Nonsurgical cleaning potential of deep-threaded implants and titanium particle release: A novel in vitro tissue model

Fischer, Kai R ; Büchel, Jasmin ; Gubler, Andrea ; Liu, Chun Ching ; Sahrmann, Philipp ; Schmidlin, Patrick R

DOI: https://doi.org/10.1111/clr.14045

Received: 7 September 2022 | Revised: 19 December 2022 | Accepted: 6 January 2023

DOI: 10.1111/clr.14045

ORIGINAL ARTICLE

CLINICAL ORAL IMPLANTS RESEARCH WILEY

Nonsurgical cleaning potential of deep-threaded implants and titanium particle release: A novel in vitro tissue model

Kai R. Fischer[1] | Jasmin Büchel[1] | Andrea Gubler[1] | Chun Ching Liu[1] | Philipp Sahrmann[2] | Patrick R. Schmidlin[1]

[1]Clinic of Conservative and Preventive Dentistry, University of Zurich, Zurich, Switzerland

[2]Clinic for Periodontology, Endodontology and Cariology, University Center of Dental Medicine, University of Basel, Basel, Switzerland

Correspondence
Patrick R. Schmidlin, Clinic of Conservative & Preventive Dentistry, Division of Periodontology and Peri-implant Diseases, Center of Dental Medicine, University of Zurich, CH-8032 Zurich, Switzerland.
Email: patrick.schmidlin@zzm.uzh.ch

Abstract

Objectives: To measure the efficiency of three cleaning modalities on two implant designs with similar diameters but different thread depths as well as the presence of titanium particles.

Methods: Sixty dyed implants (30×4.8 apically tapered (ATAP) and 30×5.0 fully tapered (FTAP)) were fixed in plastic models. The horizontal bone defects were surrounded with porcine soft tissue. Three instrumentation modalities were used to clean for 150 s: Curette (CUR), ultrasonic scaler (US), and air powder waterjet device (APWJ) with erythritol powder. Afterward, implants were photographed and scanning electron microscopic (SEM) images were taken. Titanium in the soft tissues was quantified in dissolved samples and histologically confirmed.

Results: For ATAP and FTAP implants, the percentage of the cleaned surface was 26.4 ± 3.0 and 17.1 ± 2.4% for CUR, 33.7 ± 3.8% and 28.1 ± 2.3% for US, and 45.5 ± 4.1% and 24.7 ± 3.8% for APWJ, respectively. SEM images showed significant implant surface changes, especially after instrumentation with CUR and US, whereas APWJ had little to no effect. Most titanium residues were found after cleaning ATAP implants with CUR (152.0 ± 75.5), followed by US (89.5 ± 73.8) and APWJ (0.3 ± 0.8). For the FTAP implants, respective values accounted for 129.5 ± 58.6 µg and 67.0 ± 14.4 µg for CUR and US, respectively. No titanium residues were detected on ATAP with APWJ.

Conclusion: Based on in vitro data, erythritol-powered APWJ still appears to be the most efficient and gentle cleaning method. All three instruments, however, were found to have unprocessed areas depending on different implant designs, hence, clinical relevance for non-surgical approaches remains challenging and warrants further improvement.

KEYWORDS
cleaning efficiency, dental implant, implant thread design, in vitro, peri-implantitis

1 | INTRODUCTION

Inflammatory conditions around osseointegrated implants represent a common biological oral complication. The clinical importance of these inflammations is reflected by a consistently growing body of evidence in the respective literature (Tarazona-Álvarez et al., 2021). Currently, the prevalence of the two major referring clinical entities, that is, peri-implant mucositis and peri-implantitis, is reported at a patient and implant level to range between 24–88% and 10–81% vs. 10–45% and 5–23.0%, respectively (Wada et al., 2021). Several risk indicators have been described, but poor oral hygiene and lack of regular care remain the major etiologic factors related to a primarily bacterially induced but host-modulated disease (Marcantonio et al., 2015). While a history of periodontitis and diabetes have been identified as relevant risk indicators for peri-implantitis, other associations like smoking, implant superstructure, and condition of attached and/or keratinized mucosa remain a matter of some debate (Dreyer et al., 2018). However, most suspected conditions and entities share common clinical features and etiopathology relationships.

While the classical bacterial focus remains on the presence of Gram-negative bacteria, as is typical for peri-implant mucosal diseases, other microbiota, including opportunistic microorganisms and/or nonculturable species, may also be inflicted at peri-implant sites (Fragkioudakis et al., 2021). In addition, genetic predisposition and occlusal overload have been (re-)discussed as a potential risk factors. Specific local modifying factors such as macro- and micro-morphologic design aspects and chemical surface properties may also interact as biofilm-retentive factors, having a negative influence on the initiation and progression of inflammatory reactions and bone resorption as mainly shown in animal studies (Stavropoulos et al., 2021). More and more, there is an increasing discussion regarding the influence of foreign body materials. In this regard, not only excess cement material does play a role but it is hypothesized that titanium particles may be involved in the pathogenesis of inflammatory reactions (Albrektsson et al., 2018). Evidence of titanium residues in various sizes, concentrations, and forms can be increasingly detected (Messous et al., 2021). In this process, it might be the presence of such local deposits of metallic materials that stimulate immune cell migration and inflammatory responses. Such particles can also enter the bloodstream and accumulate in other tissues. Therefore, iatrogenic generation of metal particles should be minimized in all phases of (peri)-implant prevention and therapy.

Regardless of all the numerous possible influences and side effects on the inflammatory process of peri-implant surfaces and defects, bacteria as the cause of inflammation remain a central issue, even or especially when it comes to the therapy of contaminated implant surfaces, which seem especially difficult to clean. Special emphasis has therefore always been on the thoughtful evaluation of cleaning efficiency and different models and instruments (Francis et al., 2022). Most laboratory models aim to standardize defects around implant-related difficult-to-clean areas and to determine different cleaning protocols and potentials. These studies have their limitations like—among others—a lack of naturally matured soft and hard deposits mimicking reliably the nature, simplified bone defects and—of course—a lack of an intraoral vital soft tissue complex.

To date, no consensus has been identified as to which technique for implant decontamination works best. However, mechanical means still seem to provide better results than laser or chemical methods, and air abrasion shows the best cleaning effectiveness in this context. Noteworthy, combinations are possible and have been discussed to optimize cleaning outcomes and may provide better clinical results than a single treatment modality. The clinically achievable accessibility of the affected implant surface, especially by physical means, remains the most challenging obstacle (Steiger-Ronay et al., 2017).

New macro-retentive implant designs with deep threads and narrow core diameter may display significant advantages in the primary therapy of missing teeth when it comes to achieving optimized primary stability especially in challenging cases as for instance immediate implant placement and immediate loading (Emmert et al., 2021; Francisco et al., 2021). The afterpains, though, could be correspondingly great in case of peri-implant inflammation and bone loss with accompanying thread exposure.

This study aimed to establish a new model encompassing a standardized soft tissue collar to simulate peri-implant mucosa and a nonsurgical approach in a moist environment that simulates the clinical situation more precisely. In this context, we sought to measure the cleanability and accessibility of two implant designs with similar diameters though different thread depths as well as the presence of titanium particles in the surrounding soft tissues after instrumentation with three cleaning modalities, tjhat is, curette, ultrasonic scaler, and air powder waterjet device. The null hypothesis was that there was no difference in view of the two evaluated outcome parameters.

2 | MATERIALS AND METHODS

2.1 | Dental implants and defect model

In the present investigation, 60 dental implants with comparable surface quality, roughness (Sa value 1.5 µm), and implant length (12 mm) were used (30 BLT and 30 BLX implants, Straumann). Both implant types displayed comparable diameters (BLX 5.0 mm vs. BLT 4.8 mm) but had different thread and core designs: The fully tapered BLX implants (FTAP) displayed an interrupted, aggressive thread design with a thread distance of 1.15 mm, and a thread depth ranging from 0.25 to 1.00 mm, while apically tapered BLT implants (ATAP) had a continuous thread design with thread depths of 0.3 mm and thread distance of 0.8 mm.

In order to simulate horizontal peri-implant bone defects (90°), 60 plastic cylinders made of polyvinyl-chloride were customized with a standardized height of 15 mm and a diameter of 20 mm

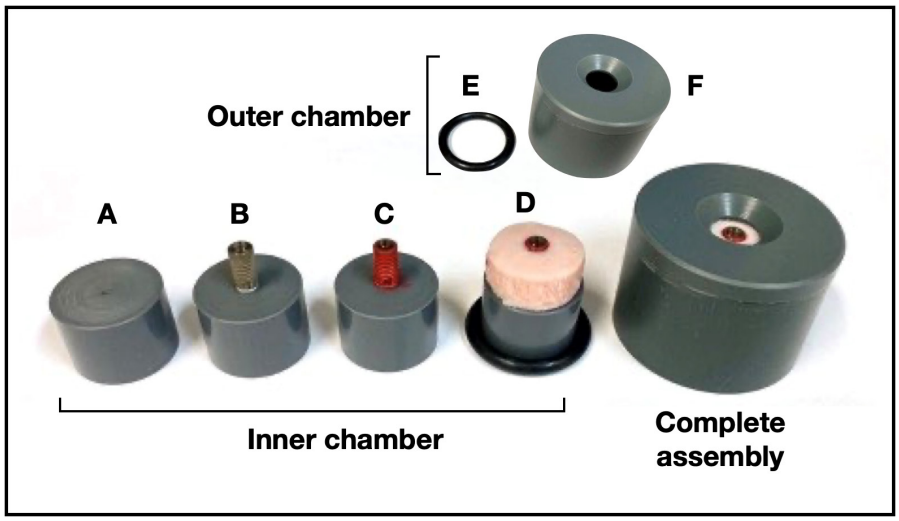

FIGURE 1 Representation of the defect model and the materials used (the different reference letters are marked in the text) [Colour figure can be viewed at wileyonlinelibrary.com]

(Figure 1) and implants were placed 2 mm into each plastic cylinder using a milling device (EMCO FB-2, MAIER & Co.). In order to distinguish between cleaned and uncleaned surfaces after instrumentation, implants were inked with a red acrylic color (Van Gogh Acrylic Paint Naphthol Red medium, Royal Talens). Before application, the paint was diluted with water in a ratio of 1:2 (paint:water) and mixed using a SpeedMixer (FlackTek SpeedMixer, DAC 330–100 SE) for 90 s at 2000 rpm. The paint was then thinly applied to the implant with a brush and allowed to air dry for 24 h.

In the next step, a punched porcine soft tissue collar was gently placed over the stained implant in order to allow for blinded subgingival cleaning. The tissue was obtained from the mucosa of the lips of freshly slaughtered pig jaws using a biopsy punch (Emporte Pieces Jumelables, Boehm) with respective diameters of 20 mm and a height of 4 mm. To do so, the lips were removed from the jaws using a scalpel, deep-frozen, and cut to a thickness of 10 mm. When used in the model, they were defrosted and kept moist in a 0.9% NaCl solution for maximum of 4 h until the start of the experiment. Notably, the animals in this study were raised and slaughtered for food production according to the Swiss standards for animal welfare. The study protocol did not influence in any way the premortal fate of the animals or the slaughtering process. Therefore, this investigation was not classified as an animal study, and the institutional ethics committee did not have any objections to the protocol.

Subsequently, a second plastic cylinder with a height of 30 mm, an outer diameter of 42 mm, and an inner diameter of 20 mm were fabricated. A lid with an outer diameter of 20 mm and an inner diameter of 10 mm was additionally anchored on top of the second chamber. To prevent the plastic blocks from shifting during the test procedures and to allow firm closure between the two plastic chambers, a silicone ring was fabricated to enclose the inner cylinder. The actual two-chamber model thus finally encompassed a small cylinder in which the implant was anchored and the superimposed second chamber with a lid. Thereby, a deep submucosal horizontal (90°) peri-implant bone defect with a depth of 10 mm was simulated.

2.2 | Cleaning and assessment procedures.

Ten samples each of both, FTAP and ATAP implants were randomly allocated to one of three following cleaning modalities:

1. Air powder waterjet device (APWJ, Airflow® One, EMS electro medical systems) with erythritol powder (Airflow® Powder Plus, EMS) applied with a so-called Perioflow handpiece and nozzle for subgingival/submucosal instrumentation (Airflow, AIR). The nozzle was changed after each implant. The intensity of the water spray was set to maximum (level 10) and the one of the powder to level 5.
2. An ultrasonic scaler (US, Dentsply Sirona). SiroSonic TL was used as the handpiece and the SiroSonic No. 4L tip as the attachment. The intensity setting of the instrument was set to medium level (Teneo, Dentsply Sirona).
3. Curette (CUR, M23A, Deppeler) serves as control therapy. After each implant, the sharpness of the curette was checked and, if necessary, re-sharpened with the aid of an Arkansas stone.

All implants were treated for a time period of 150 s by one single operator (JB).

Cleaning efficiency was determined using standardized photographs, which were taken with a single-lens reflex camera (Canon) and flash applying the following settings: ISO 100, exposure time 2 s, distance 10 cm, aperture f/18. One photograph was taken with help of a tripod holder from four sides. Only perpendicular images were taken to avoid any blind spots by the more overhanging thread design in the FTAP group. The captured images were analyzed using image processing software (ImageJ version 1.53k, Wayne National Institutes of Health) by a blinded investigator (JB). In this context,

the cleaned surface area was planimetrically recorded, and the percentage of cleaned surface was determined.

2.3 | Titanium release and remnants

After treatment, the soft tissue collars of six randomly selected samples were dissolved in a 25 mL beaker with 5 mL HCl 36% for 2 h at 150°C under constant stirring.

After 2 h, samples were completely dissolved and the solution was transferred to a 10 mL volumetric flask and 100 µL KCL 10% was added. Afterward, 10 mL deionized water was added and well mixed. The solution was then filtered (pore size 0.22 µm). The herby obtained solution was analyzed in an atomic absorption spectroscopy device (ASS, Contr AA 300, AnalytiK Jena), which allowed quantifying the elements of the solution by measuring extinction at characteristic wavelengths (Lambert Beer-equation). An air vaporizer and an acetylene/ nitrous oxide flame were used to vaporize the solution. After a preheating/preburning of the flame for 15 min, the AAS was calibrated twice with a solution of 0, 1, 2, 3, 5, 10, 25, and 50 ppm titanium concentrations, respectively. For each sample, four measurements were performed. The first one was always discarded. The three last measurements were used to get a mean value. After 20 samples, a quality control measurement was performed.

In addition to this quantification procedure, four remaining soft tissue samples were cut in half, directly stored in 10% formalin (HT501128-4L, Sigma Aldrich), and fixed at room temperature for 3 weeks. Samples were watered for 2 h in deionized water (solution renewal every 15 min) and subjected to an alcoholic dehydratation series (70, 80, 90, 94, 100% EtOH, xylene 100%) followed by methyl methacrylate (MMA, M55909-1L, Sigma Aldrich) infiltration and incubation for 72 h at 4°C. Samples were transferred to an MMA embedding mix (425 mL Methyl Methacrylate Item number: 000020 M55909-1l Sigma Aldrich; 2.5 g Perkadox 16S, number: G425.0025, Grogg Chemicals; 75 mL Dibutyl phthalate Article, number: 8.00919.2500 VWR; 0.05 g Novoscave (Pentaerythritol tetrakis(3,5-di-tert-butyl-4-hydroxyhydrocinnamate), number: 441783, Sigma-Aldrich) into a disposable plastic container (PP25ml container, Art 2062, Semadeni) and incubated at 28C° and 32°C 72 h each in a convection oven until completely cured. Afterward, samples were removed from plastic containers, cut using a precision cutoff saw (Isomed Low-Speed Saw, Buehler) and diamond cutting wheel (MOD10 Katno 40000043, Struers) and polished on one side (1200, 2000 and 4000 grit – in that order, Struers). Samples were fixed on Plexiglas with the ground side down using Technovit (7210VLC, Kulzer GmbH). Thin sections were made to 300 µm with a precision cutoff saw (Isomed Low Speed Saw, Bühler) followed by repeated grinding (1200, 2000, and 4000 grit, Struers) until a final thickness of about 150 µm. Specimens were stained using Van Gieson and overview images at high resolution were recorded in a slide scanner (slide scanner, Zeiss Axio Scan. Z1, Carl Zeiss AG).

2.4 | Implant surface evaluation using SEM

Micro-morphological status of treated and untreated control implants was studied using a scanning electron microscope (SEM; GeminiSEM 450, Zeiss). For this purpose, three randomly selected implants per implant type and cleaning method were selected; one noninstrumented implant of each implant type served as a control. Selected implants were fixed to SEM carriers using a carbon pad and were sputtered with gold (layer thickness 10 nm) using a sputtering unit (CCU-010, Safematic). Working distance was set at 10 mm and accelerating voltage accounted for 10 kV. Images of the implants were taken at magnifications of 70- and 200-fold.

2.5 | Statistical analysis

Sample size was adapted to previous studies of our group with an analogous study design (Ronay et al., 2017; Steiger-Ronay et al., 2017), which proved to have sufficient power with a confidence interval of 95% and an intergroup difference of 10% at a significance level of 0.05.

For descriptive purposes, mean values (±SD), medians as well as interquartiles were calculated and box plots were generated.

All statistical analyses and plots were computed with the statistical software R (R Foundation for Statistical Computing) including the packages tidyverse, robustbase and emmeans.

For each data set, the presence of interactions between the explanatory variables (implant design, treatment modality) with respect to the target variable (cleaned surface) was tested using two-way ANOVA. To account for potential outliers present in the data, we used robust linear models. Finally, pairwise comparisons were used to determine whether the differences in estimated marginal means are significantly different from zero. *p* value adjustment was done by applying the Tukey method.

3 | RESULTS

3.1 | Cleaning efficiency

A pure first visual inspection reveals the persistence of distinct color residues after all of the different implant cleaning options, predominantly present in the area between the implant threads (Figure 2). Especially the CUR left more residues behind than the other instruments.

The more coronal aspects seemed more reliably accessed than the threaded and apically located aspects.

After cleaning with APWJ, the implant surface appeared dull, whereas the other two instruments.

Planimetric evaluation of cleaned implant surfaces highlighted that no cleaning method showed an overall mean accessibility rate of more than 50% on either implant type (Figure 3). On ATAP

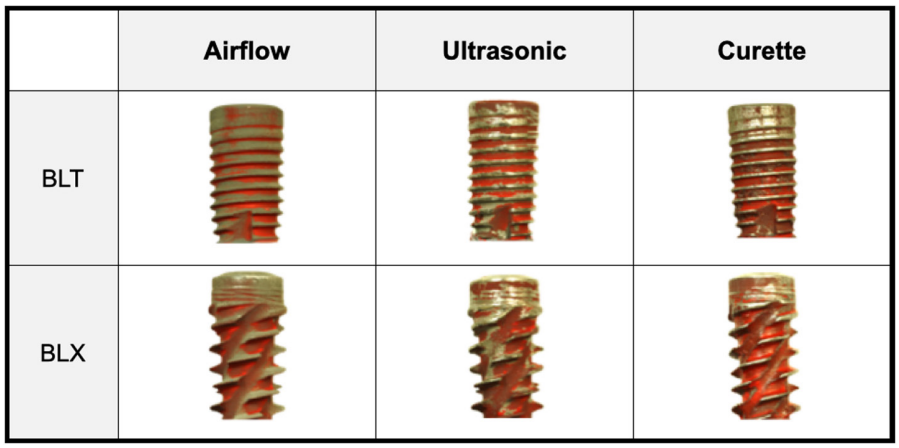

FIGURE 2 Representative photographs of treated implant surfaces [Colour figure can be viewed at wileyonlinelibrary.com]

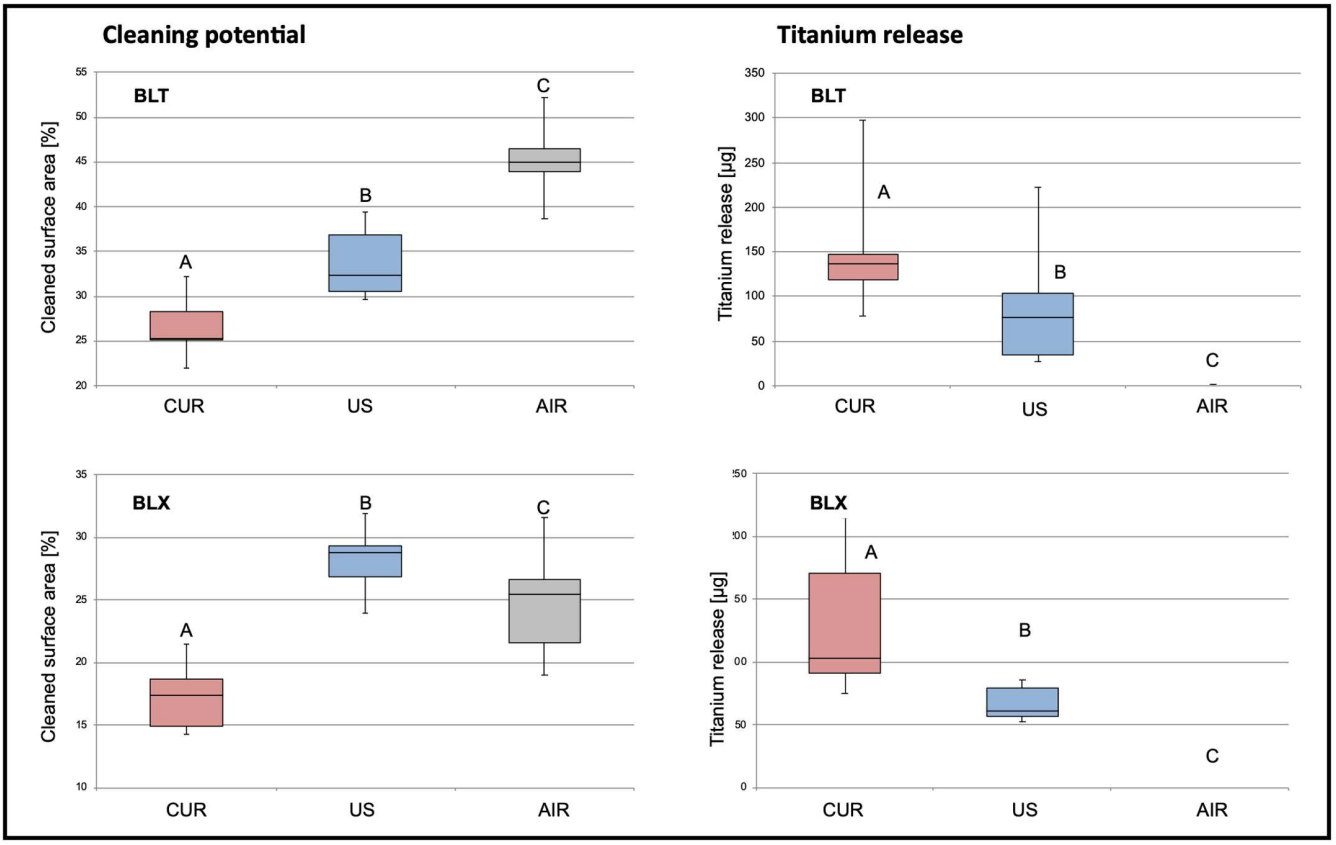

FIGURE 3 (a) Box-plot representation of cleaned implant surfaces (%) with three different instruments on ATAP and FTAP surfaces, respectively. (b) Determined measurable titanium residues in µg after cleaning ATAP and FTAP implants with different cleaning instruments [Colour figure can be viewed at wileyonlinelibrary.com]

implants, APWJ showed the best cleaning rate (45.5 ± 4.1%) followed by US (33.7 ± 3.8%) and CUR (26.4 ± 3.0%); results between the three instruments were statistically significantly different ($p < .001$). On FTAP implants, the cleaning rates of all tested instruments were lower. In contrast, the cleanest implant surface was found after instrumentation with US (28.1 ± 2.3%), followed by APWJ (24.7 ± 3.8%) and CUR (17.1 ± 2.4%). Statistically significant differences were found between the three instruments ($p < .001$; Figure 3a).

3.2 | Titanium release and tissue remnants

Titanium wear after instrumentation showed significant differences ($p = .001$) regarding the different cleaning instruments. In general, a tendency for higher titanium wear was observed in the ATAP group than with the FTAP implant, regardless of the instrument (Figure 3b).

Curette (CUR) showed the highest titanium release in ATAP implants (152.0 ± 75.5 µg), followed by US (89.5 ± 73.8 µg). The same

result was also found for FTAP implants, where CUR (129.5 ± 58.6 µg) caused the most titanium abrasion followed by US (67.0 ± 14.4 µg). With APWJ, only minute abrasion was observed and only in some samples in the ATAP group (0.3 ± 0.8 µg), whereas no abrasion could be detected after instrumentation of FTAP implants with the respective device.

Titanium particles were detectable in the histological sections, which were treated with CUR or US. No particles were identifiable at any magnification in the airflow group. Particles were observed in all areas without a clear pattern of distribution, i.e., from the apical to the coronal aspect of the simulated defect. Some particles were found within the tissues. In general, particle size was bigger after debridement with CUR with a tendency toward smaller ones after instrumentation with the US (Figure 4).

3.3 | Microscopic evaluation

Besides system-inherent macromorphological differences between the two thread designs of the two implants with comparable surface structure and roughness, SEM images showed evident micromorphological changes of implant surfaces in both implant types after instrumentation, especially in samples cleaned with CUR and US (Figure 5). Scratch-like defects were frequently found after US resulting from the tip. Both latter instrumentation modalities showed evident signs of wear at the threads. In contrast, merely no structural changes were detectable after cleaning with APWJ and erythritol powder. Furthermore, color and tissue debris residues were visible, especially on those implants, which were cleaned with US and CUR.

4 | DISCUSSION

This laboratory study investigated the cleaning ability of three different instruments on dental implants with different thread designs in terms of cleaning efficiency, titanium wear, and implant surface structure changes using a novel nonsurgical laboratory surrogate model.

For this purpose, standardized models were manufactured to simulate horizontal peri-implant bone loss (Sahrmann et al., 2013).

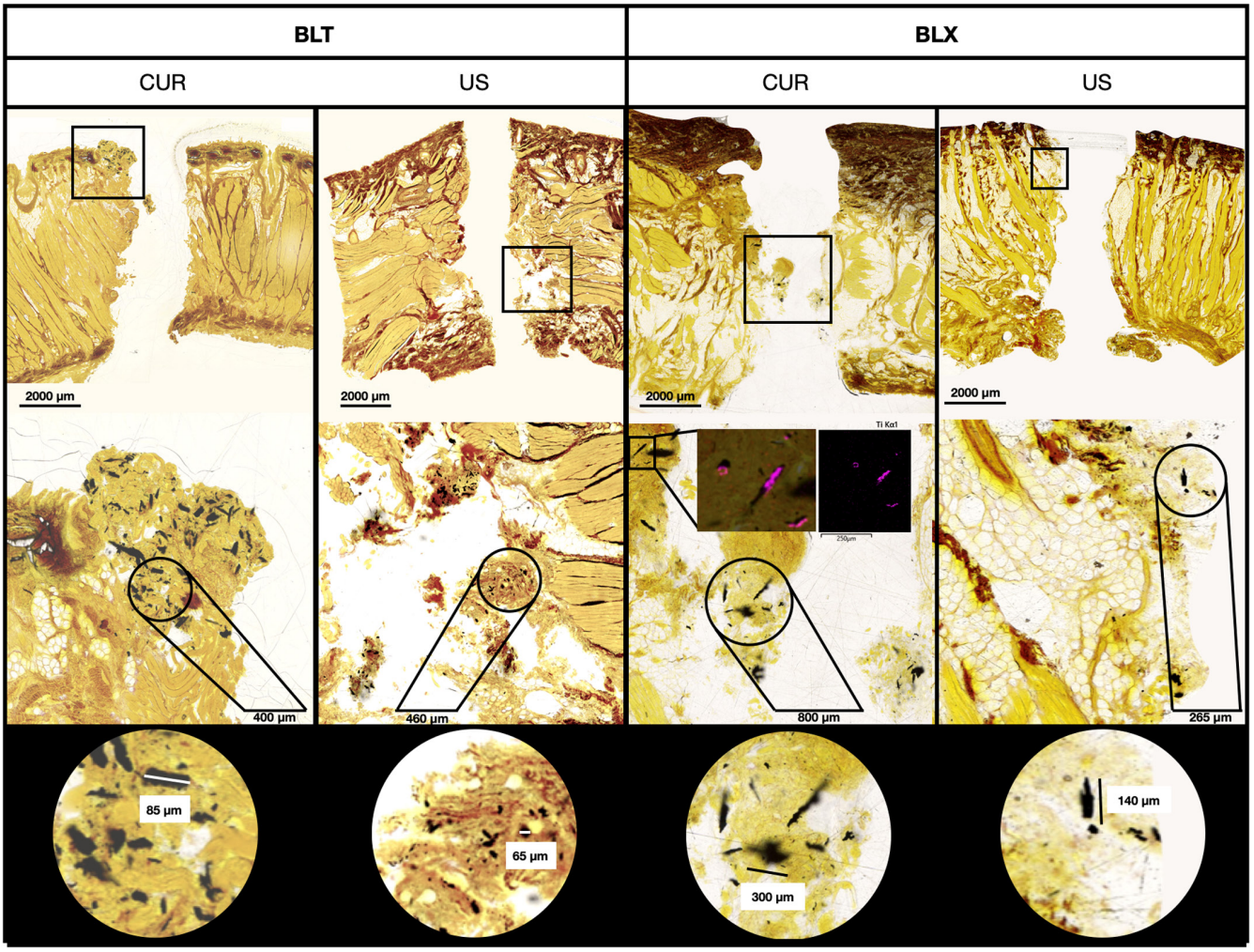

FIGURE 4 Representative histological images; overview provided at the top. In the middle, respective magnifications from the square highlight areas, with particle accumulation (black) at different locations. Bottom: Visible titanium particles with variable size and shape, which could be proven to be Ti by EDX (see, e.g., FTAP-CUR) [Colour figure can be viewed at wileyonlinelibrary.com]

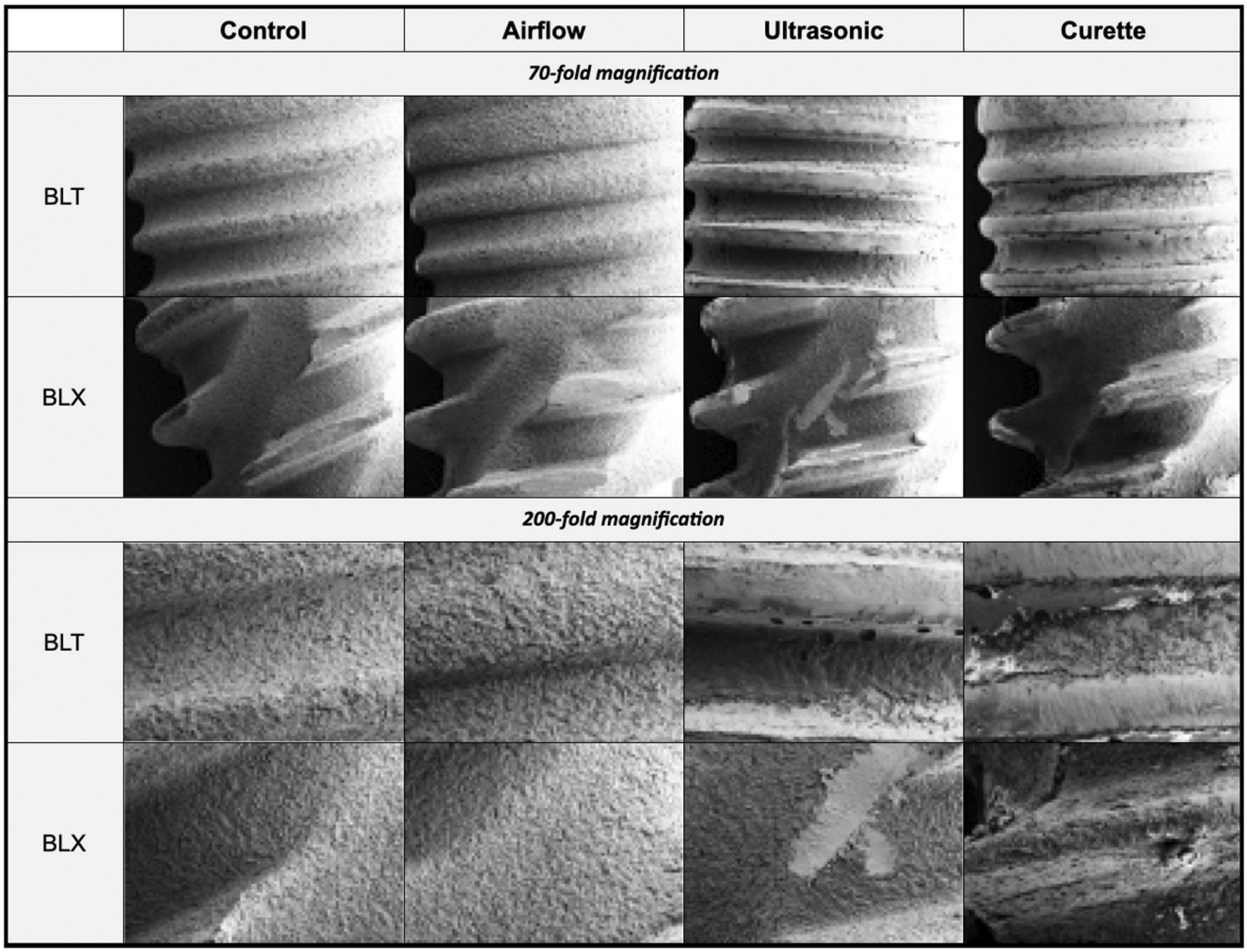

FIGURE 5 Representative SEM images at two magnifications (70 fold and 200×) of untreated control and treated implant surfaces (APWJ, US, CUR) of the two investigated implant types

This setup has already proven to reflect a valuable model, which has been adopted in several follow-up investigations ever since (Iatrou et al., 2021; Steiger-Ronay et al., 2017). In this study, only a horizontal defect was simulated, as it has the most convenient access to all implant surfaces, especially in a nonsurgical approach (Ronay et al., 2017). In the present investigation, however, a particularly deep bone defect depth of 10 mm was selected, which aimed to bring cleaning to its limits, especially in the apical parts, since especially nozzles for the APWJ unit are reportedly suitable for cleaning up to a pocket depth of 9 mm (Cobb et al., 2017). This might also explain—in part—the incomplete cleaning results obtained in the present study but also highlights the challenges and limitations of subgingival cleaning as has been shown in previous work highlighting in particular implant threads located furthest apically are the most difficult to clean (Sahrmann et al., 2013).

Not surprisingly, the results of the present study corroborated the findings of previous studies, i.e., that the type of cleaning instrument has an influence on the proportion of cleaned implant surface on one hand, but also that none of the physicomechanical approaches was able to completely clean the surface on the other. The exceptionally deep bone defect may have had a major impact on the reduced overall stain removal capacity as compared to the existing literature (Iatrou et al., 2021; Keim et al., 2019; Sahrmann et al., 2015). In the implant representing a rather conventional thread design (i.e. ATAP), air powder abrasion was again the most efficient treatment modality as reported in other studies (Iatrou et al., 2021; Keim et al., 2019; Sahrmann et al., 2015; Tuchscheerer et al., 2021). In contrast, greater amounts of color residue were found on FTAP implants with their deeper threads and reduced core diameter. Overall, the cleaning efficiency of the APWJ device dropped in the FTAP group and was performing significantly behind the US. This may also be explained by the fact that the thread pitch of the FTAP implant was 1.15 mm, which is much wider than the one of ATAP, which has a pitch of 0.8 mm only. As a result, the curved tip of US may reach the threads in FTAP more reliably and serve as a guiding structure for instrumentation within the threads. In addition, two other factors might have also contributed to this finding: (1) the actually achievable working distance of the nozzle, which might have reached a critical gap with deeper threads and (2) the moist soft tissue environment, which might

have absorbed and clogged particles and thus limiting the cleaning effect in terms of hampering a ricochet effect of powder particles. Thread surfaces especially in the apical region facing toward hard and flat surfaces can benefit from an additional secondary beam caused by a ricochet effect of defect models, especially if they have a defect and bone walls (Sahrmann et al., 2013); however, in the present set-up, only a central beam of the airflow with increased working distance was existing.

Another factor, which might have had also an impact on stain removal efficiency, was the biofilm surrogate model as such, i.e., the water-diluted acrylic color, which was used to simulate biofilm on the implant surface. It is not known whether the removal of the indicator solution is equivalent to the biofilm. A major advantage, however, of this kind of indicator solution is the fact that uncleaned areas (colored implant surface) are reliably visible after the cleaning, which facilitates assessment. Furthermore, the stains can be evenly applied in a standardized and repeatable way, which might not be the case with a laboratory biofilm. In addition, the handling and manipulation during set-up and cleaning are much easier and controllable. The use of indelible stains in this context has probably therefore become more or less a standard for such investigations and applications.

To simulate peri-implant soft tissues, this work has notably broken new ground: Instead of using nontransparent custom-made mucosa masks made of opaque gelatin or duplicating silicone (Iatrou et al., 2021; Steiger-Ronay et al., 2017), mucosa samples were taken from the lip of porcine jaws. This allowed also for blinded nonsurgical cleaning of peri-implantitis while acting as a real body tissue model, which was of outmost importance to more realistically mimic the clinical situation and the adherence/adsorption of titanium particles ex vivo. In preliminary tests, we tried to obtain more collagen-containing tissues from the palate, but the samples were irregular in size, form, and consistency and were not fitting well with the model. Notably, lip tissues were revealed to be much more consistent in these aspects, however, they are consisting more of glandular and muscular tissues in the peri-implant mucosa. Nevertheless, they exhibit an epithelial surface structure and adequate tissue turgor, and they fitted well around the implants still mimicking a clinically comparable situation. It was found that mucosa pieces around ATAP implants could be placed and removed more easily than around the FTAP implant, which can also be explained by the more accentuated and retentive thread design. Notably, when the mucosal piece was removed from both implant types, minute pieces of the mucosa were sometimes left on the implant surface. This circumstance, in turn, could confound both the results of histological examination and the amount of titanium debris but mainly resulting in an under- and not an overestimation. Notably—in this critical aspect—we could not mechanically or chemically remove all these remnants as this might have interfered with the cleaning evaluation, which was our primary outcome parameter.

A recent study investigated the extent to which subgingival instrumentation has an impact on soft tissues (Petersilka et al., 2018). This work showed that changes in the mucosa were present in particular after instrumentation with a curette as well as with the ultrasonic scaler, which resulted in distinct damage to the epithelial layer and the basement membrane, which were actually no longer intact. In contrast, only minor changes were caused by glycine and erythritol powders used in APWJ. In this view, the use of the porcine lip material with no epithelial lining within the submucosal area could be even an advantage, since particle deposition within this fragile tissue is more likely.

In this study, we demonstrate that titanium particles were produced and translocated during the cleaning procedure, especially after cleaning with CUR as well as with the US. Various studies have already shown that titanium particles could also be detected in the bone after insertion of the implant (Deppe et al., 2018; Meyer et al., 2006; Senna et al., 2015). The released titanium particles can lead to an activation of monocytes, macrophages as well as osteoclast differentiation, which may result in tissue inflammation (Haleem-Smith et al., 2012). The presence of metal ions and particle release in peri-implant soft tissue was also demonstrated in smears of peri-implant mucosa from clinical specimens with and without peri-implantitis, while a significantly higher titanium concentration was evident in peri-implantitis tissues (Fretwurst et al., 2016, 2018; Olmedo et al., 2013). It must be assumed that particles are also present after mechanical instrumentation and higher titanium contents in peri-implant mucosa can potentially aggravate inflammation, which might reduce the prognosis of treatment interventions (Pettersson et al., 2019), especially if implant surface changes are observed after instrumentation. Severe surface changes—as corroborated in the present study, especially with CUR and US—may likely result in the release of metal particles as also shown in this study and, therefore, lead to cell activation and tissue inflammation (Obando-Pereda et al., 2014). Thus, the cleaning method should be as minimally invasive as possible. Since it is widely accepted that cleaning results are influenced by the mode of physicomechanical treatment modality (including powder type used), application time, defect characteristics, and (non)surgical approach (Tastepe et al., 2012). The choice of the instrument for mechanical cleaning should always be critically and carefully evaluated in the treatment of peri-implantitis. When selecting dental implants, care should also be taken to ensure that implant threads can ideally be reliably cleaned in the event of peri-implantitis, which might likely occur in the long-term maintenance phase. Nevertheless, the clinical impact of the difference in surface accessibility and, consequently, cleanability on peri-implant disease resolution needs to be interpreted with caution since no treatment modality removed more than 50% in both tested implant designs within the limitations of the present study. Maximizing biofilm removal, potentially causing "damage" to the implant surface, for example, using the US clinically, has been shown to be effective and of utmost importance for disease resolution (Blanco et al., 2022; Liñares et al., 2019; Nart et al., 2020).

The following shortcomings need to be encountered before interpreting these results and making any conclusions. It should be taken into account that the pressures applied by the examiner during the cleaning of implants, especially with the curette, may defer between operators and are difficult to control in this setup. This might influence also surface changes as well as titanium wear

rates. On the other hand, working time was standardized for all instrumentation modes. The use of acrylic paint imitating plaque and biofilms might also be a shortcoming as mentioned already since the question as to what extent the removal of the paint can be equated with the removal of real bacterial coatings cannot be definitely answered. In addition, differences in coating thickness might have occurred although different approaches have been evaluated before study initiation to assure a standardized methodology; meticulous care was taken to apply the same amount of acrylic paint. As this is an in vitro model, it might be speculated that living tissues might take up titanium particles differently during surface cleaning. One has to acknowledge in this context that the used tissue anatomically differs from inflamed peri-implant mucosa and that clinically, vital tissues may react variously due to bleeding and exudate. Particle uptake into the blood or lymphatic system is also not displayed in this model. In general, this study still reflects an in vitro evaluation, and only clinical studies can reflect the actual effects in patients; but this is, again, almost impossible to several ethical, technical, and methodological problems, which reflect almost insurmountable hurdles to clinical investigation of this problem. Therefore, for the time being, laboratory models that are as lifelike as possible still remain the most suitable option to assess and compare different cleaning options and negative side effects like particle production and release.

5 | CONCLUSIONS

Air powder waterjet devices with erytrithol-based powders still reflect the most promising physicomechanical cleaning method with the least structural changes on the implant surface and the lowest titanium abrasion. Within the limitation of the in vitro study design, the macro-geometry of the implant seems to reflect a distinct hurdle for the overall cleaning efficiency in a non-surgical approach. Finally, our approach provides a valuable model to study peri-implant cleaning methods in an updated more holistic approach, which merits further development and evaluation.

AUTHOR CONTRIBUTIONS

P.R.S/K. R. F. conceived the idea and prepared the protocol; J.B./A.G. validation; J.B. Sample preparation and treatment/J.B./A.G. data analysis; J.B./P.S. performed the statistical analysis; A.G./C.C.L. visualization; P.R.S. original draft preparation; P.R.S./C.C.L./P.S./K.F.R. led the writing and all authors reviewed the manuscript.

ACKNOWLEDGMENTS

The implants for this study were kindly provided by Straumann AG. Open access funding provided by Universitat Zurich.

FUNDING INFORMATION

This study was funded by the researcher's institution.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

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

ORCID

Kai R. Fischer https://orcid.org/0000-0001-8632-3879
Philipp Sahrmann https://orcid.org/0000-0001-5568-2529
Patrick R. Schmidlin https://orcid.org/0000-0002-1377-0325

REFERENCES

Albrektsson, T., Chrcanovic, B., Mölne, J., & Wennerberg, A. (2018). Foreign body reactions, marginal bone loss and allergies in relation to titanium implants. *European Journal of Oral Implantology*, *11*(Suppl 1), S37–S46.

Blanco, C., Pico, A., Dopico, J., Gándara, P., Blanco, J., & Liñares, A. (2022). Adjunctive benefits of systemic metronidazole on non-surgical treatment of peri-implantitis. A randomized placebo-controlled clinical trial. *Journal of Clinical Periodontology*, *49*(1), 15–27.

Cobb, C. M., Daubert, D. M., Davis, K., Deming, J., Flemmig, T. F., Pattison, A., Roulet, J. F., & Stambaugh, R. V. (2017). Consensus conference findings on supragingival and subgingival air polishing. *Compendium of Continuing Education in Dentistry*, *38*(2), e1–e4.

Deppe, H., Wolff, C., Bauer, F., Ruthenberg, R., Sculean, A., & Mücke, T. (2018). Dental implant surfaces after insertion in bone: An in vitro study in four commercial implant systems. *Clinical Oral Investigations*, *22*(3), 1593–1600.

Dreyer, H., Grischke, J., Tiede, C., Eberhard, J., Schweitzer, A., Toikkanen, S. E., Glöckner, S., Krause, G., & Stiesch, M. (2018). Epidemiology and risk factors of peri-implantitis: A systematic review. *Journal of Periodontal Research*, *53*(5), 657–681.

Emmert, M., Spille, J., Behrens, E., Ayna, M., Karayurek, F., Wiltfang, J., Acil, Y., & Gülses, A. (2021). Comparative assessment of the primary stability of Straumann® BLX implant design using an in-vitro sinus lift-simultaneous implant insertion modelPrimary stability of Straumann® BLX implant design. *Journal of Oral Implantology*, *48*(4), 269–275.

Fragkioudakis, I., Tseleki, G., Doufexi, A. E., & Sakellari, D. (2021). Current concepts on the pathogenesis of peri-implantitis: A narrative review. *European Journal of Dentistry*, *15*(02), 379–387.

Francis, S., Iaculli, F., Perrotti, V., Piattelli, A., & Quaranta, A. (2022). Titanium surface decontamination: A systematic review of In vitro comparative studies. *International Journal of Oral & Maxillofacial Implants*, *37*(1), 76–84.

Francisco, H., Finelle, G., Bornert, F., Sandgren, R., Herber, V., Warfving, N., & Pippenger, B. E. (2021). Peri-implant bone preservation of a novel, self-cutting, and fully tapered implant in the healed crestal ridge of minipigs: Submerged vs. transgingival healing. *Clinical Oral Investigations*, *25*(12), 6821–6832.

Fretwurst, T., Buzanich, G., Nahles, S., Woelber, J. P., Riesemeier, H., & Nelson, K. (2016). Metal elements in tissue with dental peri-implantitis: A pilot study. *Clinical Oral Implants Research*, *27*(9), 1178–1186.

Fretwurst, T., Nelson, K., Tarnow, D. P., Wang, H. L., & Giannobile, W. V. (2018). Is metal particle release associated with peri-implant bone destruction? An emerging concept. *Journal of Dental Research*, *97*(3), 259–265.

Haleem-Smith, H., Argintar, E., Bush, C., Hampton, D., Postma, W. F., Chen, F. H., Rimington, T., Lamb, J., & Tuan, R. S. (2012). Biological responses of human mesenchymal stem cells to titanium wear debris particles. *Journal of Orthopaedic Research*, *30*(6), 853–863.

Iatrou, P., Chamilos, C., Nickles, K., Ratka, C., Eickholz, P., & Petsos, H. (2021). In vitro efficacy of three different nonsurgical implant

surface decontamination methods in three different defect configurations. *International Journal of Oral & Maxillofacial Implants*, *36*(2), 271–280.

Keim, D., Nickles, K., Dannewitz, B., Ratka, C., Eickholz, P., & Petsos, H. (2019). In vitro efficacy of three different implant surface decontamination methods in three different defect configurations. *Clinical Oral Implants Research*, *30*(6), 550–558.

Liñares, A., Pico, A., Blanco, C., & Blanco, J. (2019). Adjunctive systemic metronidazole to nonsurgical therapy of Peri-implantitis with Intrabony defects: A retrospective case series study. *International Journal of Oral and Maxillofacial Implants.*, *34*(5), 1237–1245.

Marcantonio, C., Nicoli, L. G., Marcantonio Junior, E., & Zandim-Barcelos, D. L. (2015). Prevalence and possible risk factors of peri-implantitis: A concept review. *J Contemp Dent Pract*, *16*(9), 750–757.

Messous, R., Henriques, B., Bousbaa, H., Silva, F. S., Teughels, W., & Souza, J. (2021). Cytotoxic effects of submicron-and nano-scale titanium debris released from dental implants: An integrative review. *Clinical Oral Investigations*, *25*(4), 1627–1640.

Meyer, U., Bühner, M., Büchter, A., Kruse-Lösler, B., Stamm, T., & Wiesmann, H. P. (2006). Fast element mapping of titanium wear around implants of different surface structures. *Clinical Oral Implants Research*, *17*(2), 206–211.

Nart, J., Pons, R., Valles, C., Esmatges, A., Sanz-Martín, I., & Monje, A. (2020). Non-surgical therapeutic outcomes of peri-implantitis: 12-month results. *Clinical Oral Investigations*, *24*(2), 675–682.

Obando-Pereda, G. A., Fischer, L., & Stach-Machado, D. R. (2014). Titanium and zirconia particle-induced pro-inflammatory gene expression in cultured macrophages and osteolysis, inflammatory hyperalgesia and edema in vivo. *Life Sciences*, *97*(2), 96–106.

Olmedo, D. G., Nalli, G., Verdú, S., Paparella, M. L., & Cabrini, R. L. (2013). Exfoliative cytology and titanium dental implants: A pilot study. *Journal of Periodontology*, *84*(1), 78–83.

Petersilka, G., Heckel, R., Koch, R., Ehmke, B., & Arweiler, N. (2018). Evaluation of an ex vivo porcine model to investigate the effect of low abrasive airpolishing. *Clinical Oral Investigations*, *22*(7), 2669–2673.

Pettersson, M., Pettersson, J., Johansson, A., & Molin Thorén, M. (2019). Titanium release in peri-implantitis. *Journal of Oral Rehabilitation*, *46*(2), 179–188.

Ronay, V., Merlini, A., Attin, T., Schmidlin, P. R., & Sahrmann, P. (2017). In vitro cleaning potential of three implant debridement methods. Simulation of the non-surgical approach. *Clinical Oral Implants Research*, *28*(2), 151–155.

Sahrmann, P., Ronay, V., Hofer, D., Attin, T., Jung, R. E., & Schmidlin, P. R. (2015). In vitro cleaning potential of three different implant debridement methods. *Clinical Oral Implants Research*, *26*(3), 314–319.

Sahrmann, P., Ronay, V., Sener, B., Jung, R. E., Attin, T., & Schmidlin, P. R. (2013). Cleaning potential of glycine air-flow application in an in vitro peri-implantitis model. *Clinical Oral Implants Research*, *24*(6), 666–670.

Senna, P., Antoninha Del Bel Cury, A., Kates, S., & Meirelles, L. (2015). Surface damage on dental implants with release of loose particles after insertion into bone. *Clinical Implant Dentistry and Related Research*, *17*(4), 681–692.

Stavropoulos, A., Bertl, K., Winning, L., & Polyzois, I. (2021). What is the influence of implant surface characteristics and/or implant material on the incidence and progression of peri-implantitis? A systematic literature review. *Clinical Oral Implants Research*, *32*, 203–229.

Steiger-Ronay, V., Merlini, A., Wiedemeier, D. B., Schmidlin, P. R., Attin, T., & Sahrmann, P. (2017). Location of unaccessible implant surface areas during debridement in simulated peri-implantitis therapy. *BMC Oral Health*, *17*(1), 1–7.

Tarazona-Álvarez, B., López-Roldan, A., Vidal-Infer, A., López-Padilla, D., & Alonso-Arroyo, A. (2021). Bibliometric analysis of the scientific production of literature on peri-implant diseases in the web of science. *Clinical Implant Dentistry and Related Research*, *23*(4), 625–634.

Tastepe, C. S., van Waas, R., Liu, Y., & Wismeijer, D. (2012). Air powder abrasive treatment as an implant surface cleaning method: A literature review. *International Journal of Oral & Maxillofacial Implants*, *27*(6), 1461–1473.

Tuchscheerer, V., Eickholz, P., Dannewitz, B., Ratka, C., Zuhr, O., & Petsos, H. (2021). In vitro surgical and non-surgical air-polishing efficacy for implant surface decontamination in three different defect configurations. *Clinical Oral Investigations*, *25*(4), 1743–1754.

Wada, M., Mameno, T., Otsuki, M., Kani, M., Tsujioka, Y., & Ikebe, K. (2021). Prevalence and risk indicators for peri-implant diseases: A literature review. *Japanese Dental Science Review*, *57*, 78–84.

How to cite this article: Fischer, K R., Büchel, J., Gubler, A., Liu, C C., Sahrmann, P., & Schmidlin, P R. (2023). Nonsurgical cleaning potential of deep-threaded implants and titanium particle release: A novel in vitro tissue model. *Clinical Oral Implants Research*, *34*, 416–425. https://doi.org/10.1111/clr.14045