**FIGURE 3** | Chipping of veneered porcelain. (A) Two-year follow-up. (B) Chipping of the incisal edge observed at the 4-year follow-up.

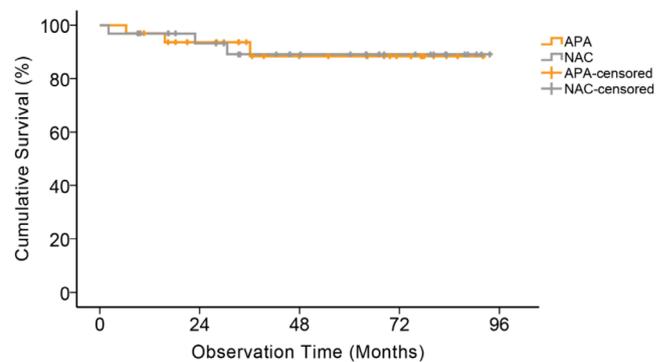


**FIGURE 4** | Kaplan–Meier retention curve for all RBFDPs. Censored events are indicated at the time of the last follow-up. RBFDP, resin-bonded fixed dental prosthesis.

and required no replacement after minor polishing of the incisal edge.

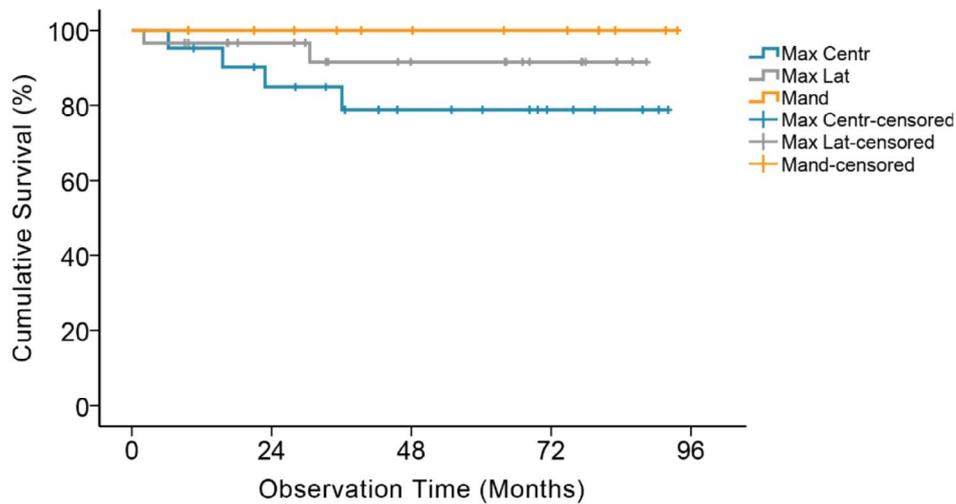
After a mean  $\pm$  standard deviation observation period of  $61.4 \pm 22.1$  months, considering retention, the cumulative success rate for all RBFDPs was 88.8% (Figure 4). The cumulative success rate was 88.4% for the NAC and 89.1% for the APA group (Figure 5), with no statistically significant differences between the groups (log-rank,  $p=0.99$ ). No statistically significant differences between bonding surface areas were found ( $p>0.05$ ) (Table 1), indicating no influence of the surface area on the differences between the survival rates of the APA and NAC groups. Kaplan–Meier analysis of retention rates according to pontic position indicated the highest cumulative retention in Group 3 (mandibular incisors, 100%), followed by Group 2 (maxillary lateral incisors, 88.8%) and Group 1 (maxillary central incisors, 79%); however, these differences were not statistically significant (log-rank test,  $p=0.18$ ) (Figure 6).

Six debondings occurred, three in the APA group and three in the NAC group. Before rebonding, all restoration surfaces were reconditioned by airborne-particle abrasion, and all rebonded restorations remained functional thereafter. In the APA group, one debonding occurred after 6.3 months following traumatic impact, while two occurred spontaneously after 15.6 and 36.1 months. In the NAC group, debondings occurred at 2.1, 22.9, and 30.6 months after cementation. The first two were associated with traumatic impacts, and the third occurred spontaneously.



**FIGURE 5** | Kaplan–Meier retention curves for airborne-particle abraded (APA) and alumina-coated (NAC) groups (Probability value from log-rank test = 0.99). Censored events represented by the last follow-up.

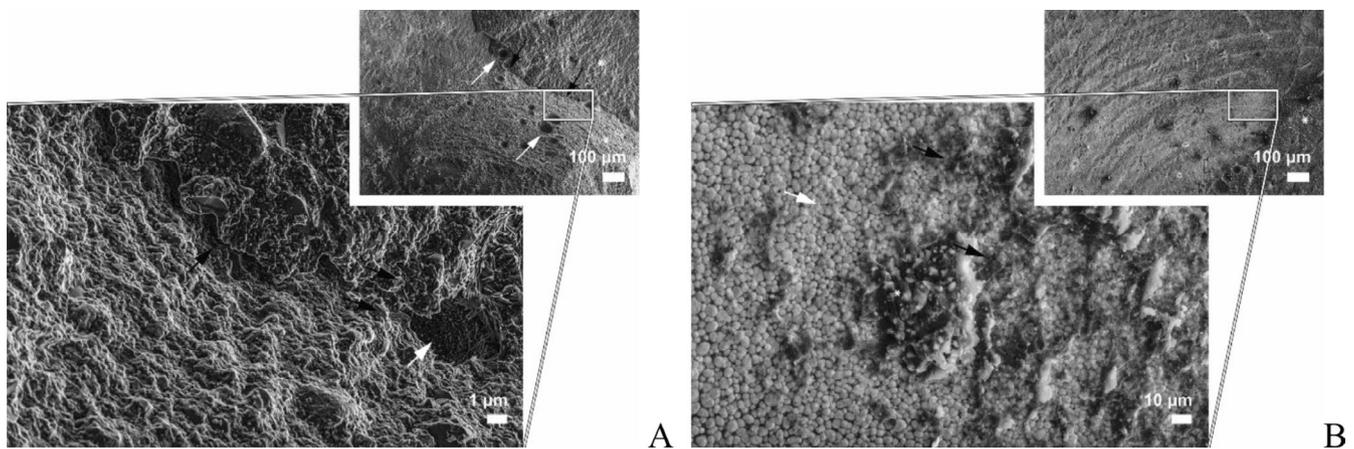
In both examined groups, the cement remained mainly adhered to the debonded surfaces of the abutment teeth (Figure 7). Analysis of the debonded retainer wings under SEM revealed mixed failure characteristics (Figure 8). SEM analysis of the debonded APA retainer wing showed small cement remnants forming thin, void-containing layers, with delaminations indicating cohesive fracture progressing to complete separation from the zirconia surface (Figure 8A). In contrast, the NAC retainer wing exhibited a similar amount of cement remnants and small areas of zirconia covered with NAC residues, consistent with a predominantly adhesive failure pattern (Figure 8B).



**FIGURE 6** | Kaplan–Meier retention curve for RBFDPs according to pontic position (Probability value from log-rank test = 0.18). Censored events represented by the last follow-up.



**FIGURE 7** | Debonding after 36.1 months. (A) Before debonding. (B) Debonded restoration showing the majority of resin cement remaining on the enamel surface.



**FIGURE 8** | Scanning electron micrographs of debonded zirconia retainer wings. (A) Low magnification (original magnification  $\times 100$ ) of debonded APA retainer wing (Figure inset) showing an area of residual resin cement (\*) with a delamination through the thin cement layer progressing to complete separation from the zirconia surface. Higher magnification (Original magnification  $\times 1000$ ) reveals delamination of a partial cement layer (black arrow) containing voids (white arrow). (B) Low magnification (original magnification  $\times 100$ ) of debonded NAC retainer wing (Figure inset) showing an area of residual resin cement (\*) and exposed zirconia. Higher magnification (Original magnification  $\times 5000$ ) reveals cement remnants covering NAC, exposed NAC residues that are less compact (black arrow), and exposed zirconia grains (white arrow).

#### 4 | Discussion

Based on the findings of this prospective, randomized, controlled, double-blind clinical trial, comparable performance of zirconia RBFDPs pretreated with NAC and APA was observed. Further, no significant differences in retention and

survival rates were detected; therefore, the null hypothesis was accepted.

Retention loss remains the most frequently reported clinical complication of cantilevered zirconia RBFDPs, with a prevalence rate of 12.2%, mainly attributable to the limited predictability of

bonding to inert zirconia [32, 36, 37]. Clinical reports on the potential of zirconia RBFDPs have increased over the past decade [3, 4, 7, 11–13], yet long-term studies with larger sample sizes remain scarce. Evidence from randomized controlled trials assessing the clinical performance of different bonding systems remains especially limited [1, 5, 13, 32], with NAC representing the only alternative zirconia pretreatment method investigated to date and demonstrating promising short-term results.

The present study on NAC-coated RBFDPs included a larger cohort and a longer observation period, thereby strengthening the validity of clinical findings [32] and, to the best of the authors' knowledge, representing the largest randomized controlled trial to date evaluating different zirconia surface modifications. The overall retention rate of 88.8% (Figure 4) and the absence of significant differences between the APA and NAC groups further support previous short-term results [32], establishing NAC as a reliable alternative surface treatment.

The findings of this clinical trial are consistent with the literature. Short-term studies report high success and retention rates, although outcomes vary with the bonding protocol. The omission of airborne-particle abrasion [8] or a separate MDP-containing primer [3] has been associated with reduced retention rates of 60%–82%. In contrast, the use of MDP-based cement alone in this study did not compromise retention, highlighting the importance of careful clinical handling during bonding, particularly in the early post-insertion phase. Mid-term trials with 4- to 6-year observation periods show more consistent outcomes, with survival rates typically exceeding 90% [4, 6, 7], including a 93.3% five-year survival for zirconia RBFDPs cemented with a similar MDP-based bonding system as used in the present study [5]. Our results over a comparable period corroborate these findings, indicating that once early debonding risk is overcome, mid-term retention remains stable.

The available long-term data, while scarce, support favorable outcomes. In a small trial of 10 restorations, debonding was the main complication, resulting in an 80% 10-year retention and success rates, with most failures occurring early [12]. The most comprehensive long-term evidence from a large cohort shows success and retention rates of 92.4% at 10 years, declining to 82.6% at 15 years [11]. Despite a large cohort of 310 restorations, a subset of restorations reached the longest endpoint. The present trial, with follow-up extending up to 8 years and a mean observation period of 5 years, provides complementary mid- to long-term evidence.

Differences in retention were observed depending on the pontic position, although statistical analysis was probably limited by the small number of debonding events (Figure 6). The higher incidence of debonding among maxillary central incisors is consistent with previous reports [11] and may be explained by their greater exposure to occlusal and traumatic stresses. In support of this, numerous debonding events in the present study were associated with traumatic impacts, with a case of veneer chipping in a maxillary central incisor further suggesting the central incisor pontic position's susceptibility to functional loading [11].

In the present study, six debonding events were observed within the first 3 years of function, half of which were associated with

traumatic impacts or excessive masticatory forces during the early post-insertion period. Three spontaneous debondings, two in the APA group and one in the NAC group, occurred early in function, suggesting that inadequate bonding surface preparation or procedural errors during cementation may have contributed to the failures. These findings are consistent with previous reports indicating that roughly half of debonding events result from trauma, while the remainder occur spontaneously [32]. The restoration surface area in both groups was comparable (Table 1), therefore, its influence on survival differences between APA- and NAC-treated zirconia RBFDPs was excluded.

Given the sensitivity of zirconia bonding to procedural variables, contamination control during the try-in phase represents an important clinical consideration. To avoid confounding the effects of the investigated pretreatments, air-abrasion was performed after the final try-in, eliminating the need for additional chemical cleaning agents and ensuring that the observed retention rates reflected the effects of the pretreatment method alone. Chemical and nonabrasive cleaners have been proposed for decontamination of zirconia; however, their efficacy is generally lower than that of airborne-particle abrasion [38]. In contrast, for NAC-coated surfaces, 37% phosphoric acid was applied after try-in. This protocol has been shown to most effectively remove saliva-derived organic contaminants from NAC surfaces and restore bonding performance [35]. Owing to its nanostructured, high-surface-area morphology and pronounced hydrophilicity, the NAC coating is particularly susceptible to salivary adhesion [39]. Consequently, chemical acid cleaning is effective and nondeleterious to the coating in contrast to invasive airborne-particle abrasion, which would result in its removal [40]. However, phosphoric acid treatment remains ineffective against silicone contamination. Therefore, the use of silicone-based fit-checking materials should be approached with caution when bonding NAC-coated RBFDPs [35].

Scanning electron microscopy of the debonded restorations revealed slightly different failure characteristics (Figure 8). In the APA group, failures were primarily adhesive, with minor areas of cohesive failure within the resin cement, corroborating previous FEA findings that cohesive fractures occur in the highly stressed areas of RBFDP's retainer wing [31]. NAC-pretreated restorations exhibited adhesive failures predominantly at the NAC–zirconia interface, with a few residual NAC remnants visible. These observations differ slightly from previous *in vitro* studies, in which more extensive NAC residues were typically found on the zirconia surface after debonding [31]. Nevertheless, similar failure patterns have been reported in an earlier clinical trial [32]. Overall, these findings suggest subtle differences in the interfacial bonding mechanisms between the two surface treatments and indicate that optimizing the NAC calcination protocol could further strengthen NAC bonding to zirconia and reduce the risk of interfacial delamination.

No framework fractures were observed in the present study, which employed high-strength 3Y-TZP zirconia. To date, only a single clinical investigation has reported framework fractures in zirconia RBFDPs [13], and it remains the only study evaluating anterior RBFDPs fabricated from translucent zirconia. Given the increasing use of these more damage-prone zirconia with increased yttria concentration of up to 5 mol% [19, 20, 41], less

invasive surface pretreatment methods are gaining clinical relevance. Among these, NAC is a promising alternative to the more aggressive APA technique.

The present study remains the only randomized controlled clinical trial to date assessing an alternative zirconia pretreatment method in a mid- to long-term setting. Although retention rates did not differ significantly, the comparable performance of NAC relative to the well-established APA protocol is clinically relevant, particularly given concerns regarding the potential weakening effect of APA on high-translucent zirconia. Although this study included a relatively large sample compared to previous controlled trials [32], further clinical investigations with a larger cohort and especially with a longer observation period are needed to confirm long-term outcomes and determine whether NAC offers advantages in terms of retention and mechanical reliability.

## 5 | Conclusions

Within the limitations of the present study, the following conclusions can be drawn: Both pretreatment methods showed comparable outcomes, with up to 8-year retention rates of 88.4% for NAC and 89.1% for APA zirconia RBFDPs. Debonding failures were mainly adhesive, with coating delamination indicating the NAC–zirconia interface as the weakest link. Retention rates were the highest for RBFDPs replacing mandibular and lowest for maxillary central incisors, although no statistically significant differences were detected.

### Acknowledgments

The authors have nothing to report.

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### Ethics Statement

The study protocol was approved by the National Medical Ethics Committee (Approval No. 0120-438/2018/6). The study was conducted at the Department of Prosthodontics, Faculty of Medicine, University of Ljubljana, Slovenia.

### Consent

Written informed consent was obtained from all participants or their legal guardians prior to participation. The trial was registered at ClinicalTrials.gov (NCT04693949).

### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## References

1. A. Y. Alqutaibi, M. A. Alghauli, S. A. Almuzaini, et al., “Failure and Complication Rates of Different Materials, Designs, and Bonding Techniques of Ceramic Cantilever Resin-Bonded Fixed Dental Prostheses for Restoring Missing Anterior Teeth: A Systematic Review and Meta-Analysis,” *Journal of Esthetic and Restorative Dentistry: Official Publication of the American Academy of Esthetic Dentistry* 36, no. 10 (2024): 1396–1411.
2. D. Edelhoff and J. A. Sorensen, “Tooth Structure Removal Associated With Various Preparation Designs for Posterior Teeth,” *International Journal of Periodontics & Restorative Dentistry* 22, no. 3 (2002): 241–249.
3. M. Kern, N. Passia, M. Sasse, and C. Yazigi, “Ten-Year Outcome of Zirconia Ceramic Cantilever Resin-Bonded Fixed Dental Prostheses and the Influence of the Reasons for Missing Incisors,” *Journal of Dentistry* 65 (2017): 51–55.
4. M. Sasse and M. Kern, “Survival of Anterior Cantilevered All-Ceramic Resin-Bonded Fixed Dental Prostheses Made From Zirconia Ceramic,” *Journal of Dentistry* 42, no. 6 (2014): 660–663.
5. M. Sasse and M. Kern, “CAD/CAM Single Retainer Zirconia-Ceramic Resin-Bonded Fixed Dental Prostheses: Clinical Outcome After 5 Years,” *International Journal of Computerized Dentistry* 16, no. 2 (2013): 109–118.
6. I. Sailer and C. H. Hammerle, “Zirconia Ceramic Single-Retainer Resin-Bonded Fixed Dental Prostheses (RBFDPs) After 4 Years of Clinical Service: A Retrospective Clinical and Volumetric Study,” *International Journal of Periodontics & Restorative Dentistry* 34, no. 3 (2014): 333–343.
7. A. Klink and F. Huttig, “Zirconia-Based Anterior Resin-Bonded Single-Retainer Cantilever Fixed Dental Prostheses: A 15- To 61-Month Follow-Up,” *International Journal of Prosthodontics* 29, no. 3 (2016): 284–286.
8. S. Shahdad, M. J. Cattell, J. Cano-Ruiz, E. Gamble, and A. Gamboa, “Clinical Evaluation of All Ceramic Zirconia Framework Resin Bonded Bridges,” *European Journal of Prosthodontics and Restorative Dentistry* 26 (2018): 201–211.
9. N. P. Quigley, D. S. S. Loo, C. Choy, and W. N. Ha, “Clinical Efficacy of Methods for Bonding to Zirconia: A Systematic Review,” *Journal of Prosthetic Dentistry* 125, no. 2 (2021): 231–240.
10. M. Ozcan and M. Bernasconi, “Adhesion to Zirconia Used for Dental Restorations: A Systematic Review and Meta-Analysis,” *Journal of Adhesive Dentistry* 17, no. 1 (2015): 7–26.
11. M. Kern, L. Türp, and C. Yazigi, “Long-Term Outcome of Anterior Cantilever Zirconia Ceramic Resin-Bonded Fixed Dental Prostheses: Influence of the Pontic Location,” *Journal of Prosthetic Dentistry* 133, no. 4 (2025): 1017–1023.
12. N. Naenni, G. Michelotti, W. Z. Lee, I. Sailer, C. H. Hammerle, and D. S. Thoma, “Resin-Bonded Fixed Dental Prostheses With Zirconia Ceramic Single Retainers Show High Survival Rates and Minimal Tissue Changes After a Mean of 10 Years of Service,” *International Journal of Prosthodontics* 33, no. 5 (2020): 503–512.
13. H. Bilir, E. Yuzbasioglu, G. Sayar, D. D. Kilinc, H. G. G. Bag, and M. Özcan, “CAD/CAM Single-Retainer Monolithic Zirconia Ceramic Resin-Bonded Fixed Partial Dentures Bonded With Two Different Resin Cements: Up to 40 Months Clinical Results of a Randomized-Controlled Pilot Study,” *Journal of Esthetic and Restorative Dentistry* 34, no. 7 (2022): 1122–1131.
14. Y. Zhang, B. R. Lawn, E. D. Rekow, and V. P. Thompson, “Effect of Sandblasting on the Long-Term Performance of Dental Ceramics,” *Journal of Biomedical Materials Research. Part B, Applied Biomaterials* 71, no. 2 (2004): 381–386.
15. Y. Zhang, B. R. Lawn, K. A. Malament, P. Van Thompson, and E. D. Rekow, “Damage Accumulation and Fatigue Life of Particle-Abraded

- Ceramics," *International Journal of Prosthodontics* 19, no. 5 (2006): 442–448.
16. H. Wang, M. N. Aboushelib, and A. J. Feilzer, "Strength Influencing Variables on CAD/CAM Zirconia Frameworks," *Dental Materials: Official Publication of the Academy of Dental Materials* 24, no. 5 (2008): 633–638.
  17. C. Oblak, I. Verdenik, M. V. Swain, and T. Kosmac, "Survival-Rate Analysis of Surface Treated Dental Zirconia (Y-TZP) Ceramics," *Journal of Materials Science. Materials in Medicine* 25, no. 10 (2014): 2255–2264.
  18. C. Oblak, A. Kocjan, P. Jevnikar, and T. Kosmač, "The Effect of Mechanical Fatigue and Accelerated Ageing on Fracture Resistance of Glazed Monolithic Zirconia Dental Bridges," *Journal of the European Ceramic Society* 37, no. 14 (2017): 4415–4422.
  19. F. Zhang, H. Reveron, B. C. Spies, B. Van Meerbeek, and J. Chevalier, "Trade-Off Between Fracture Resistance and Translucency of Zirconia and Lithium-Disilicate Glass Ceramics for Monolithic Restorations," *Acta Biomaterialia* 91 (2019): 24–34.
  20. T. Mirt, A. Abram, N. Van de Velde, et al., "Effect of Airborne-Particle Abrasion of Yttria-Containing Zirconia Dental Ceramics on Mechanical Properties Before and After Regeneration Firing," *Journal of the European Ceramic Society* 42, no. 12 (2022): 5035–5044.
  21. S. S. Atsu, M. A. Kilcarslan, H. C. Kucukmen, and P. S. Aka, "Effect of Zirconium-Oxide Ceramic Surface Treatments on the Bond Strength to Adhesive Resin," *Journal of Prosthetic Dentistry* 95, no. 6 (2006): 430–436.
  22. T. Derand, M. Molin, and K. Kvam, "Bond Strength of Composite Luting Cement to Zirconia Ceramic Surfaces," *Dental Materials: Official Publication of the Academy of Dental Materials* 21, no. 12 (2005): 1158–1162.
  23. C. Y. Lung, E. Kukk, and J. P. Matinlinna, "The Effect of Silica-Coating by Sol-Gel Process on Resin-Zirconia Bonding," *Dental Materials Journal* 32, no. 1 (2013): 165–172.
  24. P. Everson, O. Addison, W. M. Palin, and F. J. Burke, "Improved Bonding of Zirconia Substructures to Resin Using a "Glaze-On" Technique," *Journal of Dentistry* 40, no. 4 (2012): 347–351.
  25. J. H. Phark, S. Duarte, Jr., M. Blatz, and A. Sadan, "An in Vitro Evaluation of the Long-Term Resin Bond to a New Densely Sintered High-Purity Zirconium-Oxide Ceramic Surface," *Journal of Prosthetic Dentistry* 101, no. 1 (2009): 29–38.
  26. F. Egilmez, G. Ergun, I. Cekic-Nagas, P. K. Vallittu, M. Ozcan, and L. V. Lassila, "Effect of Surface Modification on the Bond Strength Between Zirconia and Resin Cement," *Journal of Prosthodontics* 22, no. 7 (2013): 529–536.
  27. M. N. Aboushelib, C. J. Kleverlaan, and A. J. Feilzer, "Selective Infiltration-Etching Technique for a Strong and Durable Bond of Resin Cements to Zirconia-Based Materials," *Journal of Prosthetic Dentistry* 98, no. 5 (2007): 379–388.
  28. T. Malgaj, A. Kocjan, and P. Jevnikar, "The Effect of Firing Protocols on the Resin-Bond Strength to Alumina-Coated Zirconia Ceramics," *Advances in Applied Ceramics* 119 (2019): 267–275.
  29. P. Jevnikar, K. Krnel, A. Kocjan, N. Funduk, and T. Kosmac, "The Effect of Nano-Structured Alumina Coating on Resin-Bond Strength to Zirconia Ceramics," *Dental Materials: Official Publication of the Academy of Dental Materials* 26, no. 7 (2010): 688–696.
  30. T. Malgaj, T. Mirt, A. Kocjan, and P. Jevnikar, "The Influence of Nanostructured Alumina Coating on Bonding and Optical Properties of Translucent Zirconia Ceramics: In Vitro Evaluation," *Coatings* 11, no. 9 (2021): 1126.
  31. T. Malgaj, R. Papšik, A. Abram, A. Kocjan, and P. Jevnikar, "Bonding Performance of Surface-Treated Zirconia Cantilevered Resin-Bonded Fixed Dental Prostheses: In Vitro Evaluation and Finite Element Analysis," *Materials (Basel, Switzerland)* 16, no. 7 (2023): 2646.
  32. T. Malgaj, A. Abram, A. Kocjan, and P. Jevnikar, "Influence of Nanostructured Alumina Coating on the Clinical Performance of Zirconia Cantilevered Resin-Bonded Fixed Dental Prostheses: Up to 3-Year Results of a Prospective, Randomized, Controlled Clinical Trial," *Journal of Prosthetic Dentistry* 129, no. 5 (2023): 725–731.
  33. K. F. Schulz, D. G. Altman, and D. Moher, "CONSORT 2010 Statement: Updated Guidelines for Reporting Parallel Group Randomised Trials," *BMJ (Clinical Research Ed)* 340 (2010): c332.
  34. *Adhasivbrucken* (Quintessenz Publishing Deutschland, 2017).
  35. S. Zhang, A. Kocjan, F. Lehmann, T. Kosmac, and M. Kern, "Influence of Contamination on Resin Bond Strength to Nano-Structured Alumina-Coated Zirconia Ceramic," *European Journal of Oral Sciences* 118, no. 4 (2010): 396–403.
  36. G. Sterzenbach, R. Tunjan, M. Rosentritt, and M. Naumann, "Increased Tooth Mobility Because of Loss of Alveolar Bone Support: A Hazard for Zirconia Two-Unit Cantilever Resin-Bonded FDPs In Vitro?," *Journal of Biomedical Materials Research. Part B, Applied Biomaterials* 102, no. 2 (2014): 244–249.
  37. M. M. M. Gresnigt, G. Tirlet, M. Bosnjak, S. van der Made, and J. P. Attal, "Fracture Strength of Lithium Disilicate Cantilever Resin Bonded Fixed Dental Prosthesis," *Journal of the Mechanical Behavior of Biomedical Materials* 103 (2020): 103615.
  38. L. Musharbash, K. Fnu, F. Ozer, E. Anadioti, and M. B. Blatz, "Effectiveness of Cleaning Agents on Bond Strength to Contaminated Zirconia," *Journal of Esthetic and Restorative Dentistry: Official Publication of the American Academy of Esthetic Dentistry* 37, no. 11 (2025): 2451–2458.
  39. A. Kocjan, A. Dakskobler, and T. Kosmač, "Superhydrophobic Nanostructured Boehmite Coatings Prepared by AlN Powder Hydrolysis," *International Journal of Applied Ceramic Technology* 8 (2010): 848–853.
  40. J. Moritz, A. Abram, M. Čekada, et al., "Nanoroughening of Sand-blasted 3Y-TZP Surface by Alumina Coating Deposition for Improved Osseointegration and Bacteria Reduction," *Journal of the European Ceramic Society* 39, no. 14 (2019): 4347–4357.
  41. T. Malgaj, A. Plut, A. Eberlinc, M. Drevensek, and P. Jevnikar, "Anterior Esthetic Rehabilitation of an Alveolar Cleft Using Novel Minimally Invasive Prosthodontic Techniques: A Case Report," *Cleft Palate-Craniofacial Journal* 58 (2020): 912–918.