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Surface decontamination of explanted peri-implantitis-affected implants

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Abstract

Aim

The present study aimed at evaluating the effect of air-polishing (AP) and a combination of AP and alkaline electrolysed water (AEW) in surface decontamination of explanted peri-implantitis-affected implants.

Materials and Methods

Twenty-five patients with 34 dental implants scheduled for explantation due to severe peri-implantitis were included. Following implant removal, the apical part of each implant was embedded in acrylic blocks. Implants were randomly allocated to surface decontamination using AP with or without AEW. Four implants were left untreated and used as negative controls. Specimens were analysed using scanning electron microscopy (SEM) and energy-dispersive x-ray spectroscopy (EDS). Area of residual bacteria was the primary outcome.

Results

SEM analysis revealed that both treatment protocols were effective in biofilm removal and only small proportions of target areas of the implants showed residual bacterial or mineralized deposits. Although differences between the treatment protocols were small, implant thread loci (top/flank/valley), zones of the implant (apical/middle/coronal), implant surface characteristics and gender influenced the results. In addition, EDS analysis showed that zones influenced the atomic% of carbon and calcium and that implant surface

characteristics affected the atomic% of titanium.

Conclusions

AP, with or without AEW, is an effective method in removing biofilm from peri-implantitis-affected implants.

Clinical Relevance

Scientific rationale for study: Effective removal of the bacterial biofilm from implant surfaces is a prerequisite for resolution of inflammation in peri-implant tissues in the treatment of peri-implantitis.

Principal findings: Surface decontamination using an air-flow device was effective in removing the bacterial biofilm from the explanted peri-implantitis-affected implant surface. The benefit of the adjunctive use of alkaline electrolysed water was minor. Implant geometry and surface characteristics influenced cleaning efficacy.

Practical implications: Potential benefits of the use of air-polishing device in the treatment of peri-implantitis should be assessed in randomized clinical controlled trials.

1 INTRODUCTION

Peri-implantitis is a pathological condition occurring in tissues around dental implants. It is caused by microorganisms and characterized by inflammation in the peri-implant connective tissue and loss of the supporting bone (Berglundh et al., 2018). The goal of treatment of peri-implantitis is to resolve inflammation and to arrest further loss of the supporting bone. In a consensus report from the XVIII European Workshop on Periodontology (EWOP), clinical practice guidelines on treatment of peri-implant diseases were established (Herrera et al., 2023). It was reported that the management of peri-implantitis is challenging and associated with significant morbidity. In addition, treatment of peri-implantitis was recommended to be performed sequentially, and to encompass an initial non-surgical step, followed by a surgical step, depending on the outcomes of the initial treatment. The consensus report also stated that the purpose of a surgical approach in the management of peri-implantitis is to provide access to the implant to facilitate surface decontamination. Although a standard surgical procedure was suggested to include cleaning/decontamination of the implant surface using, for example, small pieces of gauze soaked in saline and removal of mineralized

deposits with curettes, additional implant surface decontamination procedures were suggested to include mechanical/physical methods and/or chemical agents (Herrera et al., 2023). Results from systematic reviews performed in conjunction with the EWOP indicated that only few controlled studies exist on additional implant surface decontamination methods (Ramanauskaite et al., 2023; Wilensky et al., 2023). Hence, recommendations on their use were in general careful and negative (Herrera et al., 2023).

Although there is no doubt that controlled clinical trials are required to provide evidence on the clinical efficacy of a certain treatment protocol, such studies should be preceded by experiments using highly sensitive methods for evaluation. Thus, in vitro studies that mimic a surgical scenario and demonstrate the efficacy in, for example, biofilm removal and potential damage to the implant surface are essential in the early stages of testing. Subsequent evaluations, however, should apply study designs that enhance the clinical relevance of methods.

In two in vitro studies (Ichioka et al., 2021, 2022), different mechanical and chemical decontamination protocols on biofilm-coated titanium discs were evaluated. It was demonstrated that air-polishing (AP) was the superior mechanical method, while alkaline electrolysed water (AEW) was the most effective chemical agent. AEW, containing hypochlorite ion and hypochlorous acid, has potential cleaning and antimicrobial effects (Fukuzaki et al., 2004; Ichioka et al., 2021). The aim of the present study was to evaluate the effect of AP and a combination of AP and AEW in the surface decontamination of explanted peri-implantitis-affected implants.

2 MATERIALS AND METHODS

The study protocol was approved by the Swedish Ethical Review Authority (Dnr 2021-02515/2021-06484-02). Patients were provided with detailed information, and written consent was obtained before the start of the study.

2.1 Patient sample

Twenty-five patients presenting with 34 dental implants scheduled for explantation due to severe peri-implantitis at three specialist clinics (Clinics for Periodontics in Gothenburg, Uddevalla and Borås, Public Dental Health Services, Region Västra Götaland, Sweden) were included in the study. Demographic data on patients and implant characteristics are given in Table 1.

TABLE 1. Demographic data on patients and characteristics of explanted implants.

	Total	AP + NaCl	AP + AEW	Untr
Patients, *N*	25			
Age, mean (range), year	71.6 (39–87)			
Gender, *n* (%)				
Male	11 (44.0)			
Female	14 (56.0)			
Implants, *n*	34	15	15	4
Jaw, *n* (%)				
Maxilla	27 (79.4)	13 (86.7)	11 (73.3)	3 (75
Mandible	7 (20.6)	2 (13.3)	4 (26.7)	1 (25
Location, *n* (%)				
Anterior	11 (32.4)	6 (40.0)	3 (20.0)	2 (50
Posterior	23 (67.6)	9 (60.0)	12 (80.0)	2 (50
Prosthetics, *n* (%)				
Cement-retained	5 (14.7)	2 (13.3)	2 (13.3)	
Screw-retained	29 (85.3)	13 (86.7)	13 (86.7)	

Abbreviations: AP + AEW, air-polishing and gauze soaked in alkaline electrolysed water; AP + NaCl, air-polishing and gauze soaked in saline; BOP, bleeding on probing; MBL, marginal bone level; PPD, probing pocket depth.

[a] A: TiUnite (Nobel Biocare AB); B: TiOblast (Astra Tech Implant System; Dentsply Sirona Implants); C: OsseoSpeed (Astra Tech Implant System); D: Ankylos (Dentsply Sirona Implants); E: SLA (Straumann).

2.2 Assessments prior to implant retrieval

Clinical assessments of probing pocket depth (PPD) and bleeding on probing (BOP) were performed, and information related to the target implant (e.g., brand, surface, dimensions, time of function, history of treatment of peri-implantitis) was collected (Table 1). Intra-oral radiographs were obtained, and the distance between the implant margin and the marginal bone level (MBL) was measured at the mesial and distal aspects of the implant by one investigator (YI) using an image analysis software (ImageJ2, 2.3.1/1.53q; National Institutes of Health, Bethesda, MD, USA). The scale of the radiographic images was adjusted to the known

inter-thread distance (in millimetres). MBL assessments were performed in duplicate. The mean difference between the two assessments was 0.34 ± 0.37 mm with an intra-class correlation coefficient of 0.97 (95% confidence interval [CI]: 0.93–0.98). The included implant sites had a mean PPD of 9.1 ± 1.9 mm, circumferential BOP and an MBL of 9.3 ± 1.9 mm.

2.3 Implant retrieval

Seven out of 34 implants were removed in a non-surgical manner using forceps, while the remaining 27 implants were explanted in conjunction with a surgical flap procedure. These implants were removed using either a reverse torque device (FR Kit, NeoBiotech, Den Bosch, Netherlands) or by elevators and/or forceps (applied only to the neck area of the implant). In three cases, the peri-implant bone was resected by rotating or trephine burs to facilitate implant removal. During all procedures, care was taken to avoid damage to the implant and the biofilm/calculus residing on the implant surface.

Immediately after explantation, the implants were immersed in VMGA III (Viability Medium Gothenburg; Dahlén et al., **1993**, Department of Microbiology, University of Gothenburg, Sweden) transport medium and stored at 4°C. Surface decontamination was performed after a mean storage time of 3.5 days (range: 0–16 days).

2.4 Implant surface decontamination

Decontamination procedures were performed in a standardized manner by one trained operator (YI). Following irrigation with saline, the apical part (3 mm) of each implant was embedded in acrylic blocks. Implants were then randomly allocated to one of two surface decontamination protocols by coin toss. In the first protocol, surface decontamination was performed by a combination of AP and wiping with sterile 10 × 10 mm gauzes soaked in 0.9% NaCl (pH 7.0, Fresenius Kabi, Sweden). In the second protocol, AP was combined with wiping with a gauze soaked in 0.1% AEW (pH 9.0, Aoi Engineering Inc., Shizuoka, Japan).

AP (Airflow Prophylaxis Master, EMS, Nyon, Switzerland) was carried out with AIR-FLOW powder PLUS (EMS) containing erythritol (sugar alcohol, 14 μm), amorphous silica and 0.3% chlorhexidine. The handpiece was moved in a horizontal direction along implant threads from an apical to a coronal position for a total treatment time of 60 s per implant. The AP device was adjusted to a power setting of 5 bar static pressure and a maximum level of irrigation with water.

The AEW and NaCl solutions were warmed to 60°C in a water bath prior to treatment. Wiping was done in a horizontal direction along implant threads for 60 s. Gauzes were exchanged after 30 s.

Four explanted peri-implantitis-affected implants from four patients were left untreated and used as negative controls (untreated).

2.5 Sample preparation and analysis

Immediately after surface decontamination, the implants were placed in a fixative (2.5% glutaraldehyde [GA] buffered in 0.1 M PIPES) for 24 h and subsequently transferred to 0.25% GA and stored at 4°C. The samples were washed for 6× 5 min with 0.1 M PIPES buffer and then incubated in 1% osmium tetroxide in PIPES for 45 min. After an additional washing with dH_2O (5× 3 min) and dehydration in increasing concentrations of ethanol, specimens were dried with hexamethyldisilazane (Fluka, Buchs, Switzerland). No coating was performed prior to analysis.

Scanning electron microscopy (SEM; GeminiSEM 450, ZEISS, Germany) was used to evaluate residual bacterial and mineralized deposits on the decontaminated implant surfaces. First, low-magnification images (25× and 100×) were obtained using a secondary electron detector at 8 kV under vacuum at a distance of approximately 45 mm. The region of interest (ROI), that is, parts of the implant that had been exposed to peri-implantitis, was determined by the bone loss dimensions assessed on intra-oral radiographs. The apical 3-mm part of the implant used for embedding was disregarded. Three zones (apical, middle and coronal) of the ROI were established by applying a grid (Figure 1), and images were acquired at 100× magnification. The position of the three zones was memorized by a plug-in system. Using a working distance of 4–6 mm, 4 kV and 80% depth of field, six micrographs (magnification 3000×, total field area: 8489 μm^2) were obtained from each zone with detectors for secondary electrons (SEs) and backscattered electrons (BSEs) from different loci: top of a thread (two images), the flank (two images) and valleys between threads (two images) (Figure 1). BSE images were analysed with Trainable Weka Segmentation (Arganda-Carreras et al., 2017) or an ROI manager plugged in an image analyser (ImageJ2, 2.3.1/1.53q). The areas of residual bacteria and mineralized deposits were measured and expressed in square micrometres.

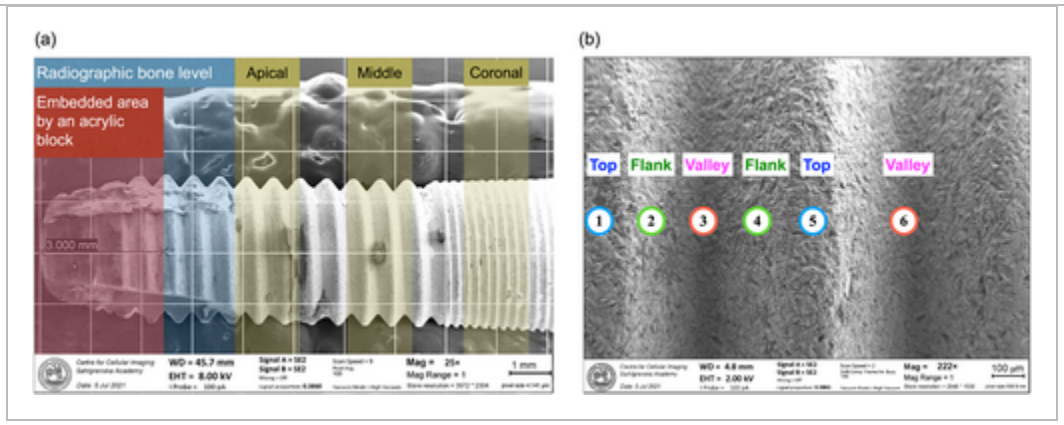

FIGURE 1

Open in figure viewer | PowerPoint

(a) Regions of interest for scanning electron microscopy/energy-dispersive x-ray spectroscopy analysis. (b) Implant thread loci (top, flank and valley) in a targeted zone. EHT, electron high tension; WD, working distance.

Energy-dispersive x-ray spectroscopy (EDS; XFlash Detector 6|60, Bruker, Germany) was used at 'valley sites' within the three zones (apical, middle and coronal) using the following setting: working distance of 7 mm and voltage of 10 kV at a magnification of 3000×. The target elements of the analysis were carbon (C), oxygen (O), titanium (Ti) and calcium (Ca). The atomic% of the chemical elements was calibrated by the ESPRIT 2.3 software (Bruker Nano, Germany). EDS/SEM mapping images of the randomly selected sites at different magnification (300–3000×) were acquired and image segmentation was performed post processing with the ESPRIT 2.3 software.

2.6 Data analysis

The primary outcome of the SEM analysis was the surface area colonized by residual bacteria. Secondary outcomes in the present study were surface area covered by mineralized deposits and atomic% of elements (C, O, Ti and Ca). As the study samples showed an unbalanced distribution of potential confounders (e.g., patient characteristics, implant characteristics), an adjusted multilevel linear regression analysis (STATA 17.0, StataCorp, College Station, TX, USA) was applied to further evaluate potential differences between the treatment groups (AP + NaCl vs. AP + AEW). The analysis included 270 measurements at loci level and considered clustering at implant level ($n = 30$). Residual bacterial area was predicted with 95% CIs using a p-value of .05. Post hoc testing with Bonferroni correction was applied for multiple comparisons. Overall mean areas of bacterial deposits, calculus and clean titanium were also analysed by Mann–Whitney U test. The data on atomic% of carbon, oxygen, titanium and calcium obtained in the EDS analysis were evaluated by regression analysis.

3 RESULTS

Data from quantitative image analyses for area containing bacteria are shown in Figure 2. The analyses revealed that the overall mean areas of residual bacteria amounted to 629.2 ± 958.4 μm^2 (7%) and 324.7 ± 310.1 μm^2 (4%) following the use of AP + NaCl and AP + AEW, respectively ($p = .18$). Bacterial deposits were detected primarily at the flank and valley sites (Figure 2). Differences between loci (top vs. flank/valley) were more pronounced in the AP + NaCl treatment group than in the AP + AEW group (Figure 2). Regarding mineralized deposits, the overall mean areas for the AP + NaCl and AP + AEW groups were 981.2 ± 813.1 μm^2 (12%) and 529.0 ± 790.4 μm^2 (6%), respectively ($p = .03$). Calculus was observed more frequently and in greater abundance in the coronal zone of the implants and typically followed the outline of the

implant thread geometry. Overall, no residual powder-like deposits were evident on any of the evaluated surfaces, although gauze deposits were rarely detected at the analysed magnification.

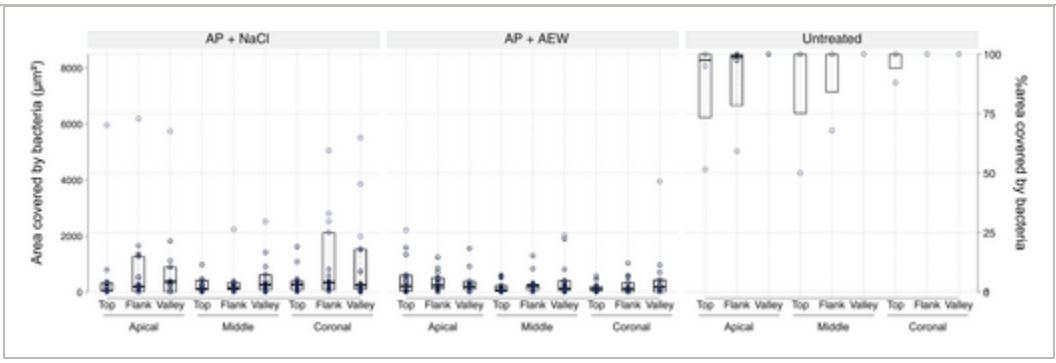

FIGURE 2

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Results from scanning electron microscopy image analysis. Areas of remaining bacteria in the AP + NaCl (left) and AP + AEW (centre) treatment groups. Area covered by bacteria on untreated implants (right). Results are expressed in square micrometres and %area. Boxes illustrate medians and quartiles. AEW, alkaline electrolysed water; AP, air-polishing.

The pattern of residual bacterial biofilm was influenced by implant surface characteristics (Figure 3). Thus, blasted and acid-etched surfaces (OsseoSpeed, Astra Tech Implant System, Dentsply Sirona Implants, Mölndal, Sweden) showed residual bacteria mainly at gaps located between crystals, while anodic oxidized surfaces (TiUnite, Nobel Biocare, Kloten, Switzerland) showed residual bacteria in the typical porous structures. On sand-blasted and acid-etched surfaces (SLA, Straumann, Basel, Switzerland), areas of residual bacteria were observed mainly between micro pits.

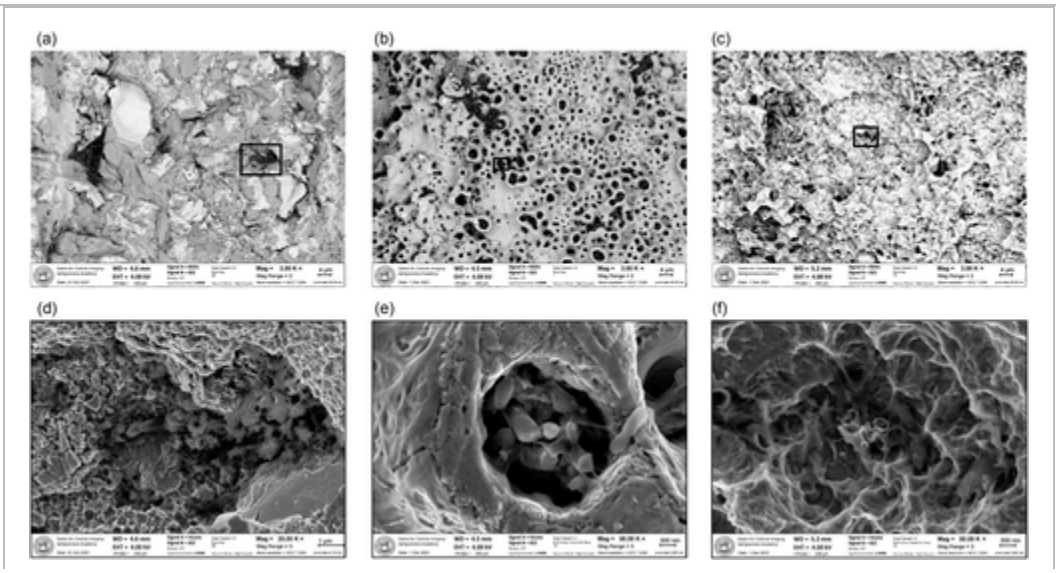

FIGURE 3

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Scanning electron microscopy images on residual biofilm on (a) OsseoSpeed surface, (b) TiUnite surface and (c) SLA surface. Images (d, e and f) represent Larger magnification images of inserts in (a, b and c), respectively.

Regression analysis revealed that the overall area of residual bacteria in the AP + AEW group was not statistically significantly different from that of the AP + NaCl group (Figure 4 and Table 2; $p = .732$). Multilevel analysis showed that locus (top, flank and valley), zone (apical, middle and coronal), implant surface characteristics and gender influenced the area of residual bacteria (Table 2). Thus, an overall smaller predicted area of remaining biofilm on OsseoSpeed implants was measured when compared with TiUnite implants, while treated implants retrieved from female patients showed less remaining biofilm. The predicted area of residual bacteria at top sites was significantly less than that at valley loci in the AP + NaCl group (Figure 4; $p = .029$).

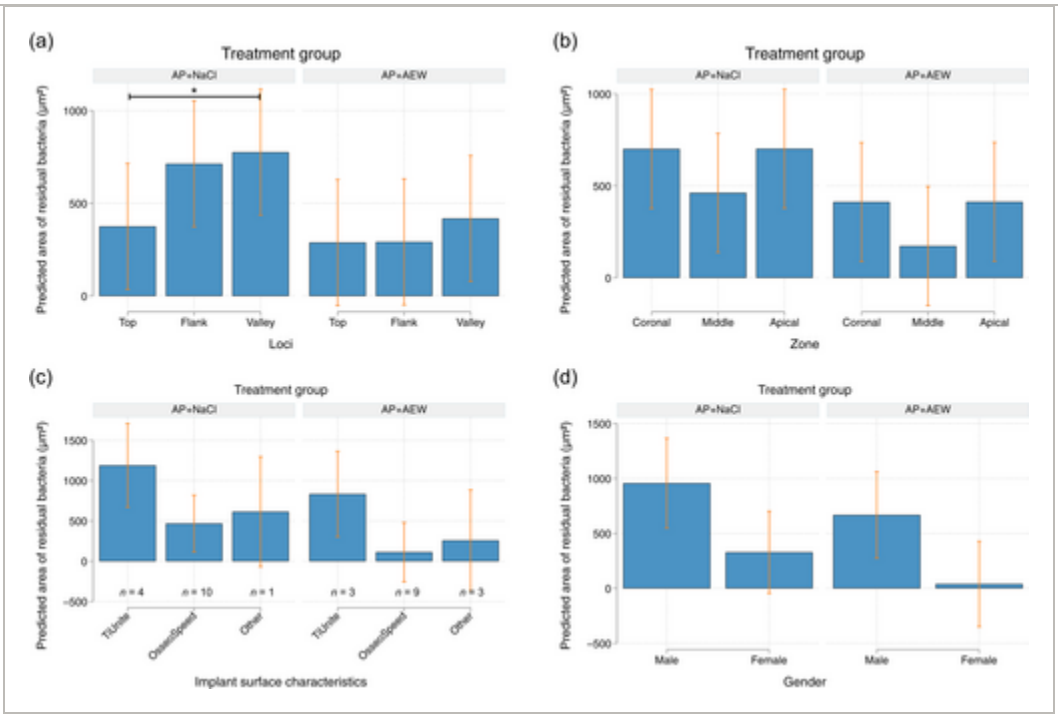

FIGURE 4

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Predicted area of residual bacteria (in square micrometres). The predicted area was estimated using by multilevel regression analysis. Bars represent the mean, and error bars represent the 95% confidence intervals based on the statistical model illustrated in Table 2. Statistically significant differences ($p < .05$) are noted by symbols. AEW, alkaline

electrolysed water; AP, air-polishing.

TABLE 2. Results from multilevel linear regression analysis on residual bacteria after decontamination.

Multilevel linear regression analysis				
Area colonized by residual bacteria (μm^2)	**Coefficient**	***p*-Value**	**95% CI**	
Treatment group				
AP + NaCl	(Reference)			
AP + AEW	−87.04	.732	−585.85	411.78
Locus				
Top	(Reference)			
Flank	337.84	.009	84.77	590.91
Valley	400.28	.002	147.21	653.35
Treatmentgroup#Locus				
AP + AEW#Flank	−334.37	.067	−692.26	23.53
AP + AEW#Valley	−270.55	.138	−628.45	87.34
Zone				
Coronal	(Reference)			
Middle	−238.86	.009	−417.81	−59.92
Apical	0.90	.992	−178.04	179.85

Note: The analysis was adjusted for locus, zone, gender, implant surface characteristics, marginal bone level and history of surgical therapy of peri-implantitis.

Abbreviations: AP + AEW, air-polishing and gauze soaked in alkaline electrolysed water; AP + NaCl, air-polishing and gauze soaked in saline; CI, confidence interval.

[a] A, TiUnite (Nobel Biocare AB); B, TiOblast (Astra Tech Implant System; Dentsply Sirona Implants); C, OsseoSpeed (Astra Tech Implant System); D, Ankylos (Dentsply Sirona Implants); E, SLA (Straumann). *p*-Values less than .05 were considered statistically significant.

3.1 EDS area-scan analysis

At.% of carbon, oxygen, titanium and calcium in the AP + NaCl, AP + AEW and untreated groups are shown in Figure 5. The overall mean atomic% of carbon for the AP + NaCl and AP + AEW groups was 7.3% and 5.0%, whereas the corresponding value for the untreated group was 69.8%. The AP + NaCl group presented with significantly higher atomic% for both carbon and calcium in the coronal segment than in the apical parts. Adjusted multilevel regression analysis showed that no statistically significant differences between the AP + NaCl and AP + AEW groups were observed for the atomic% of carbon, oxygen, titanium and calcium. It was also noticed that zones (apical, middle and coronal) of the ROI influenced the outcomes of the atomic% of carbon, titanium and calcium, while implant surface characteristics significantly affected the outcomes of the atomic% of titanium.

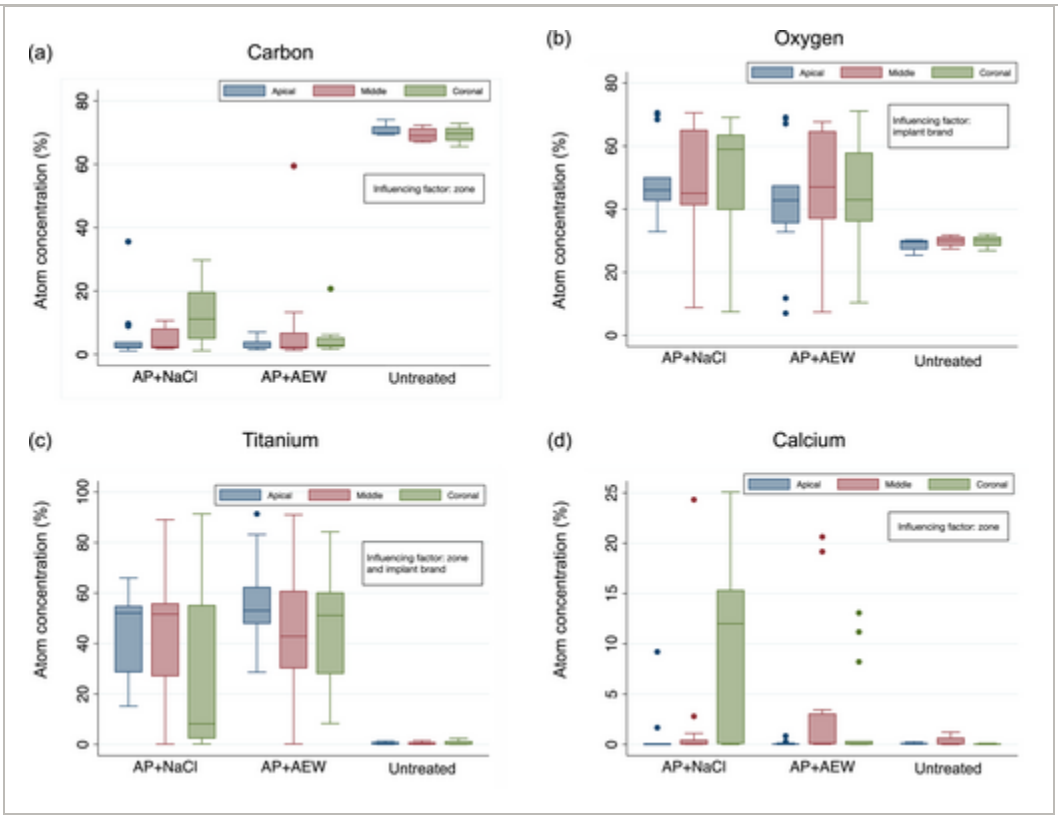

FIGURE 5

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Atomic percentages of carbon (a), oxygen (b), titanium (c) and calcium (d) in treated (AP + NaCl and AP + AEW) and untreated groups. Data are shown as box plots. Dots indicate outliers. Influencing factors are based on the regression analysis. AEW, alkaline electrolysed water; AP, air-polishing.

4 DISCUSSION

The present study evaluated the effect of AP and a combination of AP and AEW in surface decontamination of explanted peri-implantitis-affected implants. The experimental model aimed to mimic cleaning during surgical therapy of peri-implantitis. Results from the SEM analysis showed that both treatment protocols were effective in biofilm removal and only small proportions of target areas of the implants had residual bacterial or mineralized deposits after treatment. Although differences between the treatment protocols were small, implant thread loci (top, flank and valley), zone (apical, middle and coronal), implant surface characteristics and patient gender influenced results. In addition, EDS analysis showed that target zones of the implant (apical, middle and coronal) influenced the atomic% of carbon and calcium and that implant surface characteristics affected the atomic% of titanium. This suggests that AP with or without AEW is an effective tool in removing biofilm from peri-implantitis-affected implants.

The strategy applied in the present study to use explanted peri-implantitis-affected implants as targets for testing surface decontamination protocols is not new. Indeed, several studies have used SEM and EDS techniques to assess the cleaning efficacy of in vitro treatment procedures in biofilm removal from implants that were removed due to severe peri-implantitis (e.g., Hakki et al., 2017; Mouhyi et al., 1998; Tong et al., 2021). Although some of the tested cleaning protocols had limited clinical relevance for surgical treatment of peri-implantitis, pertinent methods to be applied under realistic clinical conditions were included. In an earlier published report on decontamination protocols, Mouhyi et al. (1998) evaluated six different chemical and physical cleaning methods on 17 implants that were removed from nine patients. The cleaning protocols included rinsing in either ethanol or citric acid, the use of an air-powder abrasive device and CO_2 laser. It was reported that the air-powder abrasive technique was effective in removing contaminants but was associated with persisting powder particles following therapy. Best results were obtained following rinsing in citric acid followed by deionized water. In a study on 27 explanted implants, Hakki et al. (2017) applied 10 different cleaning protocols including curettes, rotating titanium brush, ultrasonic scaler, air-powder abrasive together with citric acid and Er:YAG laser. Results indicated that air-powder abrasive/citric acid treatment and laser were superior to other protocols. Tastepe et al. (2018) analysed the effect of air-powder abrasive treatment with different powders on 13 implants that were explanted due to peri-implantitis. Analysis of the implant surfaces before and after treatment showed that the superficial parts of the calculus had been removed and that a thin layer remained on some of the implants. Although most parts of the biofilm were removed, clusters of powder particles persisted on some of the implants. Tong et al. (2021) reported on the outcomes of five different decontamination protocols applied to 30 explanted peri-implantitis-affected implants. Although ultrasonic scalers with polyether ether ketone (PEEK) tips were more effective in removing visible contamination than air-powder abrasive devices, analysis revealed that implant surfaces frequently retained remnants of the PEEK material. The reported findings regarding the efficacy of air-powder abrasive techniques in biofilm removal are in agreement with

observations made in the present study. Thus, bacterial deposits following treatment using AP, with or without AEW, occupied only 4%–7% of the target area of the implant surfaces.

The primary goal of a decontamination procedure in the treatment of peri-implantitis is to remove the biofilm from the implant surface without damaging its microstructure or elemental profile. Evaluation protocols in in vitro studies should therefore include sensitive techniques such as SEM to detect potential physical damage of the microstructure of the implant surface. EDS is a powerful tool to assess the elemental composition of the implant surface. In an in vitro study, Cha et al. (2019) examined the effect of five mechanical decontamination methods on the surface topography of pristine commercially available implants. They reported that ultrasonic metal-tip scalers caused marked damage to the implant surface and that the use of PEEK-plastic scalers resulted in plastic remnants on the implant surfaces. Although titanium brushes of different designs flattened the thread profile, minimal alterations of surface topography were observed after the use of the air-powder abrasive device. Similar observations were made in another in vitro study by Ichioka et al. (2022). The authors evaluated different mechanical decontamination procedures on biofilm-covered titanium discs and reported that cleaning with an ultrasonic device with a PEEK-fibre tip resulted in the deposition of plastic material on the discs. AP was the most effective decontamination procedure in removing biofilm without causing damage to the titanium surface.

The EDS analysis in the present study showed that the atomic% of carbon was lower at treated implants than at untreated peri-implantitis-affected implants. Furthermore, the atomic% of Ti of implants was higher in both treatment groups than in untreated controls and was influenced by the surface characteristics of the peri-implantitis-affected implants. As the target implants of the present material represented several different brands with varying implant geometry and surface characteristics, assessments of surface element profiles of pristine implants were not feasible. In contrast, the target implants in the studies referred to above were all of one type, for example, Brånemark system implants with turned surfaces (Mouhyi et al., 1998), Straumann implants with SLA surface preparations (Tastepe et al., 2018; Tong et al., 2021) or two types; Zimmer; Screw-Vent and SwissPlus (Hakki et al., 2017). Thus, the EDS and EDX evaluations included pristine and contaminated implants of corresponding brands and surface characteristics. Comparisons between pristine and explanted peri-implantitis-affected implants revealed that, irrespective of the treatment protocol, decontamination procedures failed to rejuvenate implant surfaces to exhibit element profiles such as those in pristine implants.

The additional use of AEW to AP in the present study did not improve the outcomes, as no significant differences between treatment groups were observed regarding bacterial deposits or atomic% for titanium, carbon, calcium and oxygen. The overall mean percentage of remaining area of mineralized deposits, however, was significantly larger on AP + NaCl-treated implants than on implants treated with AP + AEW. The reason for this difference is not fully

understood. As results from previous in vitro studies indicated that AEW may possess antimicrobial effects due to its content of hypochlorite ions and hypochlorous acid (Fukuzaki, 2006; Fukuzaki et al., 2004), it may be suggested that the effect on mineralized deposits may be attributed to the hypochlorous acid component of AEW. In an in vitro study on different chemical decontamination procedures on biofilm-covered titanium discs, Ichioka et al. (2021) reported that AEW and citric acid were effective in removing biofilm from both smooth and rough surfaces and that AEW and *N*-acetyl-L-cysteine (NAC) were superior in restoring surface biocompatibility. Despite the limited additional effect of using AEW as adjunct to AP in the present study, the findings may nevertheless add to the understanding of potential benefits of using AEW in implant surface decontamination procedures.

Although the present study showed that AP, with or without AEW, was effective in removing biofilm from explanted peri-implantitis-affected implants, there are limitations that need to be considered. The study design was limited to one specific mechanical cleaning protocol, with or without the additional application of a chemical agent. While a study design in general would benefit from using several treatment protocols, it must be realized that the recruitment of patients to the present study entailed a variation in implant brands with different geometry and surface topography. Also, imaging techniques did not allow for pre–post evaluations due sample processing. As our sample size was limited, it is possible that baseline conditions were not balanced across groups, despite random allocation. This may have confounded the outcomes. When interpreting results from the present study, differences between an in vitro situation of implant surface decontamination and a clinical procedure performed during surgical therapy of peri-implantitis should be considered. Not only are differences in accessibility to peri-implantitis-affected implants of importance, for example, due to defect configuration (Sahrmann et al., 2015), variations of decontamination effects regarding implant thread loci (top, flank and valley) and target zones (apical, mid and coronal) of the implant also need to be emphasized. It is possible that time of treatment may impact the cleaning efficacy. In this context, our choice of a 60-s instrumentation was based on clinical/practical considerations. It should also be noted that AP during surgery is currently not recommended (Herrera et al., 2023). In one of the few clinical evaluations on the topic, Hentenaar et al. (2022) failed to identify any clinically relevant benefits of AP in the surgical treatment of peri-implantitis.

In conclusion, the present in vitro study showed that AP, with or without AEW, is an effective tool in removing biofilm from explanted peri-implantitis-affected implants. Clinical studies are needed to assess the efficacy of the implant surface decontamination protocol during surgical treatment of peri-implantitis.

AUTHOR CONTRIBUTIONS

All authors contributed to study conception and design; Yuki Ichioka performed all experiments and collected the data; Yuki Ichioka and Jan Derks contributed to data analysis. All authors contributed to interpretation of data, drafting and critically revising the manuscript. They agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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CONFLICT OF INTEREST STATEMENT

Dr. Derks reports personal fees from Osteology Foundation, Dentsply Sirona Implants and Straumann Group and received research grants from Dentsply Sirona Implants, Eklund Foundation and Electro Medical Systems. Dr. Berglundh reports grants and personal fees from Dentsply Sirona Implants and grants from Osteology Foundation, outside the submitted work.

DATA AVAILABILITY STATEMENT

Data are available upon reasonable request made to the corresponding author.

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